CAFixD – A CASE-BASED REASONING METHOD FOR FIXTURE DESIGN

by

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Abstract

Fixtures accurately locate and secure a part during machining operations such that the part can be manufactured to design specifications. To reduce the design costs associated with fixturing, various computer-aided fixture design (CAFD) methods have been developed through the years to assist the fixture designer. Much research has been directed towards developing systems that determine an optimal fixture plan layout, but there is still a need to develop a CAFD method that can continue to assist designers at the unit level where the key task is identifying the appropriate structure that the individual units comprising a fixture should take. This research work details the development of a CAFD methodology (called CAFixD) that seeks to fill this hole in the CAFD field. The approach taken is to consider all operational requirements of a fixture problem, and use them to guide the design of a fixture at the unit level. Based upon a case-based reasoning (CBR) methodology where relevant design experience is retrieved and adapted to provide a new fixture design solution, the CAFixD methodology adopts a rigorous approach to indexing design cases in which axiomatic design functional requirement decomposition is adopted. Thus, the design requirement is decomposed in terms of functional requirements, physical solutions are retrieved and adapted for each individual requirement, and the design re-constituted to form a complete fixture design. Case adaptation knowledge is used to guide the retrieval process. Possible adaptation strategies for modifying candidate cases are identified and then evaluated. Case and adaptation strategy combinations that result in adapted designs that best satisfy the preferences of the designer are used as the final design solutions. Possible means of refining the effectiveness of the method include combining adaptation strategies and considering the order in which design decisions are taken.

Keywords: axiomatic design, case-based reasoning, fixture design, retrieval-by-adaptability.

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Chapter 1 – Introduction

A key concern for a manufacturing company is the ability to design and produce a variety of high quality products in as short a time as possible. Quick release of a new product into the market place, ahead of any competitors, is a crucial factor in being able to secure a higher percentage of the market place and a higher profit margin. As a result of the consumer desire for variety, batch production of products is now more the norm than mass production, which has resulted in the need for manufacturers to develop flexible, agile manufacturing practices to achieve a rapid turnaround in product development.

A key aspect of developing a product is the design stage in which ideas for a product must be generated and evaluated. This can be a lengthy, complex, and often iterative affair involving many phases such as:

- identifying the need for a product;
- generating initial ideas for a potential solution;
- evaluating these ideas;
- refining them and adding greater levels of detail;
- testing them for the purposes of further evaluation;
- producing complete specifications for the chosen solution;
- preparing all necessary documentation such as manufacturing drawings and materials listings.

Not only must the product itself be designed, but so too must the means by which it will be produced. Thus all the above steps must be repeated to design a suitable production setup. Obviously therefore the financial costs and time delays that can accrue during the design of both the product and the manufacturing set up can be detrimental to a company's ability to meet the demands of the marketplace

Over the past twenty years or so, computers have been employed more and more to assist these activities. Computer-aided design (CAD) and computer-aided manufacturing (CAM) systems are used to aid design and manufacturing tasks, with the objective of reducing the duration and costs of these steps in the production process. Many systems have been developed to provide assistance with particular aspects of the design and manufacturing stages. During design, for example, CAD systems can predict the expected behaviour of designs, assist the designer during decision making processes, and help rapidly evaluate different designs. During manufacture, CAM systems can assist with aspects such as planning, data communication, material requirement planning, and generating of machine tool cutting paths, to name but a few.

Such computer tools are used to support many parts of the production process. One important component within production is fixturing. Whilst undergoing many of the operations that form part of its manufacturing process, a product must be held securely in position. A fixture is a special tool used to rapidly and accurately position (or "locate" as is the more commonly used term) the workpiece, and support and secure it adequately such that all parts that are produced using this fixture will be within the design specifications for that part. This accuracy facilitates the interchangeability of parts that is prevalent in much of modern manufacturing. There are many types of manufacturing operations such as various forms of heat treatment, welding, chemical treatments, and so on. For the purposes of this dissertation the focus will be on fixtures used in machining processes such as milling and drilling, in which, the accuracy of location is measured relative to the position of the machine tool performing the machining operation.

1.1 The Structure of a Fixture

Physically a fixture is comprised of devices capable of supporting and clamping the workpiece (Rong, 1999). There are many means of achieving this, ranging from simple vice grips or lathe chucks to more unusual fixtures that are based upon phase change materials in which the physical property (such as temperature or pressure) of a certain material is manipulated to initially change the material's phase from liquid to solid in order to locate and secure the workpiece, before being altered again to allow the material to revert back to a liquid form from which the workpiece can be removed. For the purposes of this dissertation however more conventional fixtures such as that illustrated in Figure 1 will be studied.

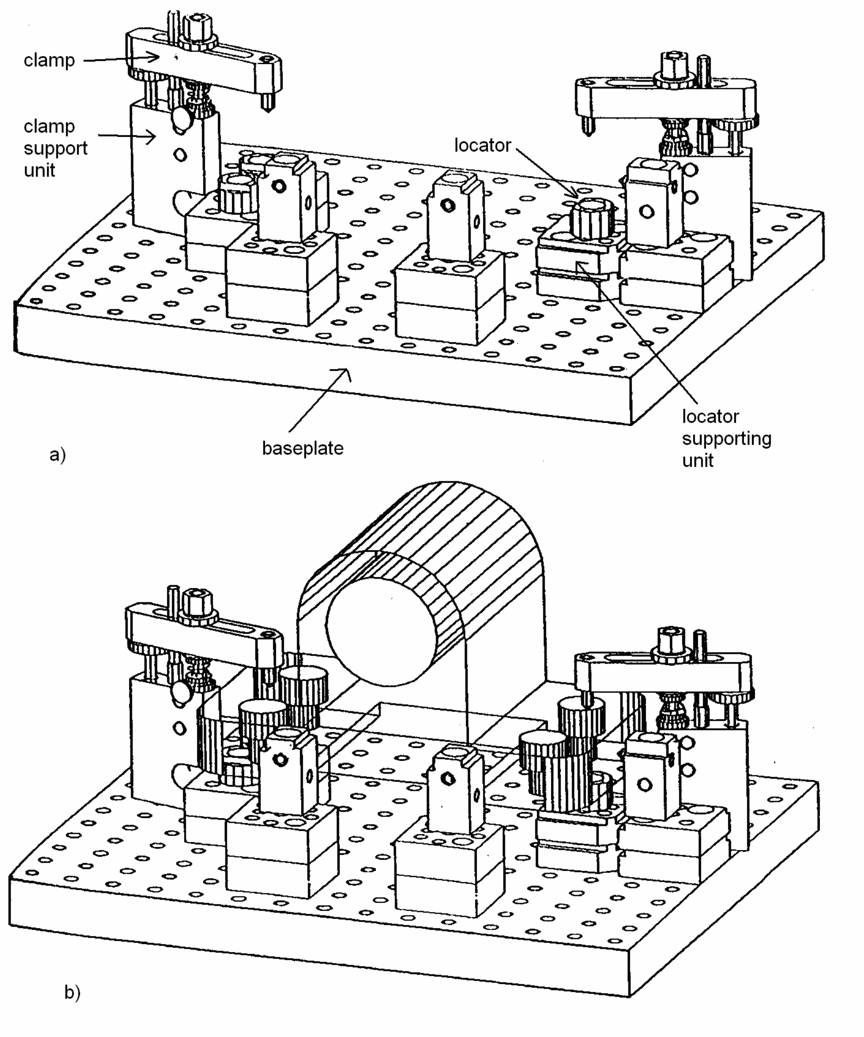


Figure 1: A typical modular fixture, shown a) without and b) with a workpiece (Rong, 1999)

In such typical fixtures the workpiece rests on locators that accurately locate the workpiece. Clamps are used to hold the workpiece against the locators during machining thus securing the workpiece's location. The typical structure of a fixture consists of a base-plate, to which the clamping and locating units are attached. The locating units themselves consist of the locator supporting unit and the actual locator. The locator is the part of the locating unit that contacts the workpiece. The clamping units consist of a clamp supporting unit and a clamp that actually contacts the workpiece and exerts a clamping force on it. Fixtures may contain different numbers and different types of clamping and locating units, but units generally always follow the same basic format that consists of a supporting unit upon which sits a particular type of locator or clamp.

Although the primary function of a fixture is to accurately locate and secure a workpiece, there are many other criteria that it should attempt to satisfy, most often concerned with ergonomic factors. These may include that the fixture should be:

- be simple and quick to operate (by facilitating easy loading and unloading of the workpiece from the fixture);
- be error-proof (prevent the workpiece from being loaded into the fixture incorrectly orientated);
- offer some means of preventing unnecessary chip accumulation during machining;
- provide extra support where necessary for unusually shaped or large workpieces;
- offer some means of guiding the tool onto the workpiece (fixtures that have this particular feature are often referred to as jigs).

Finally one of the most important aspects of a fixture is that it should not add unnecessarily to production costs, whether the cost is incurred as a result of fixture assembly time, expensive materials, fixture manufacture costs, and so on.

A further aspect related to fixture design is that different design considerations often conflict with each other. For example a heavy fixture can be advantageous as this aids the stability of the fixture. However increasing the weight of a fixture can have an adverse effect upon cost due to the increase of material costs that this would incur and also because the fixture would become more difficult to handle as a result of its weight. All of these considerations contribute therefore to making the fixture design process a complex one.

Fixtures have a direct effect upon machining quality, productivity, and the cost of products. Indeed, the costs associated with fixture design and manufacture can account for 10 – 20% of the total cost of a manufacturing system (Bi & Zhang, 2001). These costs relate not only to the material costs of the fixture and the labour involved in assembling and operating them, but also to the cost of designing these fixtures. Hence there are significant benefits to be reaped by reducing the design costs associated with fixturing.

There are two approaches that have been pursued with this aim. One has concentrated on developing flexible fixture systems, the other on simplifying the design process. The most prominent example of the former approach is the development of modular fixture systems. These systems consist of a set of standard fixture components that can be connected together in a variety of configurations to produce a large range of fixtures from a fixed number of individual components. Other, though lesser used flexible fixturing techniques include the use of phase-changing materials to hold workpieces in place (Hazen & Wright, 1990), programmable fixtures (Tuffentsammer, 1981), and adjustable fixtures (Zhu & Zhang, 1990; Jiang et al., 1988). However, the significant limitation of the flexible fixturing mantra is that it does not address the difficulty of designing fixtures. To combat this problem, an alternative approach adopted to reduce fixturing costs has been to simplify the fixture design process.

1.2 Fixture Design

Various computer-aided fixture design (CAFD) systems, normally employing artificial intelligence techniques, have been developed through the years to assist the designer during the various stages of fixture design (see Figure 2).

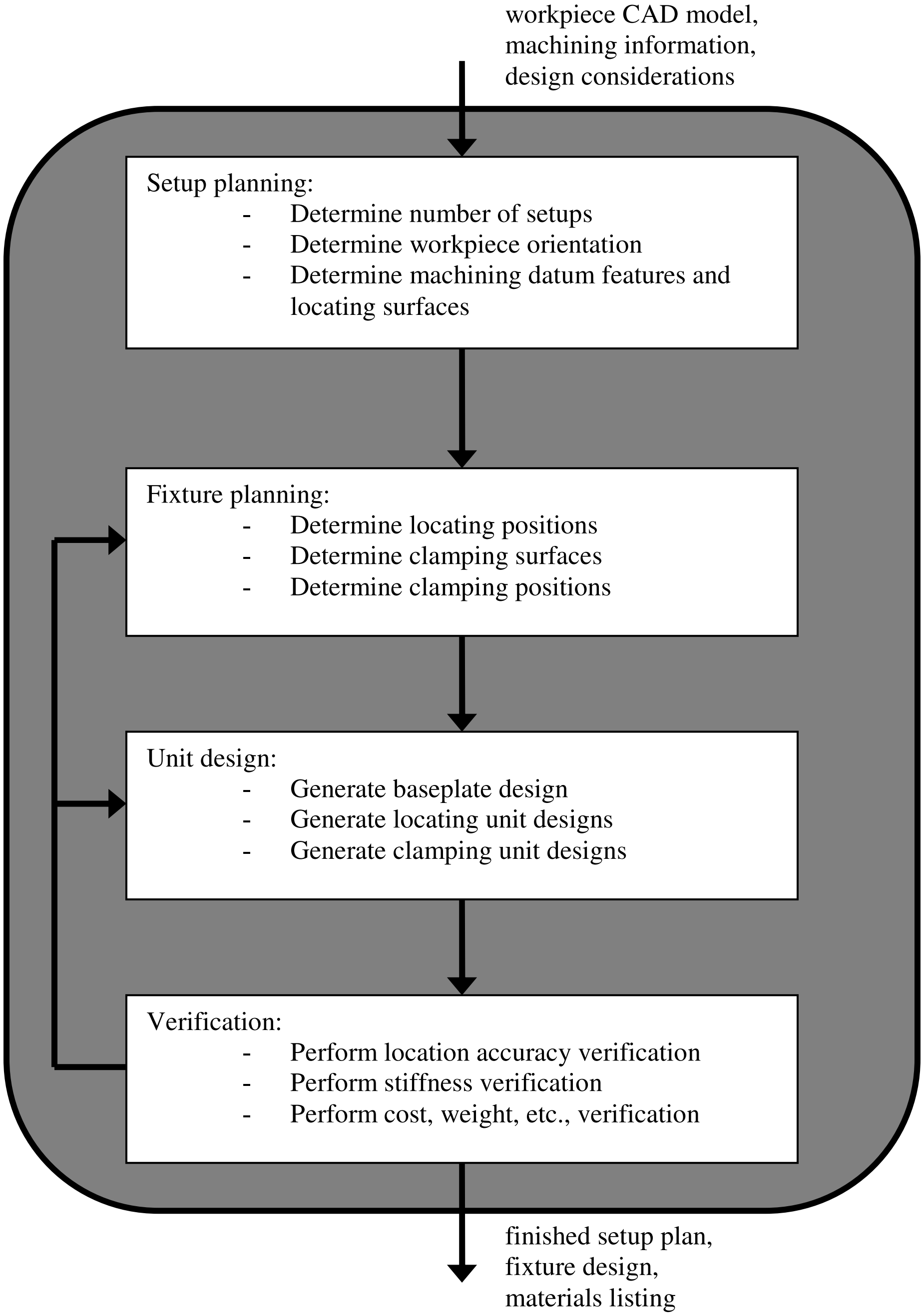


Figure 2: The basic elements of the fixture design process (Kang et al., 2003)

There are four main stages within the fixture design process. These are setup planning, fixture planning, fixture unit design, and verification. The inputs to the design process are the workpiece model (geometry and tolerances), the machining information (type of machining operation, toolpath), and also other design considerations such as the desired cost and weight of the fixture. The output of the design process is a completed fixture design, such as that presented in Figure 1, detailing component geometry and the materials listing.

Setup planning determines the number of setups required to perform all the required machining processes, the orientation of the workpiece in each setup, and the appropriate machining datum surfaces for each setup. A setup represents the combination of processes that can be performed on a workpiece by a single machine tool without having to alter the position or orientation of the workpiece manually. Setup planning is driven by the design datum surfaces contained in the workpiece CAD model. Wherever possible these design surfaces are also used as the machining datum surfaces that contact the locators and thus ensure that machining accuracy is obtained. For each identified setup the fixture planning, fixture unit design, and verification stages must be performed to generate a fixture design for that particular setup.

During fixture planning, the surfaces upon which the clamps must act are identified, together with the actual positions of the locating and clamping points on the workpiece. The number and position of locating points must be such that the workpiece is adequately constrained during the machining process. There are six degrees of freedom (DOFs) that must be constrained so that the workpiece can be uniquely positioned and oriented (Boyes, 1999). Three of these DOFs are linear motions (in the x, y, and z directions) and three are rotational motions (around the x (α_x) , y (α_y), and z (α_z) axes), as illustrated in Figure 3. The locating points must be arranged such that all DOFs are constrained. There are various ways of arranging locating points to achieve this depending upon the types of surfaces used for locating, but the most common is the 3-2-1 locating principle presented in Figure 4. Here locator L1 constrains the z DOF, locator L2 acting in conjunction with L1 constrains the α_y DOF, and locator L3 acting in conjunction with primarily L2 constrains the α_x DOF. Locator L4 constrains the y DOF, locator L5 acting in conjunction with L4 constrains the α_z DOF, and locator L6 constrains the remaining linear DOF, x.

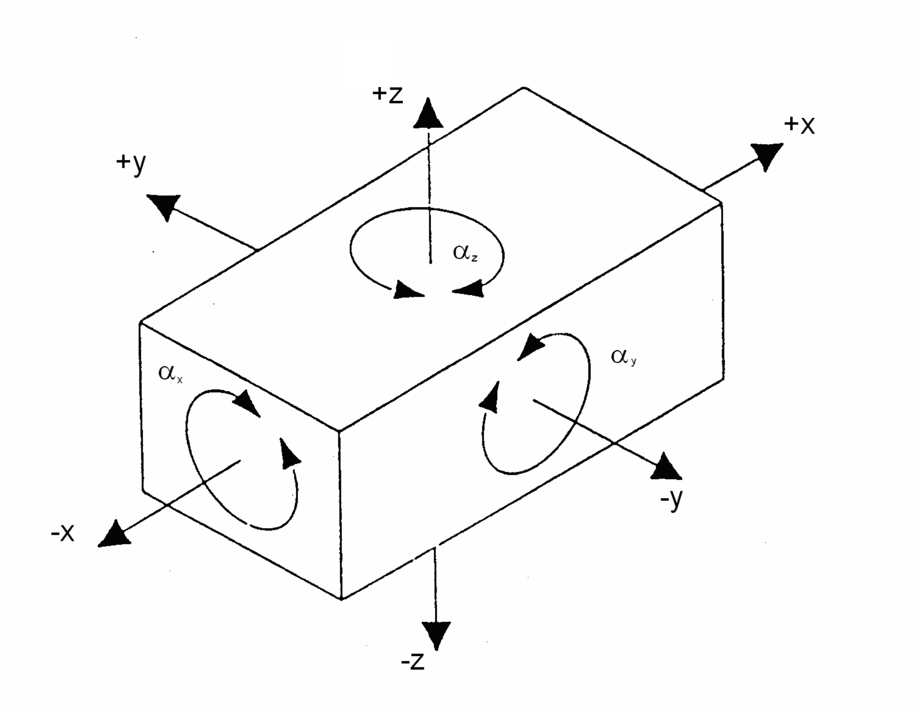


Figure 3: The six degrees of freedom

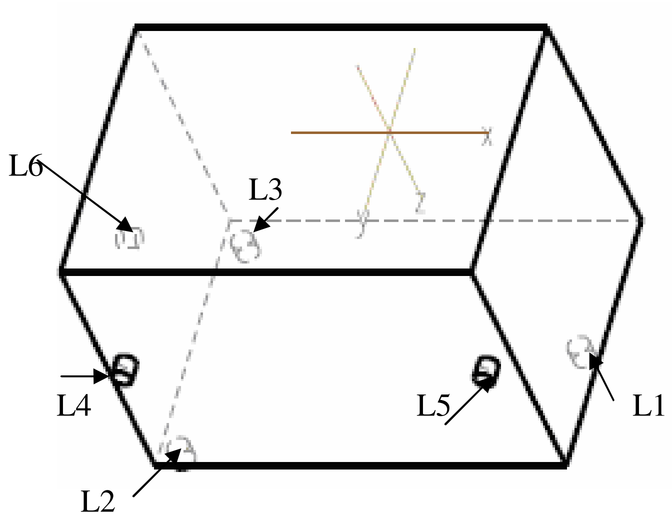


Figure 4: The standard 3-2-1 locating model

In the third stage of fixture design suitable unit designs that comprise the fixture (i.e., the locating and clamping units, together with the base plate) are generated. These units will deflect as a result of the forces experienced during the machining operations. When they deflect, the position or orientation of the workpiece will change. Therefore it is important that these units do not deflect to the extent that the design specifications for the part cannot be satisfied. During the verification stage the design is tested to ensure that all units have sufficient stiffness and that the tolerance requirements of the workpiece can be achieved. The design also has to be verified to ensure that it meets other design considerations that may include fixture cost, fixture weight, workpiece loading time, assembly time, and workpiece unloading time.

1.3 Motivation

Within the CAFD field, much work has been performed on developing CAD tools to assist specific aspects of the fixture design process. These efforts are described in greater detail in the following chapter but a brief description now will help to highlight the need for the research that is the subject of this dissertation. With regard to previous efforts in this area, there has been a significant focus on developing systems to aid fixture planning. The outputs of such systems are the positions of the locating and clamping points: i.e., the points where the workpiece contacts the fixture. Typical efforts in this field have resulted in the development of knowledge-based expert systems such as that created by Nee & Kumar (1991). Other work has resulted in systems based upon genetic algorithms (Krishnakumar & Melkote, 2000; Wu & Chan, 1996), finite element analysis (Mason, 1995), and screw theory analysis (Fuh & Nee, 1994).

Although considerable progress has been made in determining optimal locating positions, less attention and progress has been made regarding the physical structure that a fixture and its constituent units should assume. Some work has however been performed in this field. Kumar et al. (1999) attempted to conceptually design individual fixture units using a combined genetic algorithm/neural network approach. However, their output was essentially a high level conceptual design of a fixture unit that specified its basic type and the nature of its components. Attempts at designing complete fixture units have been largely based upon geometric approaches (Wu et al., 1998; An et al.,1999) where the basic concept is to identify the critical dimension of a particular fixture unit (normally its height) and then relate all other dimensions of this component through pre-existing mathematical relationships to this critical dimension.

With regard to assisting the verification stage, Zheng (2005) developed a model to predict fixture stiffness. Kang et al. (2003) developed a CAFD tool designed to check fixtures designs for workpiece stability, locating accuracy, and accessibility of locating surfaces. In terms of assisting the setup planning stage, Hu (2001) and Yao (2003) developed techniques that determined the setups required for a workpiece and the locating positions for those setups.

Although work has been performed in most areas of CAFD, there are several issues which require attention. The first of these is that no one method or tool considers all the operational requirements of a fixture when generating their part of a design solution. For example, An et al. (1999) can produce a fixture based upon a geometric analysis. However this takes no account of other design considerations such as fixture cost which if incorporated into the design process may have a significant bearing upon the generated solution.

A second related concern is that none of these approaches seeks to *fully define* the fixturing problem. As has been mentioned already, the design of fixtures, and indeed design in general, is a complex process due to the conflicting nature of the many applicable design requirements. It is therefore difficult, if not impossible, to generate a satisfactory design if the design problem itself has not been well understood at the beginning of the solution seeking process.

A third issue relates to integrating all these separate approaches under the umbrella of a *single framework*. In such cases where would the responsibility for making decisions lie and how would these decisions be made? For example, An et al.'s system (1999) has the ability to produce a fixture design using a geometric approach. In the design process outlined in Figure 2 this design would then be subjected to various types of verification. Zheng's (2005) stiffness model could be used to attempt to validate the design. If however a problem was detected with the design and it was found to exhibit insufficient stiffness it is unclear who would be responsible for attempting to repair the design. Zheng's approach only deals with evaluation and has no capacity for modifying a design. An et al.'s system does not appear to have the flexibility to produce a new design solution and may just continually produce the same solution if left to its own devices. Would user input be required to solve the problem? If a design is to be changed then how should it be modified and what or who should guide this part of the design process. These are complicated issues that have yet to be addressed in CAFD.

A final issue is that no approach yet has been defined that attempts to perform setup planning, fixture planning, unit design, and verification *autonomously*. Most approaches concentrate on one or two stages of the design process and assume that their inputs will come from elsewhere, whether it be from the user or the output from an earlier stage of the CAFD process. Tools developed to support setup planning assume that some other tool will take their output and turn it into a physical fixture design. What appears to be lacking in the CAFD field is a tool that can take the workpiece and machining information together with the user specified design considerations and process that information to generate a satisfactory fixture.

These four points are discussed in greater depth in the following chapter but this brief summary of the current status of the CAFD field augments an understanding of the need for further research work to be carried out. It is this research work that is the focus of this dissertation.

1.4 Research Objectives

The objectives this research are:

1. Concentrate on developing an approach for assisting the unit design phase of fixture design. The aim is to generate complete fixture designs that fully detail the physical structure of the locating/clamping units based upon an understanding of the required function of each unit.
2. Develop a CAFD method that is able to generate a comprehensive formulation of a fixturing requirement (and subsequently obtain solutions for it) based upon the following design considerations:
    a. workpiece geometry;
    b. workpiece design tolerances;
    c. workpiece stability;
    d. fixture unit stiffness;
    e. fixture cost;
    f. fixture usability;
    g. fixture component collision;
    h. fixture weight.
3. Develop a CAFD method that integrates setup planning, fixture planning, unit design, and verification into a single design tool. This integration should be such that:
    a. the output from one design phase can be accepted and understood by the following phase;
    b. it should be possible to repair outputs from design phases if they fail during testing.
4. Develop a software implementation that demonstrates the operation of the CAFD methodology.

1.5 Dissertation Contents

The dissertation is divided into six chapters. Following this introduction, Chapter 2 justifies the need to develop the CAFixD approach in further detail. A literature review of various CAFD research efforts is presented, followed by a review of more general design concepts. Specifically case-based reasoning (CBR), axiomatic design, and decision-based design using utility analysis are discussed and critiqued, resulting in the formulation in the subsequent chapter of the key objectives the CAFixD method should address. Chapter 3 also outlines the means by which these objectives will be attained. Chapter 4 outlines the CAFixD methodology and then describes in greater detail its more important aspects. Specifically, the types of knowledge used in CAFixD method will be discussed together with details of how that knowledge is stored, retrieved, and used throughout the design process. Chapter 5 presents a worked example to illustrate how the CAFixD method navigates towards a final fixture design solution.

Chapter 6 details issues associated with the CAFixD system implementation. The role of the system within an integrated design environment is detailed, succeeded by an overview of the CAFixD system as a whole. The system information flows, communication methods, data modules, and user interface are then presented together with a sample of the system output. Chapter 7 presents a discussion on the project as a whole. In particular the research contributions are listed and the CAFixD methodology and software system are evaluated against the objectives detailed in Chapter 3. This chapter also proffers some suggestions for refining and expanding the effectiveness of the method.

Chapter 2 – Literature Review

Various approaches have been adopted to develop tools that assist the designer, regardless of the actual artefact being designed. This chapter presents a review and critique of various tools and methodologies that have been used to aid design. Initially, various types of CAFD systems and techniques are reviewed, followed by a discussion of more general design theories. Specifically, case-based reasoning, axiomatic design, and decision-based design using utility analysis techniques are described and critiqued.

2.1 Computer-aided Fixture Design

Various artificial intelligence tools have been used in an effort to aid the designer during the four stages of fixture design: setup planning, fixture planning, unit design, and verification. Section 2.1.1 presents an overview of some of the achievements within each of these four stages of the fixture design process. Section 2.1.2 presents a critique of the current state of research within the CAFD community and identifies some of the remaining challenges within the field.

2.1.1 Research in the CAFD Community

A review of the focus of various research efforts in the CAFD community is presented in Table 1. The majority of work has focussed on fixture planning where the key task is to determine the points of location and clamping. Several different approaches have been adopted to assist this part of the design process, ranging from those based purely upon workpiece geometry to finite element techniques that consider the effects of the machining and clamping forces applied to the workpiece during machining. However, few approaches concentrate on purely one aspect of the design process but instead attempt to assist various design stages, most commonly unit design and fixture planning.

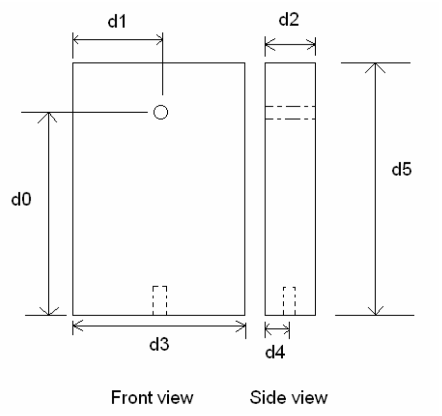
Research effort	Setup planning	Fixture planning	Unit design	Verification	System
Wu et al. (1997)			●	●	●
An et al. (1999)			●		●
Wu et al. (1998)		●	●		●
Krishnakumar (2000)		●			●
Kumar et al. (1999)			●		●
Kumar et al. (2000)			●		●
Kang et al. (2003)		●		●	●
Hu (2001)	●	●			●
Yao (2003)	●	●			●
Kumar, Fuh, & Kow (2000)		●		●	●
Nee & Kumar (1991)	●	●	●	●	●
Nnaji & Alladin (1990)		●	●		●
Trappey & Liu (1992)				●	
Roy & Liao (1999)		●		●	●
Cecil (2001)			●		
Hu & Rong (2000)				●	●
Krishnakumar et al. (2002)		●			●
Roy & Liao (2002)		●			
Liu & Strong (2003)				●	●
Hurtado & Melkote (2001)			●		●
Joneja & Chang (1999)	●	●	●	●	●
Wang (2002)		●			
Kashyap & DeVries (1999)		●			●
Zheng (2005)				●	●
Lin & Huang (1997, 2)		●	●		
Amaral et al. (2005)		●		●	●
Wu & Chan (1996)		●			●

Table 1: Summary of CAFD research focus

Wu et al. (1998) developed a fixture planning/unit design approach based upon an analysis of the workpiece geometry. A variation of the Brost & Goldberg algorithm (1996) was implemented to determine appropriate clamping and locating positions on the workpiece as well as the workpiece orientation. Having determined the points of contact with the workpiece, they then calculated the required height of the fixture units and used a rule-base to determine the modular fixturing components that could be configured to match the required height. Design considerations were restricted to satisfying the workpiece geometry alone.

Wu et al (1997) developed an automated customized fixture design system. Based upon a fixture structure analysis, fixtures are divided into functional components (locators and clamps), fixture bases, and supports. The inputs to the approach are the workpiece geometry together with the locating and clamping coordinates. A geometry-element generator generates fixture components with dimensions according to workpiece geometry and operational information. Once individual locators and clamps have been designed individually, the support units can then be generated to connect the locators/clamps to the baseplate, resulting in a complete fixture unit. Rules are used to select components. For example, to select a locator, rules will be employed to evaluate the type of surface the locator will act on, the surface texture, and the number of degrees of freedom to be constrained. Verification of the fixture concentrates on ensuring that there are no collisions between individual components of the fixture and the workpiece.

Dimensioning of components is performed in a similar way as that used by An et al. (1999) who developed a geometrically based system in which the dimensions of a fixturing component were related to the primary dimension of that component through recommended dimension relationships. Figure 5 illustrates a simple support component for which the primary dimension is its functional height, *d0*. One of the main functions of support components is to connect the baseplate to the locators contacting the workpiece, and the support unit must bridge this height gap between the base and the locator. The functional height of a support unit must match this height gap. Figure 5 also presents a set of standard dimension relationships illustrating how each dimension of the unit varies according to changes in the primary dimension. To construct whole fixture units, a fixture component relationship database is used that contains knowledge of how different components could fit together.



Primary design dimension: d0

Recommended dimension relations:
1. d2 = (d0/100) * 15
2. d4 = 0.5 * d2
3. d3 = (d0/100) * 60
4. d1 = 0.5 * d3
5. d5 = 1.3 * d0

Figure 5: A support unit with recommended dimension relations

Krishnakumar & Melkote (2000) employ a GA approach to determine an optimal fixture plan layout: i.e., the optimal locating and clamping points such that deformation as a result of clamping and machining forces is minimized. This type of technique involves discretizing a workpiece into small elements, resulting in the creation of a series of nodes (contact points) across the surface of the workpiece. The design variables, which are the clamp and locator locations, are coded in a binary string of integers. The GA then randomly generates a population of strings from this initial string, and for each initial string the deformation at each node is determined. Krishnakumar & Melkote adopt a finite element approach to determine the displacements and assume frictionless boundary conditions. The GA selects the strings that result in the least workpiece deformation and alters them using the processes of reproduction, crossover, and mutation to create new strings that result in even lower deformations. Rule-based techniques are normally employed to control the functioning of the GA.

Amaral et al. (2005) also employ a finite element analysis method to optimize the fixture layout plan through choosing locating positions that minimize the deformation of the workpiece during machining. Amaral et al. model the locating boundary conditions (i.e., the locators at their interface with the workpiece) as multiple springs in parallel that support friction loads and that the locating boundary conditions act over an area rather than acting as point contacts. Optimization of the locating points is achieved using a first order method. Inputs to the system are the workpiece geometry, the stiffness values for each point of location, and the machining values. The outputs of the system are a list of optimized locating points that minimize the workpiece deflection. Krishnakumar et al. (2002) also used a finite element approach although they applied different boundary conditions by assuming point contacts existed at each locating and clamping position. Kashyap & DeVries (1999) also use a finite element model in this fashion, but use the penalty function method as a means of optimizing the locating and clamping positions.

Kumar et al. (1999; 2000) used a GA/neural network approach to conceptually design complete fixture units. The neural network is trained with a selection of previous design problems and their respective solutions. Basic information regarding a new fixturing design problem is supplied to the system and a population of possible solutions randomly generated. The neural network then evaluates these designs and guides the genetic algorithm until a satisfactory design solution is attained, at which point the GA process is terminated. The criteria for evaluating possible solutions are related to design considerations of cost, ease of fixture operation, and effect of the fixture on production rate. A very basic fixture plan outlining the type of surfaces used for location (but no locating coordinates) is required as an input to the system. The output is a conceptual design that lists the types of components that should be used (for example types of locators or clamps) in the fixture. No locating coordinates or data regarding the structural dimensions or physical form of the fixture units are provided.

Hu (2001) and Yao (2003) developed tools to support setup planning based upon datum machining surface relationship graphs (DMSRG). A DMSRG is a set of relationship graphs $G=\{G_i\}$, $i = 1, 2, \ldots, M$, where M is the number of setups. G_i represents the relationship between the datum and machining surfaces in setup *i*. Figure 6 illustrates an example of a workpiece and its DMSRG. These DMSRG are generated by analysing the workpiece tolerance information and ascertaining which features have common design datum surfaces. Features with the same datum surfaces are grouped together into setups in which the design datum surfaces are used as the machining datum surfaces to increase the likelihood of machining the part within the required tolerance specification. In the example, features A, B, N, and N' all have X, Y, and Z as their design datum surfaces, while features C, D, and E have A, B, and Z as their design datum surfaces.

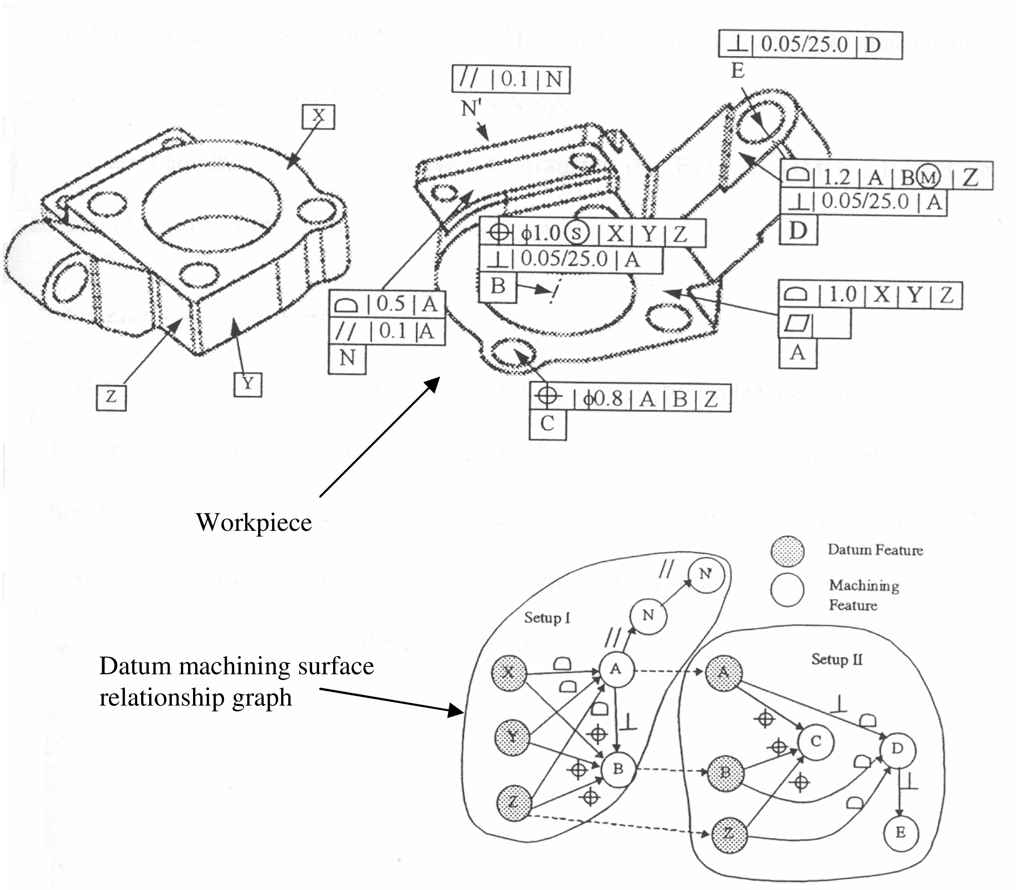


Figure 6: A workpiece and its datum machining surface relationship graph (Hu, 2001)

Hu goes on to determine the tolerance allowed at each locating point. The locating accuracy at each point is a combination of the accuracy of the locating unit tolerance (Δ_l), the machine tool tolerance (Δ_m), the workpiece deformation at the locating point (Δ_w), the deformation of the fixture at the locating point (Δ_f), the locating surface error (Δ_{ls}), and a random error (Δ_r). By either assuming or obtaining from the user values for Δ_m, Δ_w, Δ_{ls}, Δ_f, and Δ_r Hu then sets Δ_l for each locating point to a starting value (the same value of Δ_l is used for each locating point) and determines the displacement of all surfaces on the workpiece. The resultant displacement of each surface is then evaluated to determine if the design tolerance specification can be met. If the displacement is too great then the value of Δ_l is decreased. If the displacement is within the allowed design tolerance then Δ_l is increased to find the most generous value of Δ_l that will allow the design specification to be met. Changes made to Δ_l are applied simultaneously to each locating point. The output of this tolerance analysis therefore is the allowed tolerance Δ_l of each locating unit. This approach results in each locating unit having the same value of Δ_l.

Lei (1998) conducted work related to the tolerance stack up effect caused by individual components within locating units. Each component will have a tolerance associated with it. For the simple case presented in Figure 7 the individual tolerance contributions from each component C1, C2, and C3 combine to form the total variation, Δ_l, of the locating position in the vertical direction. Such variations in component geometry cause not only vertical shifts, but can also result in horizontal changes to the locating position.

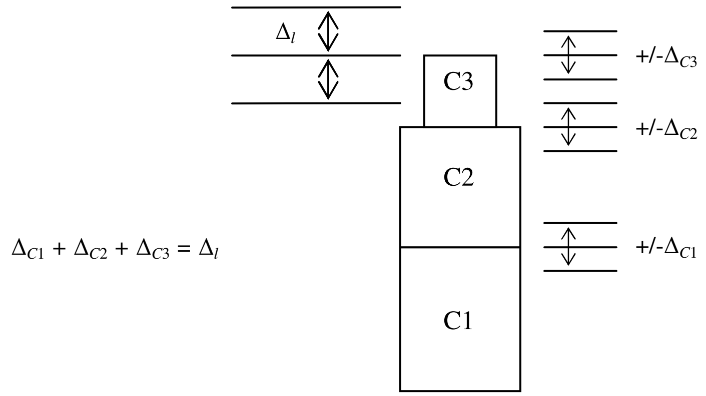


Figure 7: A vertical locating unit

Roy & Liao (1999) use geometric reasoning for the allocation of supporting and clamping positions. An initial fixture layout is generated detailing locating and clamping contact positions on the workpiece. This layout is then subjected to a finite element analysis to determine the deformations the workpiece will experience during machining. If the deformation is too great at any particular point of the workpiece then various heuristic rules that govern the reallocation of the locating positions are evaluated for possible execution. The rules are evaluated based upon an understanding of where the maximum deformation occurs relative to the overall boundary of the workpiece geometry. For this purpose Roy & Liao define three kinds of "range-box" for a workpiece. These are the mid-edge box, the corner box and the load box. Different methodologies are used to move the contact points depending upon which type of range-box the maximum deformation occurs within. Inputs to this system are the workpiece geometry, machining forces, and desired workpiece deformation limits. The output is a fixture plan detailing locating and clamping positions.

Work has also been directed towards developing verification tools to evaluate the stability of a fixture design (Trappey & Liu, 1992; Liu & Strong, 2003). A fixture design is deemed to be stable if force and moment equilibrium is maintained on the workpiece during machining. Thus the sum of all force vectors and the sum of all moments acting on the workpiece during machining must sum to zero. Inputs to such systems are the clamping and machining forces, together with the directions in which they act, the workpiece geometry, and the friction coefficients at each fixture unit/workpiece interface. A further input required is the maximum supporting force that each locating or clamping unit is capable of (this is the maximum force that the unit could sustain in reaction to the machining force acting against that unit). This needs to be defined by the system user. System output generally states whether the fixture design will ensure stability of the workpiece or not.

Roy & Liao (2002) attempt to quantify the stability that a fixture design affords a workpiece, rather than just stating whether a fixture will result in workpiece stability or not. Initially Roy & Liao determine the critical situation in which the workpiece remains stable. This is achieved by setting all clamping forces to zero and solving the equilibrium equations for force and moment for the six locators in response to the machining forces they experience. To satisfy equilibrium some of the locating forces will be negative (i.e., they will pull on the workpiece). In practice this is not possible as locators only push against a workpiece. Thus to identify the critical situation in which the workpiece remains stable, the clamping forces are incrementally increased until all locating forces are positive (i.e., all locators exert a pushing force on the workpiece). The next step is to alter the locating or clamping positions to break the equilibrium that has already been established and determine the new virtual force that would have to be added to the system to maintain equilibrium. This new force is a virtual force because it does not actually exist in the system's new equilibrium in which all reaction forces would rearrange themselves to coincide with the adjustment of the fixturing positions. It is used however in the system's equilibrium with the unchanged fixturing forces and allows the characterisation of the workpiece's stability based upon the virtual work this force would do. A negative virtual work value indicates that the new fixturing position is an improvement in workpiece stability, and the workpiece becomes more stable as the magnitude of this negative virtual work increases. Wu and Chan (1996) used a similar approach but augmented their system by using a GA as a means of optimizing the fixture plan. Hurtado & Melkote (2001) take this work a step further by developing an approach in which the required stiffness at each locating and clamping point is used to determine the structure of simple, pin array fixtures.

Kang et al. (2003) use two models (one geometric, the other kinetic) to verify a fixture's design by performing a locating performance analysis, a tolerance analysis, and a stability analysis. The geometric model describes the relationship between the workpiece and locator displacements. The kinetic model describes the relationship between external forces, fixture deformation and workpiece displacement. In the locating performance analysis, the geometric model is used to verify that all six degrees of freedom are constrained and a locator performance index (LPI) is defined to optimize the locating point layout. During the tolerance analysis the geometric model is used to assign the allowed tolerance for each locating point by means of a sensitivity analysis that ascertains the effect each locator point deviation has upon the ability of the fixture to satisfy the design tolerances of the workpiece. The kinetic model is used to perform a stability analysis. The stability analysis assumes that the displacements caused by machining forces on the locators and the stiffness of the fixture at each locating point are known. This allows the reaction forces at each locator to be determined. Stability is determined by evaluating whether slip occurs at the workpiece/locator interface on the basis of the direction of this reaction force and the coefficient of friction at the interface. Inputs to the system are the workpiece geometry and tolerances, the stiffness of each locating point and allowed displacements due to machining forces. Outputs are optimized locating point coordinates and a verification of whether the fixture is stable or not.

In Hu & Rong (2000) an interference checking algorithm evaluates the fixture design for possible interference with the cutting tool. The system supports standard modular fixture components. For each standard component a database contains a simplified projected view of the cross section of that element. During operation, the system selects the appropriate simplified 2D contour model of each element and augments it with details of the element height. The tool path is modelled on the underlying assumption that a cutter can be simplified to a cylinder and represented by the axis of a cylinder. For example on a 3-axis machine, the cylinder can be projected on to the fixture baseplate and simplified to a circle with a certain height. The 2D contours of the fixture components are expanded by the radius of the circle and the cutter itself is reduced to a dot with height information. Both the fixture components and the cutter models are now 2D geometric elements with a height value. The interference checking algorithm then evaluates when the cutting tool is within the 2D contour of the fixture components and if so it then uses the height information to determine if there is an overlap between the height of the tool and the fixture. If an overlap exists then a collision has occurred. Inputs to the system are the finished fixture plan, the unit design, the cutter toolpath, and the cutter dimensions. The output of the system is a list of any collisions that occur, details of the location of the interference, and the fixture components involved.

Kumar et al. (2000) performed interference checking using a cutter swept volume approach. The toolpath consists of a series of motions, each with their own stop and start positions. The path along which the tool travels for each of these motions can be linear or circular. Again the tool is modelled as a cylinder. A cross section of the tool is taken in the direction of the tool motion, and the toolpath swept volume is generated by extruding this cross section from the start position to the stop position for each motion. A static interference check is then performed to ascertain if this swept volume of the toolpath coincides with any volume fixture. The static interference check function is normally a standard feature on most CAD systems. Inputs required for Kumar's tool are the fixture unit designs, the cutter toolpath, and the cutter geometry.

Cecil (2001) performed some work on how to dimension strap clamps. Scope is limited to obtaining satisfactory dimensions of the clamp itself and thus precludes any attempts to determine the dimensions of the clamping support unit. Cecil's criterion is that the clamp dimensions be such that failure by stress fracture is not predicted. Inputs include the maximum force the clamp is subjected to during machining, the clamp material type, and the ultimate tensile strength of that material. Outputs are the dimensions of strap clamp, but no dimensions of the clamping unit are provided.

Wang (2002) developed a tolerance analysis method to assist fixture layout design for 2D workpieces. Wang identifies three geometrical sources of error at the workpiece/fixture interface points. These are the dimension errors of the locating unit elements themselves, the variation in the geometric shape of the locator such as a profile tolerance specified for a spherical locator, and the errors in the datum surfaces of the workpiece. Required inputs are values of these three errors, the workpiece geometry, and the points of location. Outputs are the new positions of all the to-be-machined features on the workpiece. The approach allows the user to experiment with different locator positions and different values for any of the three geometrical errors.

Lin & Huang (1997) adopt a group technology/neural network approach to generate fixture designs. They propose that there are a set number of basic types of workpiece and for each type there is a basic fixturing mode that is particularly suitable. Each of these workpiece groups are assigned a binary code according to the B-rep data of the workpiece geometry. This code contains information detailing the number of straight line edges on the workpiece, the number of arc edges, and so on. When presented with a new workpiece for which a fixture design is sought, this new workpiece is similarly encoded and a neural network employed that determines to which of the basic workpiece groups it belongs. Once the group has been identified, the basic fixturing mode associated with that group is retrieved and a heuristic rule-base used to determine the specific modular fixturing components that should be used.

Nnaji et al. (1988) and Nnaji & Alladin (1990) developed a rule-based expert system for fixturing on a CAD system using flexible fixtures, based upon an understanding of the workpiece geometry, machining operations, and machine tool. The user supplies workpiece and machining information interactively, at which point the fixturing rules in the system database are evaluated for possible execution. Outputs of the system are the locating and clamping positions, a list of the components to be used for each of the fixture units, and verification of the workpiece stability.

Nee & Kumar (1991) also developed a rule-based automated fixture design. In addition to the functionality offered by Nnaji et al. Nee & Kumar performed a limited check on the displacement likely at each locating point as a result of the machining forces and also implemented a simple justification module that employed heuristic rules to determine whether a modular (comprised from a set of standard components) or dedicated (custom) fixture design should be generated.

Joneja & Chang (1999) developed a system that attempted to perform setup planning, fixture planning, unit design, and verification. Verification is limited to ensuring that stability of the workpiece is achieved. Fixture planning is performed by a planner that exhibits preferences for a particular solution strategy. For example, the planner will always try to hold the part in a vice initially as this offers a simple, cheap solution. If the planner determines that using a vice is physically impossible, then it will turn to an alternative strategy such as using a modular fixture. Upon identifying the solution strategy, the problem is then decomposed into sub-goals that have to be achieved. Typically these are support, clamping, and location goals for modular fixtures. Solutions are found for each of these sub-goals and the solutions integrated together to form a complete fixture. The system inputs are the workpiece geometry and machining forces. Outputs are a setup plan, fixture plan, and unit designs for the locating and clamping units and the baseplate.

2.1.2 Critique of CAFD

Reviewing the current status of CAFD research, three areas of concern stand out. These are:

- there are few approaches that perform all four stages of fixture design, thus the integration of all of these disparate systems together needs to be undertaken;
- there has been a lack of focus on determining the design of individual locating and clamping units;
- few approaches attempt to derive or use a full understanding of the fixturing requirement.

2.1.2.1 Integration Issues

Table 1 listed to which phases of fixture design particular research efforts were directed. Few assisted all four stages, with the major focus being on the development of tools to aid fixture planning. Thus, if the aim of the CAFD community is to develop a tool to assist fixture design in its entirety then all of these disparate systems need to be integrated together under the umbrella of a single framework. There are two issues at the forefront of achieving this aim. The first is that the inputs and outputs of each system must be compatible with the various modules they communicate with. For example, the output of a fixture planning system must be in a format such that a unit design system can understand it and extract the relevant information it requires to allow it to generate suitable fixture units. In practice, this requires the creation of an interface program between each module that can evaluate if a format conversion is required and then perform that conversion if necessary. This is not a particularly complex task, although it is a time consuming one.

However the second integration issue is more taxing in nature. This relates to controlling the design process and deciding where responsibility for decision making should fall if a conflict occurs between any of the individual modules. This becomes an issue particularly when verification of the design is attempted. Consider that Hu’s system (2001) has developed a fixture plan that has been passed to An et al.’s (1999) tool, which subsequently generates a set of locating and clamping units. These are passed to Zheng’s (2005) stiffness verification model for testing. If however the fixture stiffness is found to be below the required level, then the design must be fixed. The questions that arise are:

- who should identify the possible means of fixing the design;
- who should decide the means of repair that should be adopted and what criteria should they use;
- who should then fix the design;

In terms of repairing the design there are different ways in which this could be achieved. One method might be to alter the fixture stiffness requirement, another to increase the stiffness of the fixture. Consider the first approach which may be to alter the stiffness requirement. This requirement is derived from the forces that arise during machining and from the tolerance requirements on specific features of the workpiece. During machining the workpiece and fixture will deform elastically and if this deformation is too great then the design tolerances will not be achieved. However the deformation can be reduced through moving the locating points to positions where the workpiece is more fully supported.

An alternative approach would be to keep the stiffness requirement as is and look to increase the stiffness of the fixture unit itself. This could be achieved by altering the physical dimensions of the unit or by altering the material from which the unit is constructed to one that has a greater modulus of elasticity. Thus there are various possible paths that can be pursued to fix the design, as illustrated in Figure 8. However none of the three systems mentioned are capable of identifying these means of repair, so a fourth party would be required to determine possible means of modification.

Option 1 – Decrease stiffness requirement:
- Move locator positions

Option 2 – Increase unit stiffness:
- Increase unit dimensions
- Increase material strength

Figure 8: Possible ways of fixing a design

The second question that must be answered is which method should be used. Moving the locator positions is possible but would result in the need to identify a suitable set of positions, to recalculate the allowed tolerances at each locating position and the forces acting on each locating unit, and finally it may require the redesign of the unit itself if the new locating position requires a unit of different height. Thus computationally moving the locator represents a significant amount of redesign.

Alternatively the unit stiffness could be increased by altering the physical dimensions of the locating unit. Care has to be taken when doing this due to constraints that may exist between different dimensions of a unit. For example, consider that a simple side locating unit (Figure 9) is to be strengthened by increasing its cross sectional area. Thus dimensions a, b, and c are increased. However doing this may result in the locating unit illustrated in Figure 9b, where the locator has increased to the extent that it now extends above the top of the supporting unit and is inadequately supported. To compensate for this, the height of the supporting unit must be increased to ensure that the locator has a solid base from which to act. Computationally it is a much simpler approach than reassigning locating positions.

The third modification approach is the simplest of all as it involves simply reassigning a stronger material and there is no need to alter any other aspect of the design. Thus from a computational point of view this is the preferred option. However there are other criteria that must be considered. For example a fairly basic issue is the cost associated with any particular change. Changing materials can be expensive depending on which new material is chosen. If the design is switched from some form of common stainless steel to tungsten (which is ten times more expensive) then this third option may not be quite so appealing. If the second modification approach were to be adopted, there would be an increased material cost associated with changing the dimensions. However it may not be as great as that caused by changing material.

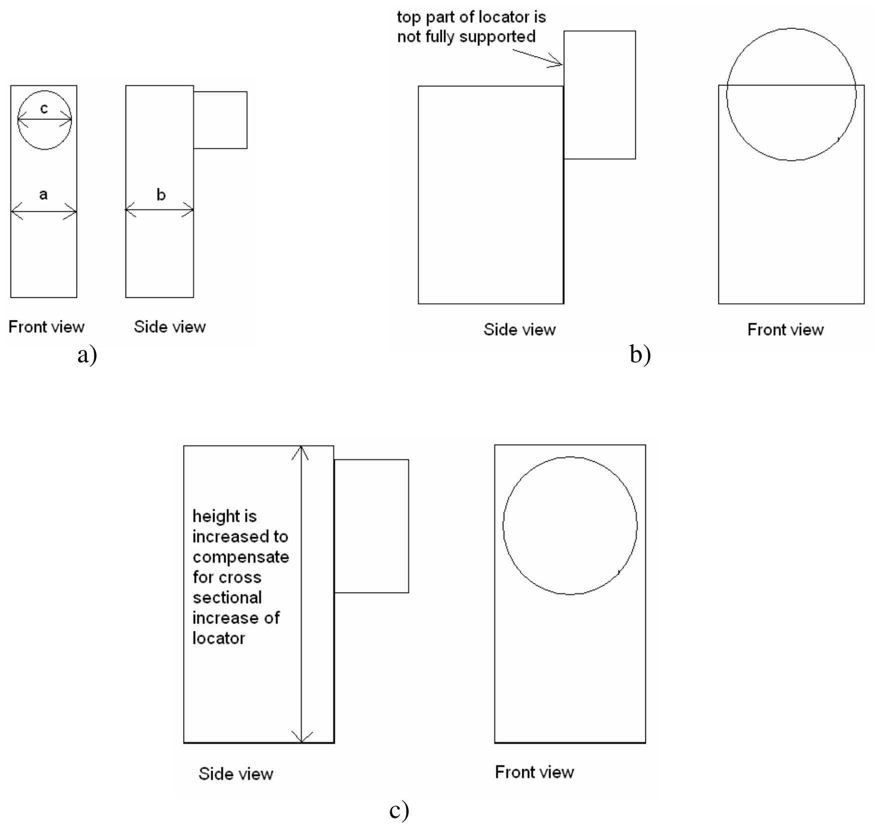


Figure 9: Modifying a horizontal locating unit

The key point is that different criteria may result in the selection of an alternative repair strategy. In summary there is no one repair strategy that is always correct. To successfully integrate different CAFD systems such as those of Hu (2001), An et al. (1999), and Zheng (2005) together, a clear method for deciding upon a modification plan needs to be defined because these systems do not contain this functionality.

The third issue concerning the repair of a design is the determination of who should perform the fix. Were moving the locating positions chosen as the modification plan then Hu's system would appear best suited. However, it does not have the ability to generate an alternative fixture plan. If asked by another module to provide a second fixture plan it would simply reproduce the same one as it has no independent means of altering its solution generation process. The same limitation applies to An et al. who would simply produce an identical set of fixture units if either the second or third repair strategies were to be implemented. Zheng's verification system has no means of performing repairs thus would not be a candidate. Thus another party, possibly human, would be required to make the modifications.

This is not to say that none of the work within the CAFD community is capable of performing repairs of this nature. Amaral et al. (2005) and Krishnakumar & Melkote (2000) for example have produced systems which for given stiffness values at each locating and clamping position will perform an optimization to select locating positions that minimize workpiece deflection during machining. Roy & Liao (1999) developed an algorithm to move locating points such that areas of the workpiece that suffer large deformations have greater support. A point of note with these systems though is that they do not actually relate the deformation experienced during machining to the tolerance requirements of the workpiece. They will attempt to minimize the workpiece displacement but will ***not*** produce a statement that says:

"The following locating and clamping positions allow the design tolerances to be attained."

The outputs from these systems must be analysed by another party to determine whether the design tolerances can be met. In a similar vein, limited work has been done to determine what the required fixture stiffness should be. These optimisation programs accept as inputs a specific stiffness for each locating and clamping point, but these stiffness values are not varied as part of the optimisation process – they remain constant throughout and this is possibly one of the reasons why little work in the CAFD domain has focussed on generating the physical structure of fixture units. Thus there has been little progress on producing a system that can say:

"The required stiffness at locating point 1 is XX lb/in. To satisfy this stiffness requirement, the locating unit at this point must have the following dimensions…."

2.1.2.2 Determining the Physical Design of Fixture Units

As Table 1 indicates, there are several systems that are capable of generating fixture unit structures, but with the exception of Hurtado & Melkote (2001) they all base unit design upon satisfying the geometry of the workpiece. In essence this means identifying the necessary acting height of the unit and then determining all other dimensions based upon some form of parametric design or heuristic rule execution. Hurtado & Melkote developed an algorithm that calculated the required stiffness at a specific locating point and then based upon the required stiffness specified the dimensions that the unit should assume. This was essentially limited to simple pin-array type fixtures such as that illustrated in Figure 10, thus there is still scope for ascertaining the form of more complex fixtures.

Although it cannot be denied that the functional height is of considerable importance in designing fixture units, it is not the only requirement that they must satisfy. Consider locating units. At a basic level, locating units have two functions to satisfy. These are to accurately locate the workpiece relative to the machine tool, and secondly to ensure that displacement of the locating point during machining is kept to a level that allows the design tolerances to be attained. With respect to the location function, some work has been performed to determine the tolerance allowed on the locating unit itself. The locating accuracy at a locating point (Δ) is a combination of the accuracy of the locating unit tolerance (Δ_l), the machine tool tolerance (Δ_m), the workpiece deformation at the locating point (Δ_w), the deformation of the fixture at the locating point (Δ_f), the locating surface error (Δ_{ls}), and a random error (Δ_r). If the values for Δ_m, Δ_w, Δ_{ls}, Δ_f, and Δ_r are known then Δ_l for each locating point can be determined as demonstrated by Hu (2001) and Wang (2002). Each approach appears to lack focus in its analysis. For example, given a location point tolerance Wang and Hu calculate the new position of all features on a workpiece to determine how far they have moved from their design position. However there should be no need to calculate all of the new positions. A more concise approach would be to perform a sensitivity analysis to identify those features that are most sensitive to the tolerance of a particular locator or locator pair and then determine the displacement of this feature for a given Δ_l. If Δ_l allows the design tolerance of this feature to be attained then it can be assumed that the tolerances of all other features affected by this locator or locator pair can be satisfied also, since they are less sensitive to variation in these locating point positions. This precludes the need for excessive computation.

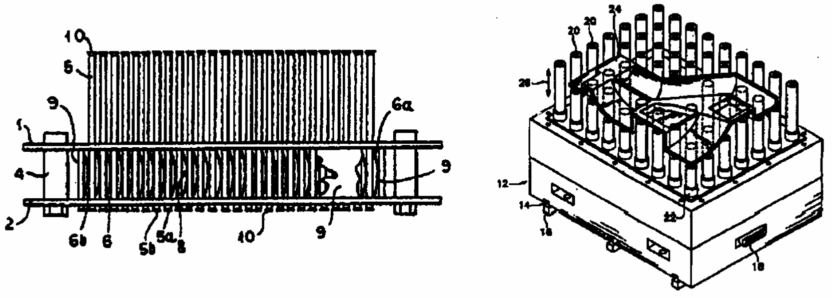


Figure 10: A pin array type fixture (Hurtado & Melkote, 2001)

Similarly, when Hu is experimenting with values of Δ_l he adopts a rudimentary approach whereby all locators' Δ_l values are simultaneously increased by the same amount (0.001 inches) until the workpiece design feature tolerances cannot be met. This results in each locating unit being assigned the same value of Δ_l. Computationally this is a lengthy process, especially given that the new positions of each feature have to be determined. However by incorporating the sensitivity analysis results into this process, a more focussed approach would allow the acceptable value of Δ_l to be calculated directly rather than by trial-and-error. For example each locator pair acts in tandem to cause a rotation about a centre point that causes the workpiece feature to displace. When doing the tolerance analysis, the two locating points and the centre point are known, as is the allowable design tolerance of the feature most sensitive to this locator pair. To determine the allowed Δ_l for each locator, a simpler approach would be to rotate the workpiece by an arbitrarily determined value θ and calculate the feature displacement, *d*. The allowed rotation of the workpiece to satisfy the design tolerance (θ') would be directly proportional to the ratio of the design tolerance divided by d: i.e., $\theta' = f(\theta * (design\ tolerance\ /\ d))$. Basic geometry can be used to convert this allowed rotation into the allowable value of Δ_l. This is a more tightly controlled means by which to determine allowable values for Δ_l.

Locating units also have to maintain accurate location when subjected to machining and clamping forces. General heuristics have been developed to assign a value to the deformation as a result of such forces (Δ_f) as a fraction of the total allowed location tolerance (Δ). As the forces acting against the locating units are also known it is theoretically possible to calculate the required stiffness of the unit using Hooke's Law (Hibbeler, 1997), and use that stiffness to generate the physical properties of the locating unit. Only Hurtado & Melkote (2001) have attempted this, but limited themselves to simple pin-array fixtures. For standard fixtures the process becomes more complex due to the increased number and configurations of components used within individual units. Thus it is necessary to first of all determine the basic shape of the unit, then decide the number of components the unit should have, and finally ascertain the dimensions and material properties required to achieve the desired stiffness.

There are basic rules that can be used to limit the possible shapes of units that can be used. For example inverted L-shaped horizontal locating units are used when a surface below the locating surface projects beyond the locating area as illustrated in Figure 11.

When deciding upon the number of components in a unit, CAFD systems that have generated unit designs compile their units from sets of standard modular components (Lin & Huang, 1997; An et al., 1999) and thus select components that will allow them to satisfy a particular height requirement. Thus if a modular set consists of blocks with heights of 1 inch, 0.5 inch, 0.2 inch, and 0.1 inch, then for a height requirement of 1.6 inches the systems will chose combinations of these blocks to satisfy this height for example a 1 inch block plus a 0.5 inch block plus a 0.1 inch block, or possibly a 1 inch block plus three 0.2 inch blocks. The general ethos behind such approaches though is to always choose the least number of components possible to reduce the time required to assemble the fixture unit.

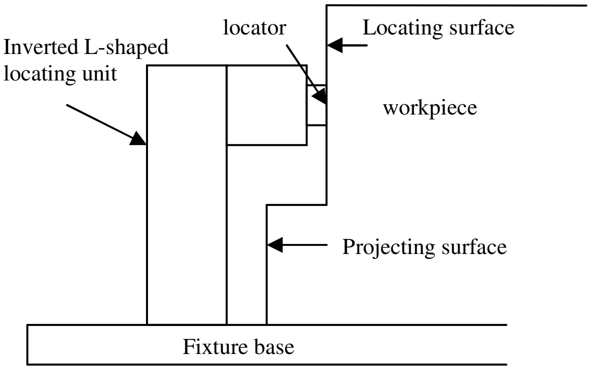


Figure 11: L-shaped locators

Other than Hurtado & Melkote (2001) no work has been found in the literature that documents approaches for determining the dimensions and material properties of standard fixtures based upon an understanding of the unit stiffness requirement. Particular challenges are similar to those raised in Section 2.1.2.1 when discussing how best to fix a design. There are several ways to achieve a specific stiffness through both physical dimensions and material choices and depending upon design considerations one choice may prove to be better than another. Means for identifying those choices and evaluating them have yet to be determined within the CAFD community. It is important to note at this point that there are other requirements in addition to locating accuracy and stiffness that a fixture unit must satisfy, yet there are few CAFD systems that generate or use a full understanding of all these requirements to guide their design process.

2.1.2.3 Understanding and Using Fixturing Requirements During the Design Process

Table 1 presented a review of areas that several CAFD researchers have contributed to. Although all stages of fixture design have been studied, few approaches use or generate a full understanding of all the requirements that a fixture may need to satisfy. The main fixture design considerations are:

- Workpiece geometry – the fixture must be capable of contacting and holding the workpiece for which it is designed.
- Workpiece design tolerances – the tolerances associated with the fixture must be such that the workpiece design tolerances can be achieved.
- Stability – no slip should occur at the fixture/workpiece interface to ensure that stability of the workpiece must be achieved at all times.
- Stiffness – the magnitude of deflections caused by machining and clamping forces should not be so great that the design tolerances can be achieved.
- Cost – the cost of the fixture should be within specified limits
- Usability – there are various usability design considerations that may form part of a fixture design requirement. These can include:
    - Assembly and disassembly time – the time taken to assemble and disassemble the fixture should not be prohibitive.
    - Operation time – the time taken to load and unload workpieces from the fixture should not be prohibitive.
    - Surface protection – the fixture should not damage the workpiece at the contact points, nor should the workpiece damage the fixture at the contact points.
    - Tool guidance - the fixture should provide means for guiding the cutting tool to specific workpiece features if required.

    - Error proofing – the fixture should prevent the user from inserting the workpiece into the fixture the wrong way around (correct orientation around the *x, y,* and *z* axes should be ensured).
    - Chip shedding – the fixture should provide a means for allowing chips to flow and thus prevent chip accumulation on either the workpiece or fixture.
- Collision detection – the fixture should prevent the following types of collisions:
    - Toolpath collision – the fixture should not obstruct the toolpath.
    - Workpiece collision – the fixture should not contact the workpiece other than at the assigned locating and clamping positions.
    - Fixture collision – the components of the fixture should not collide with each other (with the exception of assigned connection points).
- Weight – the weight of the fixture should be within specified limits. A heavy fixture can be advantageous in terms of the stability it offers, but conversely it can be difficult to handle physically.

Table 2 illustrates which of these design considerations are incorporated into the design process for each of the CAFD research efforts presented in section 2.1.1. Few approaches incorporate a significant number of these considerations into their methodology although this is understandable for those systems that concentrate on setup and fixture planning (Krishnakumar, 2000; Hu, 2001; Yao, 2003; Kang et al., 2003) where it is difficult to make qualified statements over how much cost is associated with one particular locating position against another. However it becomes more of an issue in systems that concentrate on unit design (Wu et al., 1997; An et al., 1999; Cecil, 2001; Joneja & Chang, 1999) where cost, usability, collisions, weight, stiffness, and design tolerance requirements are important considerations. For example, the locating unit tolerances must be such that the location accuracy can be achieved, yet the aforementioned unit design research efforts do not perform such an analysis, nor do they consider the deformation caused by machining and clamping forces. These are critical requirements that should guide the design of locating and clamping units. It is insufficient to use only workpiece geometry to guide the design.

Research effort	Design consideration							
	Workpiece geometry	Design tolerances	Stability	Stiffness	Cost	Usability	Collision detection	Weight
Wu et al. (1997)	●							
An et al. (1999)	●							
Wu et al. (1998)	●							
Krishnakumar (2000)	●		●	●				
Kumar et al. (1999)	●				●	●		
Kumar et al. (2000)	●				●	●		
Kang et al. (2003)	●	●	●	●			●	
Hu (2001)	●	●						
Yao (2003)	●	●						
Kumar, Kow, & Fuh (2000)	●						●	
Nee & Kumar (1991)	●	●	●	●	●		●	
Nnaji & Alladin (1990)	●							
Trappey & Liu (1992)	●		●					
Roy & Liao (1999)	●			●			●	
Cecil (2001)	●			●				
Hu & Rong (2000)	●						●	
Krishna et al. (2002)	●		●	●				
Hurtado & Melkote (2001)	●	●	●	●			●	
Roy & Liao (2002)	●		●	●				
Liu & Strong (2003)	●		●					
Joneja & Chang (1999)	●		●					
Wang (2002)	●	●						
Kashyap & DeVries (1999)	●		●	●				
Lin & Huang (1997)	●							
Amaral et al. (2005)	●		●	●				
Wu & Chan (1996)	●		●	●				

Table 2: Design considerations incorporated into previous CAFD research efforts

The most complete approach has been proposed by Nee & Kumar (1991), who attempted not only to design a system to perform all four stages of fixture design, but also attempted to satisfy a significant number of design considerations with their fixture solutions. Considerations incorporated into their system were workpiece geometry, stability, design tolerances, workpiece stiffness, cost, and toolpath collision. However Nee & Kumar do not relate the results of their stiffness analysis to the final unit designs. The locating positions are varied until the deflection of the workpiece is satisfied, but the actual stiffness used in these calculations is not used as a basis on which to determine the unit dimensions. Units are built to satisfy workpiece geometry and to account for the tolerance stack-up of components, as discussed in section 2.1.2.2. The choice of components is governed by heuristic rules, but the authors do not expand upon their contents.

Nee & Kumar also have a justification module that considers cost, batch size, and tolerance specification, but this is limited to choosing between the use of a modular fixture (made up of a number of standard components) or a dedicated fixture (a custom design fixture). No details are provided of how a dedicated fixture should be generated. Thus, as argued in section 2.1.2.2, again there is not a significant focus on unit design when compared to their efforts on fixture planning.

2.2 Case-based Reasoning

A further technique that has been employed in CAFD is case-based reasoning (CBR) (Bi & Zhang, 2001). CBR (Kolodner, 1993; Maher, 1997) involves representing, indexing, and organizing past design cases in a case library such that they can be recalled, modified, and then reused in future design situations. Basically when a new design problem is encountered, a CBR approach identifies a past case that appears best matched to the current design requirement and then modifies that case to provide a satisfactory solution to a new design situation.

CBR is an example of analogical reasoning – a technique whereby solutions are found by retrieving knowledge from similar design experiences and adapting this knowledge as required. Thus in a design situation, analogical reasoning allows the designer to recognize something that has not been encountered before by associating it with something that the designer is familiar with.

Analogies can occur at different levels of abstraction and indeed analogies can be drawn between two entirely different domains. For example, instinctively there is little to relate the domains of train design and bullet design but at a fairly high level of abstraction it is possible to relate the domains when considering the fact that aerodynamically they present similar problems: i.e., both must travel through the air and a common concern is how to minimize the drag forces they are subjected to as they move.

Traditionally however CBR is generally only capable of forming analogies within one particular domain and is not able to make the leap of comparing trains to bullets. Instead of relying solely on general knowledge of a problem domain, or making associations along generalized relationships between problem descriptors and conclusions, CBR uses specific knowledge of previously experienced, concrete problem situations (cases). When confronted with a new design situation, this knowledge is retrieved and adapted to form a new solution. In addition to previous design cases, CBR also employs general knowledge about a particular domain. Typically this general domain knowledge is used to adapt the retrieved design case so that it satisfies the new design problem. In the domain of fixture design, specific design cases might be a fixture and the general domain knowledge would be how the physical properties of the fixture and its constituent components (such as component geometry and material properties) affect its behaviour when subjected to the physical forces encountered during machining.

Overall CBR is a model of reasoning that incorporates problem solving, understanding, and learning that is strongly integrated with memory (Aamodt & Plaza, 1994). Figure 12 illustrates the CBR process, to which there are two main stages – case retrieval and case adaptation. Initially a case must be recalled so that it can then be adapted to provide a solution. Once adapted this new case is stored for future use: i.e., the case library knowledge is dynamic.

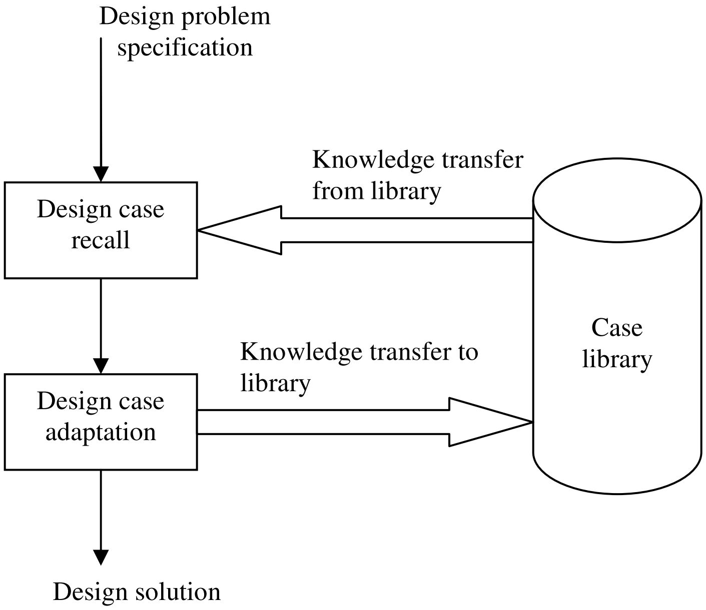


Figure 12: The CBR process (Maher, 1997)

Both case recall and case adaptation can be subdivided into three constituent parts (Figure 13). Design case recall is concerned with finding a relevant case within the case library. It subdivides into:

- indexing – this involves identifying the features that previous solutions should have relative to the current problem;
- retrieval – this stage identifies cases that have all or some of the required features;
- selection – the retrieved cases are evaluated so that they can be ranked in order of similarity.

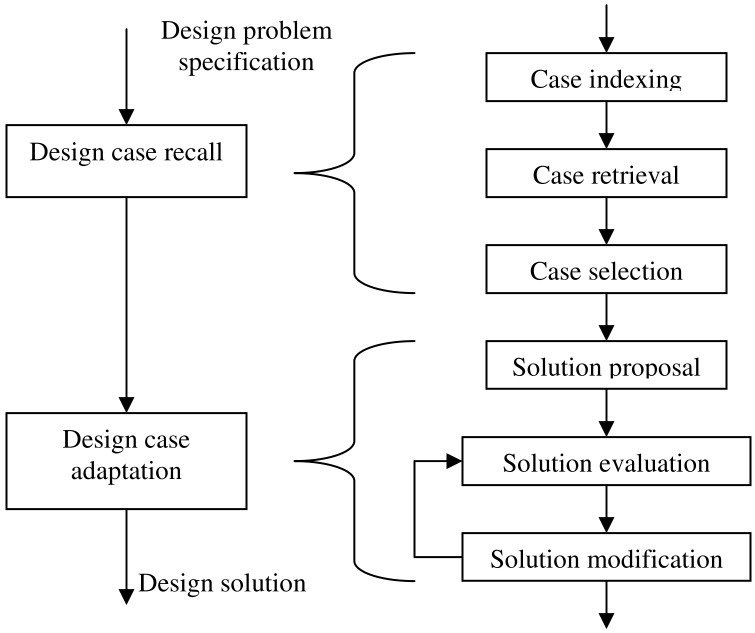


Figure 13: The decomposition of case recall and adaptation (Maher, 1997)

Normally, cases returned by the recall process will have to be modified to satisfy the new design problem. Such modifications occur during design case adaptation, which involves identifying the required changes and subsequently implementing the necessary alterations. Thus adaptation subdivides into:

- solution proposal – the top ranked design is proposed as a solution;
- evaluation – the proposed design is then evaluated to determine the changes that need to be made;
- modification – the changes are made and the design re-evaluated to confirm that the solution is satisfactory.

2.2.1 Indexing

Indexing identifies the features that previous solutions should have relative to the current problem. The task of identifying appropriate indexes in CBR is a difficult one as can be witnessed by surveying the indexes at the back of many books, some of which are far less helpful than others. A particular difficulty with indexing relates to identifying the concepts that can be used to describe an item. For example a fixture could be described by:

- its physical characteristics such as:
    - its size;
    - its shape;
    - the number of units it contains.
- its functional concepts such as:
    - the locating accuracy it can achieve;
    - the forces it can withstand;
    - the type of workpiece it could be used for;
    - the type of surfaces it can act on.
- its behavioural type such as:
    - clamping behaviour (e.g., lever principle, magnetic force, vacuum force);
    - locating behaviour (e.g., axial support, beam support).

Having defined possible indexing concepts, the difficulty then becomes deciding which ones should be used to index a case. Some are more useful than others, for example locating behaviour is not a particularly helpful attribute by which to index because it can have only two possible values – axial or beam. As a result many cases are likely to have the same locating behaviour and thus this attribute does not significantly help to differentiate between cases. Indeed a significant indexing issue in CBR is the inability to distinguish between two cases: i.e., two cases can have the same values for all indexing attributes, but it remains unlikely that both design cases will be equally suited to the current design requirements (McSherry, 2002). A CBR system itself may be unable to help the user make a choice because as far as the system is concerned the designs are identical. This condition, known as “inseparability”, is a result of inadequate indexing. The two possible root causes of inseparability are:

- an insufficient number of attributes by which designs are indexed;
- a poor choice of attributes by which the designs are indexed: i.e., the attributes and/or their values are common to all or many designs and do not distinguish between designs.

McSherry (2002) has performed some research work on investigating the issue of inseparability. He proposes a method for measuring the inseparability of a case library as a ratio of the number of inseparable design cases to the total number of cases in the library. However, he defined no structured methodology for selecting the attributes by which to index cases. This is a key area as there is a trade-off to be made between a high number of attributes to help prevent inseparability, and a low number of attributes to reduce the computational expense associated with retrieval mechanisms.

The net result of inseparability is that the designer is presented with a selection of cases, rather than just one that is preferred more than any other. The system is unable to help the designer choose one over the other as they are undistinguishable. For this reason, several CBR systems in existence necessitate the need for browsing mechanisms (Maher, 1997). The system can refine the search to a certain level, but beyond that is unable to distinguish between cases and the user must navigate through the design search space without further assistance from the CBR system.

In spite of the ongoing problems concerning indexing, there still exists no formal method for determining the indexes of a design case, the result being that it remains a highly subjective exercise deeply dependent upon the designer’s experience. In traditional CBR approaches, cases are generally indexed through attribute-value pairs. Oftentimes attributes associated with the design problem are selected as the indexes. For example Kumar & Nee (1995) index design cases using a number of attributes that describe the workpiece for which a fixture is to be designed, as illustrated in Table 3.

Case indexes
Machining features on the workpiece
Workpiece surface information
Inter-feature relationships
Unsupported features
Tolerance requirements (individual and inter-feature)
Machining direction
Workpiece size
Material
Location of center of gravity of workpiece

Table 3: Kumar & Nee (1995) Indexing Attributes

A similar approach has been taken in other domains where CBR has been employed. Sadek (2001) developed a CBR system to provide routing assistance for road traffic in case of traffic jams or congestion. Cases are indexed according to the nature or cause of the congestion (e.g., an accident blocking a certain number of lanes on a particular road), the day of the week, the time of day (e.g., early morning rush-hour) etc. Annexed to each design case is the routing plan to ease congestion and decrease journey time. Rivard (2000) developed SEED-Config to support the early phases of building design. Cases are indexed by physical properties (e.g., size, material) of building entities (e.g., First Floor would be a building entity). Redmond et al. (2002) developed a CBR system to support cooperative information sharing among police departments. Cases are indexed by facts about communities and their crime levels. The design solution associated with each case is a series of crime initiatives or policies to help control crime levels.

Kim (1997) proposes a slightly alternative approach to CBR. He uses standard domain knowledge to create an initial design in REV-ENGE, and then evaluates this design to determine what the failings of the design are. From a case base of design problems, the most similar problems are retrieved and their attached solutions invoked to repair the design. Problems associated with this method are that it is not always possible to envisage every problem that will occur, thus it is not always possible to fix a design. Secondly, it involves designing an artifact from scratch every time. Designs that have already been produced may well prove adequate or at the least a good starting point for a new design requirement, thus there is no real need to go to the expense of repeating the same design procedure to generate an initial design when several useful designs already exist. Furthermore, the output of the system is a complete design solution, not a new design problem and its solution, thus the case base is static as no knew knowledge is added to the library.

The common feature associated with the method by which many of the above authors have indexed their cases is that they have chosen attributes of the problem based upon what the system designer believes the key attributes of a design problem to be. The attributes chosen seem to be "surface features" of the problem, but a better choice of indexes may require an interpretation or analysis that identifies the interesting functional features of a situation. For successful indexing and subsequent retrieval it is important to ascertain the distinguishing features of a design case. Consider for example Kumar & Nee's (1995) choice of indexes as listed in Table 3, one of which is the tolerance requirements. The tolerance of all the features on the workpiece do not have a bearing upon the fixture solution. Rather amongst all of these tolerances one or a group of them will be critical to achieving the success of a particular fixture design in terms of locating accuracy. That is, given the linear and/or rotational displacements caused by a locator or locator pair, then as long as this critical tolerance is satisfied so will all the other tolerances.

For example, Figure 14 presents two locators $P1$ and $P3$ that given a particular variation in size of magnitude Tol_{P3} will result in a rotation θ of the workpiece. The two features on the workpiece (holes 18 and 19) will move by a distance of $H18r_{P1/P3}$ and $H19r_{P1/P3}$ respectively. Attached to each hole is a positional tolerance $TPOS$. The task is to identify the hole that is most sensitive to the rotation θ. The sensitivity ratio is the positional change for a feature expressed as a ratio of the allowed tolerance $TPOS$ for that feature. For hole 18 the sensitivity ratio is ($H18r_{P1/P3}$ / $TPOSH18$) and for hole 19 it is ($H19r_{P1/P3}$ /

*TPOSH*19). Whichever hole has the highest sensitivity ratio is the most sensitive and it is this hole tolerance that should form the basis for indexing. Also, knowing that this is the most sensitive hole it is now possible to determine the value of θ (θ_{max}) that will allow the most sensitive positional tolerance to be achieved. Thus the indexing approach could now take the form of something like "*locator pair, rotation Z axis,* θ_{max}", which says search for a previous design that consists of a locator pair resulting in the rotation θ_{max} around the *z*-axis. This is a far more focussed and useful index than simply listing all workpiece tolerances that must be achieved. Computationally this form of indexing makes it much easier to map onto a candidate case in the library.

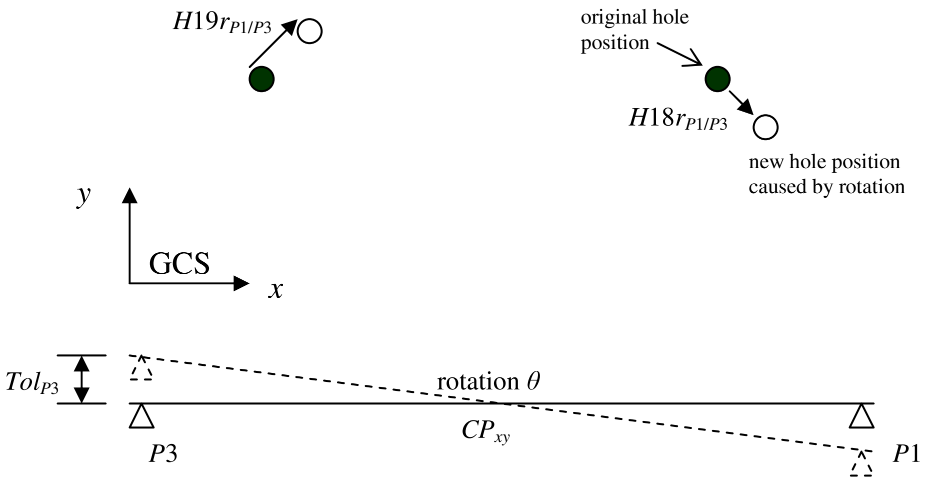


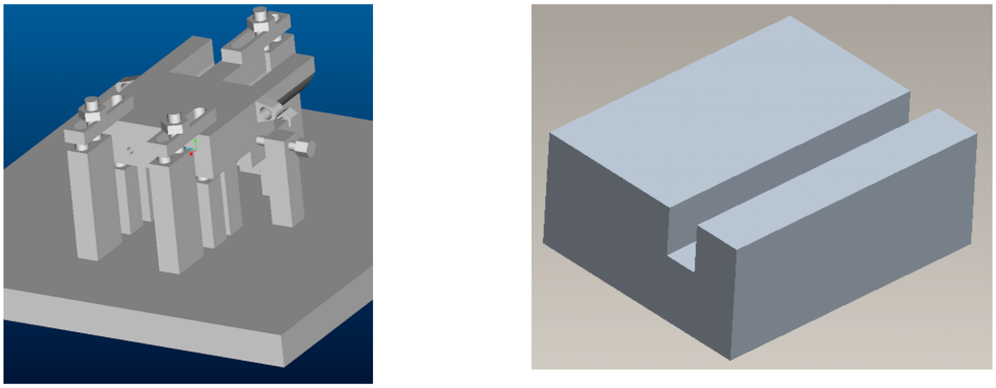
Figure 14: Identifying the critical tolerances

Rather than use surface attributes for indexing, Goel et al. (1997) developed Kritik, a CBR system in which cases (physical devices) were indexed by function. Attached to each case was a structure-behaviour-function (SBF) model that specified the functions, structure, and internal causal behaviours of the device. These causal behaviours are Kritik's understanding of how the structural components of the device relate to the functions it performs. The structure of a device is expressed in terms of its constituent components and the interactions between them. The function of a device is represented as a schema that specifies the input behavioural state of the device, the behavioural state it produces as its output, and a pointer to the internal causal behaviour of the design that causes this transformation. The causal behaviours are represented as sequences of transitions between behavioural states. For each state transition, the primitive functions and structural relationships that facilitate the transition are detailed.

Cases are recalled initially by function. Those cases which at least partially match the new design requirement are then ordered using a nearest-neighbour approach. The top ranked design undergoes adaptation, to which there are two stages – diagnosis and repair. Diagnosis involves identifying the faults with the design. This is achieved using the SBF model and the given functional differences between the new and retrieved design situations. Kritik traces through the model and identifies specific structural elements that can potentially be modified in such a way as to allow the desired function of the new design to be achieved. The diagnosis stage suggests possible remedies and during the repair stage these fixes are implemented in turn and the design tested. If the repaired design fails testing, then one of the other remedies is attempted.

A particularly interesting feature related to Kritik's use of indexing by function is that not only are these indexes used to retrieve solutions, they are also heavily involved in the adaptation process. In diagnosis the functional differences between the retrieved design case and new design problem, in conjunction with the SBF model of the retrieved case, are used to determine possible repairs. This clarity of functional requirement is one of the reasons that allows Kritik to make such diagnoses. One issue with Kritik however is that it assumes the function of a new design is already specified. Thus transformation of surface attributes into specific functions has to be done prior to employing Kritik as a means of obtaining a solution. If the concept of indexing by function is considered as a base for developing a CAFD tool, then the need still remains to generate a method that facilitates the transformation of surface attributes such as workpiece tolerances and machining processes into a list of functions that the fixture must satisfy.

Another key issue related to indexing is that indexes should be as generally applicable as possible so that they can be used in a broad set of circumstances. Kumar & Nee's CBR approach was based upon the assumption that similar workpieces would require similar fixtures. Thus workpieces were grouped together into part families and to each workpiece was attached a suitable fixture design. Now intuitively this seems to be a valid and sensible approach. However, given the wide variety of possible workpiece geometries that could exist, the case library would need to be extremely large to be able to handle them all. Figure 15 presents two workpieces, one a simple brake caliper and the other a rectangular block with a slot in its top face. Geometrically these workpieces are not particularly similar as the caliper has several cylindrical surfaces on it. If a fixture design were being sought for the rectangular workpiece then Kumar's system would not consider the caliper's as a candidate solution due to the dissimilarity of the two workpiece geometries.



a) caliper and fixture

b) rectangular block workpiece

Figure 15: Two workpieces

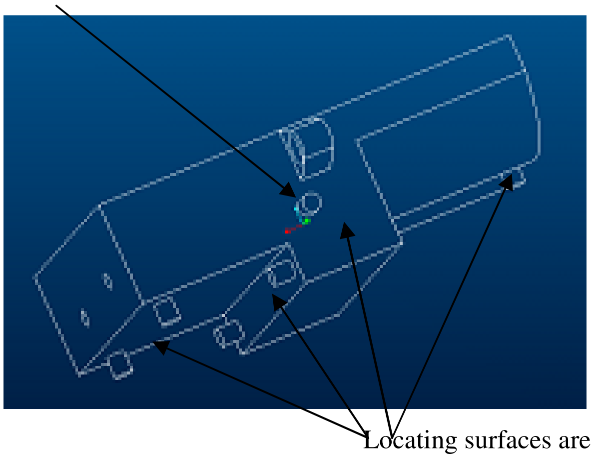


Figure 16: Caliper locating surfaces

However a closer analysis reveals that the fixture would be a plausible candidate since all the locating and clamping units act upon flat surfaces of the caliper (Figure 16). Although the caliper has many geometrical differences to the rectangular workpiece, the actual locating and clamping surfaces are similar. The rectangular block has only planar surfaces that can be used for fixturing and the caliper fixture has been designed to act upon this surface type.

Thus although the workpieces are very different, similar fixtures can be used to secure them during machining. By grouping fixtures according to part families Kumar & Nee have weakened the ability of their system to obtain design solutions for unfamiliar workpieces when in fact plausible candidate cases do exist in the case library. There is an infinitely high number of workpiece shapes but there are relatively few types of surfaces, of which the most common types are flat, polygonal surfaces, external cylindrical surfaces, and holes. A large number of workpieces are made up of these surfaces

Furthermore, by considering locating and clamping faces individually rather than entire workpieces, the opportunity arises to both simplify the fixturing problem by decomposing it into obtaining units for individual faces whilst simultaneously increasing the effective number of cases in the library without having to add any in. For example if the caliper fixture was the only solution in the library, then by indexing according to surface type the library now has twelve cases (six locating units and six clamping units) instead of only one (the entire fixture). By increasing the number of cases in the library in this manner the possibility arises of mixing and matching the best units from different fixture designs, rather than having to retrieve fixtures in their entirety. Generally speaking the larger the number of widely applicable cases that exist in a case library, the more capable the CBR system is of generating a satisfactory solution.

Overall therefore with regard to indexing the challenge remains to define a comprehensive method by which fixture design cases are indexed

2.2.2 Retrieval

Once cases have been indexed, they can then be recalled. Normally, retrieval is based upon attribute similarity so the case that has the most similar attributes is returned as the most suitable case for future adaptation. This is commonly referred to as a nearest neighbor approach (Maher, 1997). An alternative, but less well used technique is to assess the adaptation required of a candidate case during the retrieval process. In this way, the case that offers the most favourable adaptation possibilities is retrieved as the most suitable case for modification.

2.2.2.1 Similarity-based Retrieval

A standard method employed by many CBR systems (Chang et al., 2000; Varma & Roddy, 1999; Liao et al., 2000) is to use a linear weighting approach. This involves determining for an attribute i the difference between the required attribute value $P_{i,\max}$ and the recalled attribute value P_i, attaching a weighting factor w_i stating the importance of this attribute and then calculating an overall "Figure of Merit" *FOM* for the recalled attribute. This process is repeated for n attributes until a *FOM* for the complete recalled case can be computed using the equation:

$$FOM = \left[\sum_{i=1}^{n} w_i \left(P_i / P_{i,\max} \right) \right] / \sum_{i=1}^{n} w$$

A significant limitation with this approach is that a linear relationship is assumed between the performance level of a feature and the worth of that level to the designer. However, a recalled attribute may only become worthwhile to a designer when it is very close to the required level (Thurston, 1991). Consider the example in Figure 17. A clamping unit is required to exert a force of 120 lbs. A recalled case may be able to exert a force of 60 lbs, giving it a worth value of 0.55 using the linear weighting approach. However, in reality, such a force capability may be of little value to the designer as it is too low. A parabolic-style curve such as that presented in Figure 17 may be a more accurate reflection of the designer's preferences for different force capabilities. The worth of the recalled attribute is in fact much lower than 0.55 at 0.1. Thus, the linear weighting approach offers a limited means of expressing a designer preferences or importance of a design attribute. To accurately guide the retrieval process a more expressive means of capturing the desires of the designer is required.

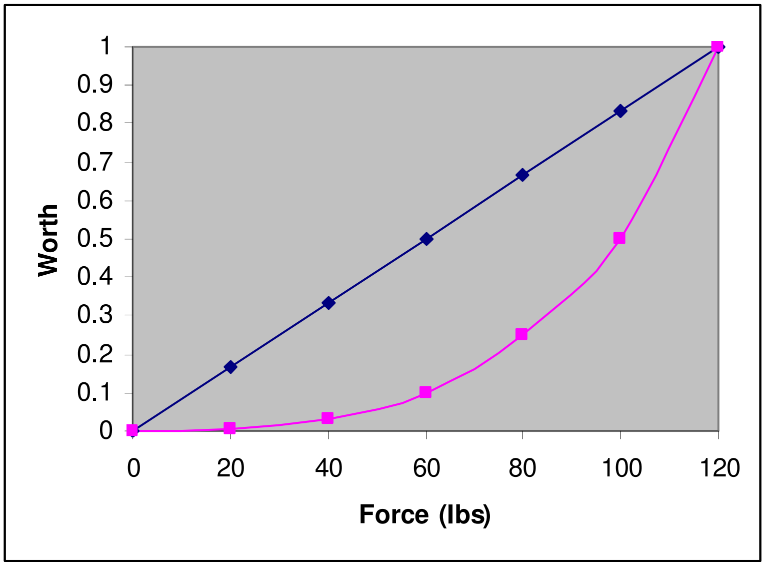
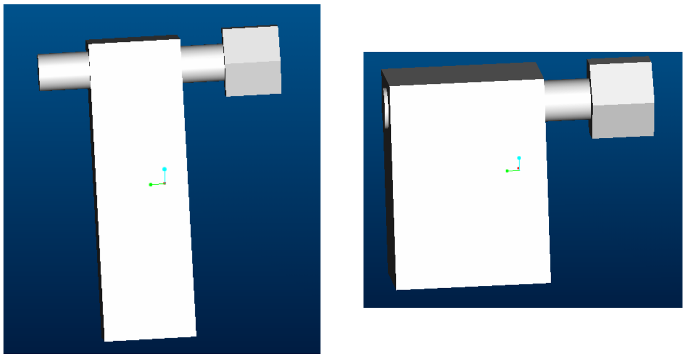


Figure 17: Limitations of linear based weighting

2.2.2.2 Adaptability-based Retrieval

The CBR systems discussed have based case recall upon attribute similarity: i.e., a nearest neighbor approach. However, this approach does not necessarily mean that a retrieved case is easily adaptable. Indeed a less similar design case may in fact be more readily adapted in certain design situations (Smyth & Keane, 1995; Leake, 1996). Consider the example in Figure 18.



Design requirement:
Stiffness = 20E6 lb/in
Height = 1 in

Design one:
Stiffness = 10E6 lb/in
Height = 1 in

Design two:
Stiffness = 20E6 lb/in
Height = 0.5 in

Figure 18: Limitations with attribute-based retrieval

The design requirement is for a clamping unit with a stiffness attribute value of 20E6 lb/in acting at a height of 1 inch. Two possible designs in the case library are presented. Design case one has the correct height but only half the required stiffness, the second case has the correct stiffness but is too short. Trying to determine the more similar case based upon attribute similarity is difficult, but if the adaptations required for each design are considered then the comparison becomes simpler. Design case one requires one design change – an increase in thickness. Design case two requires an increase in height (which will subsequently reduce the stiffness) and an increase in thickness to compensate for the reduction in stiffness caused by increasing its height. Also the design changes should be performed in that order to prevent iteration in the design process. Thus, design one is simpler to adapt in terms of the number of design decisions that have to be made. Basing retrieval on attribute similarity has not been able to distinguish between the two cases. However if adaptation of design cases is used to guide retrieval and the criteria for case selection is to pick the design that is the simplest to fix then the clear choice is to pick design case one. Adaptability-based retrieval has proved more effective than similarity-based retrieval in that it has provided a clear basis for picking one design case over the other.

Another example is presented in Figure 19. A vertical locating unit is sought that has a functional height of 1 inch and a locating tolerance of 0.01 inches. Two design cases have been retrieved from the case library and are illustrated in Figure 19. Design case one has a functional height of 1 inch and a locating tolerance of 0.02 inches. It consists of two components (the support unit and the locator) each of which has a tolerance of 0.01 inches. Design case two has a functional height of 1 inch and a locating tolerance of 0.02 inches. It consists of four components (three support units and the locator) each of which has a tolerance of 0.005 inches. Functionally design cases one and two cannot be differentiated – they act at the same height and provide the same locating tolerance. If adaptation is considered then it is possible to make a choice between the two cases. Design case one requires two changes:

- modify the tolerance allowance for the support unit from 0.1 inches to 0.005 inches;
- modify the tolerance allowance for the locator from 0.1 inches to 0.005 inches.

Design case two requires four changes:

- modify the tolerance allowance for support unit one from 0.005 inches to 0.0025 inches;
- modify the tolerance allowance for support unit two from 0.005 inches to 0.0025 inches;
- modify the tolerance allowance for support unit three from 0.005 inches to 0.0025 inches;
- modify the tolerance allowance for the locator from 0.005 inches to 0.0025 inches.

Based upon the number of design changes required then design case one is the preferred option because it requires fewer modifications. Another reason for choosing design case one is the practical reason that the tighter design tolerances required when modifying design case two are more difficult and expensive to achieve, and also the greater number of elements in the design results in a longer assembly time. Both of these effects are generally undesirable in a fixture design. Incorporating adaptation knowledge into the retrieval process has again in this instance proved beneficial not only in identifying which is the simpler design to modify but also in attempting to predict the likely effect of design changes upon the ability of the design to meet the designer's preferences.

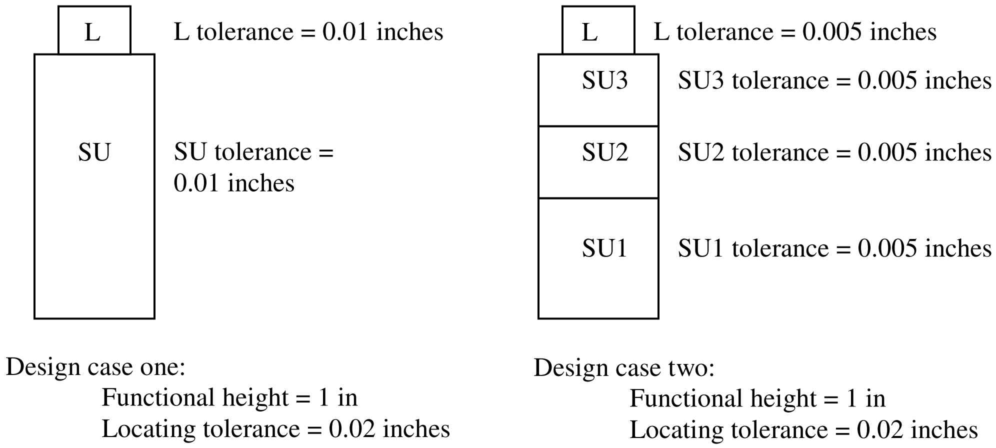


Figure 19: Comparing two cases with the same tolerance capability

Thus to alleviate possible adaptation problems, adaptation knowledge has been more closely tied to the retrieval process. Smyth & Keane (1996; 1995) perform retrieval directly on the basis of the adaptation methods required to fix a case, and choose cases that use preferred adaptation methods. Adaptation is performed using two forms of knowledge: adaptation specialists that perform specific local modifications to cases, and adaptation strategies that solve problematic interactions within cases. Retrieval is performed in three stages. Initially candidate selection is performed to remove any cases exhibiting differences that cannot be dealt with by adaptation specialists. Secondly, local adaptability assessment maps the target features with those of the candidate cases and identifies the relevant specialist. A local adaptability metric is applied to estimate the ease of adaptation in terms of the specialists involved. Thirdly, a global adaptability assessment is performed. The strategies that are applicable to each of the candidate cases are determined and a metric used to grade these cases according to the different repair methods that are suggested by each strategy. Different strategies are differently weighted according to the amount of change their repair methods incur. Overall, the candidates are ordered according to both their local and global adaptability and the case that minimizes both measures is chosen. In this approach adaptation is based upon picking the design that is simplest to modify. In reality however there is little if any relationship between the simplicity of the design process and the ability of a design to satisfy particular requirements. The primary criteria guiding the decision making process should come from the design requirements. That is not to say that the difficulty of a particular design strategy should be ignored when deciding between possible solutions, but it should not be the primary consideration. The question that should guide design is "*How well will this decision allow the design requirements to be met?*", and ***not*** "*What will make life easier for the designers?*".

Rosenman (2000) also recognizes this problem of similarity versus adaptability. He proposes a method for determining room layouts in architecture design. For example he tries to maximize the amount of sunlight entering a room by generating different alignments of rooms with varying shapes and features and calculating the amount of light for each possible combination. He has a case base of rooms with associated factors (i.e., sunlight let in, heat retention etc.) and uses a genetic algorithm to arrange rooms to achieve an optimum value in terms of requirements.

However, an area of concern with adaptability-based-retrieval is that it can be a computationally expensive approach for two reasons. One, the approach can require the CBR system to determine what changes need to be made to fix a case, to then decide how this change can be achieved (as there may be several means of affecting a change), and also to check how making a change will affect the rest of the design. This is a far more complicated process than merely checking attribute similarity. Secondly, if there are many cases in the library, then to perform the above tasks for a large number of cases requires considerable effort. Smyth & Keane vet cases by considering only cases that can be fixed, but it is not difficult to envisage the situation where a large number of cases will be fixable. Rosenman proposes no method for vetting design cases. Thus, depending on the levels of computation required to assess a single case during an adaptability-based retrieval process, there may be a need to define methods of initially constraining the search space to control the number of cases that are considered for adaptability-based retrieval.

On a related note, an inherent feature of any CBR system is its learning capability. The case base is constantly growing, with new cases being added to it. Obviously this can exacerbate the control problem and highlights the need for both an effective vetting method and a carefully controlled learning mechanism that restricts case library growth. Keeping the library small can be very important in adaptability-based retrieval, which is in contrast to similarity-based retrieval. Attribute similarity-based retrieval works on the basic heuristic that a design case having similar attribute values to the new design requirement is likely to be fixable. Specifically, the closer the design case is to the new requirement the better because it should hopefully only be necessary to "tweak" (Goel et al., 1997) the design case to generate a satisfactory solution. Therefore the greater the number of cases that exist in the case base, the greater the likelihood of finding a design that requires small amounts of adaptation.

With adaptability-based retrieval a large case base may cause problems depending upon the computational effort expended during retrieval. If large amounts of computation are required then this may prohibit the evaluation of large numbers of cases due to the time it would take to find a solution. One way of preventing this problem is to have a vetting procedure in place that limits the number of candidate cases. If so then keeping the size of the case library small is not a significant issue. However if vetting is not able to successfully limit the number of cases and the retrieval method is computationally expensive, limiting the library size can become the only means of controlling the number of candidate cases subjected to the retrieval process.

Thus, the criteria by which cases are considered for addition to the case base need to be carefully developed and should focus on whether a case contributes valuable knowledge to the library.

Overall, when considering adaptability-based retrieval, there remains a need to:

- develop a method to initially constrain the search through the solution space;
- develop a method that can effectively measure adaptability;
- develop a method that can gauge the effect of potential design decisions;
- develop a learning mechanism that can restrict the size of the case library to a feasible level, yet still allow the addition of useful knowledge.

2.3 Axiomatic Design

Previous CBR systems that were discussed in section 2.2 have used attributes either about some physical artifact or current situation to index cases. As section 2.2 argued, there is a need to develop a method that clearly determines case indexes, and thus the design requirement. An alternative approach is to consider what the solution has to do: i.e., what are its functions? Previous approaches pick whatever "surface attributes" from the design situation appear to be important to the solution and use them to index the design cases. A more focused approach should allow information about a situation to be processed to determine what exactly is required of a solution. One such method that rigorously defines the design requirement is axiomatic design.

Axiomatic design (Suh, 2001) is a design methodology that involves the processing of information across four domains (Figure 20). Mapping occurs between the customer domain, the functional domain, the physical domain, and the process domain. The needs of the customer are listed as customer attributes (CAs) in the customer domain and are subsequently formulated into a set of functional requirements (FRs) and constraints (Cs). FRs are essentially a more technically detailed and focused version of the CAs and explicitly state the performance expected of the sought design solution. A design solution to satisfy the FRs is then created through mapping between the FRs and the design parameters (DPs), which exist in the physical domain. These DPs are mapped into the process variables (PVs) which characterize the process by which a particular design solution (DP) will be manufactured. In essence, the PVs allow the DPs to be achieved, which in turn allow the FRs to be achieved, which in turn allow the CAs to be achieved. A fundamental aspect of the mapping process is the idea of decomposition. The design progresses from a higher, abstract level down to a more detailed level. This results in the formation of design hierarchies in the FR, DP, and PV domains. For each FR at any level of the hierarchy, a suitable DP and PV are obtained before decomposing to the next level of the hierarchy. The resultant hierarchies in the DP and FR domains are similar in nature to standard product functional and structural hierarchies. Axiomatic design adds the mapping of one to the other, thus it can identify which parts of a design's structure are used to perform specific functions.

Designs are judged using two axioms. These are:

- Axiom 1: The independence axiom – maintain the independence of the FRs so that each FR can be controlled independently without affecting any other FR.
- Axiom 2: The information axiom – minimize the information content of the design, where the information content is related to the probability of success in achieving the specified FRs. One important point to note is that this axiom is only applied when Axiom 1 has been satisfied.

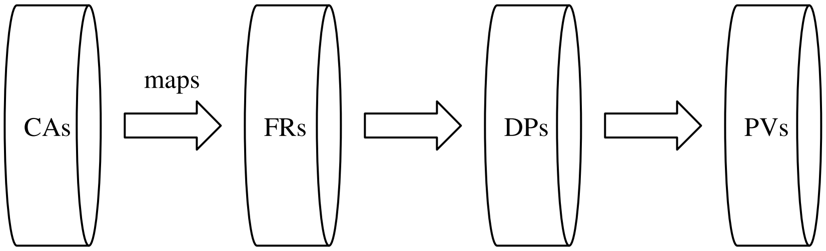


Figure 20: Axiomatic design domains (Suh, 2001)

CBR systems discussed in Section 2.2 indexed their cases according to the CAs, and attached to each set of CAs a design solution, which is essentially the equivalent of the DPs. For example, Kumar & Nee (1995) have listed the workpiece parameters (tolerances, features etc) and attached to that a fixture design. However not all tolerance requirements matter and not all features matter in terms of the final fixture design (see the discussion in section 2.2.1). These CAs are "surface attributes" only and must be processed to determine deeper attributes that represent an understanding of what is important in the current design situation and will therefore affect the final design solution. Any information found that does not affect the design solution can be discarded as having no effect on the solution. In essence, the objective is to determine the functions that the solution must perform (i.e., the FRs) and these FRs represent this deeper understanding of the design problem. Cases can then be indexed according to their FRs. In the case of fixture design, a fixture is meant to perform a specific locating and securing function and that function itself should be the primary basis for retrieval/determining similarity in a CBR system, not the actual workpiece itself. The adoption of axiomatic design principles as the means by which cases are indexed can be used to overcome the inseparability issue that is caused by a poor definition of the design problem.

Axiomatic design has been successfully applied in various domains (Chen, 2000; Bae et al., 2002; Li et al., 2001). In particular, the systematic decomposition of the design requirements/solutions is a powerful technique. However, certain concerns arise from its use. Firstly, the second axiom requires that probability density functions (pdf) for each DP be known (Figure 21). These pdfs illustrate the likelihood of a particular DP achieving its FR. The information content is a function of the area within the common range. The common range is the overlap between the design range that is desired, and the system range (the performance range that the system can provide). To minimize the information content the objective is to have the system range (and thus the common range) lying entirely within the design range.

In reality however, these pdfs are unknown and difficult to obtain. As a result, Axiom 2 is rarely used during the design process and possible design solutions are judged against each other purely on the basis of Axiom 1. In cases where Axiom 2 is used, the pdf is often simplified. Jang et al. (2002) used Axiom 2 to evaluate potential solutions when designing a foil-strut system. Their FRs were the minimization of both the bending moment experienced by the system and its weight. Different designs were evaluated on the basis of simplified pdfs that were assumed for convenience to be linear. However questions remain about how accurate these simplifications can be and also how accurate they need to be without having a negative impact upon the validity of the evaluation of different designs. In essence therefore, two issues arise from Axiom 2:

- how can the necessary pdfs be generated, and;
- if simplified pdfs can be assumed then how can they be verified as being accurate.

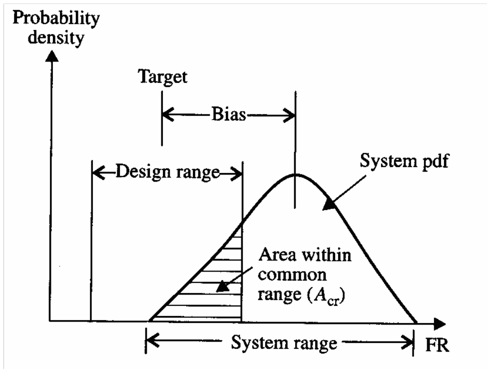


Figure 21: A sample probability density function (Suh, 2001)

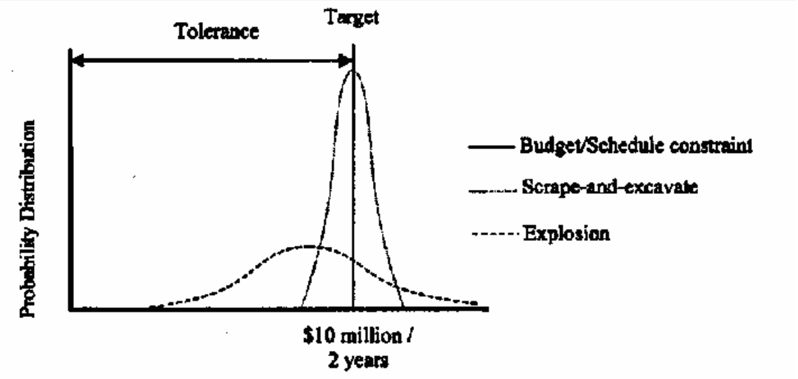
A second concern arises from the limited role that constraints play in the design process. Constraints tend to be aspects of design situations such as cost, weight, and so on. They are not essential to its function but rather are side effects that occur as a result of implementing a solution. No formal method is proposed in axiomatic design for handling constraints. Essentially as long as they are not violated, then decisions are made purely on the basis of the two axioms. However, involving the constraints more actively in the design process can alter the design solution, as found by Pena-Mora & Li (2001). They applied axiomatic design when designing workplans for fast-track construction projects.

Axiom 2 was used to evaluate designs on the basis of their ability to satisfy the design constraints.

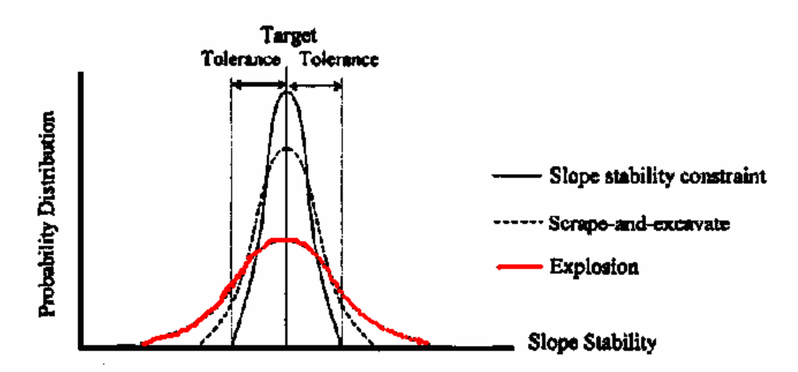
Pena-Mora & Li were evaluating two alternative excavation plans. One involved a scrape-and-excavate method, the other involved using explosives. Considered constraints were the cost and time associated with each plan, as well as the resulting slope-stability. The pdfs for each method are presented in Figure 22. When considering the expected cost and duration constraint, the explosion method has a larger common range than the scrape-and-excavate method and is therefore the more preferred option. However when considering the slope stability (the stability of the earth on the excavation site) then the scrape-and-excavate method has the larger common range and is therefore the most preferred option.

The net result is that after applying the second axiom they were unable to make a choice between the two design alternatives they were considering. They concluded that the choice of design solution depended upon which constraint criterion was more important, although they did not offer any specific technique for making the final decision. One feature of axiomatic design is that all constraints and FRs are considered to be equally important. In reality however, this is rarely the case. Some functions or aspects of a design will always be more important than others, and compromise and trade-offs are intrinsic features of the design process.

Standard weighting techniques are often used to assign relative importance to specific aspects of a design requirement, but axiomatic design does not offer this possibility as the incorporation of weights violates the integrity of Suh's equation for calculating information content (Suh, 2001). As a result of this, Suh recommends that to highlight the importance of a particular functional requirement, the designer should simply assign a tighter design range: i.e., a tighter acceptable range of performance values for an FR. However, the actual performance value of an FR and the importance of that FR are two fundamentally different aspects of a design requirement that cannot be arbitrarily lumped together by tightening the acceptable performance range. Tightening the range will indeed highlight and increase the impact of that FR's effect upon the information content of a design, but this impact is not an accurate reflection of how important this particular FR is to the designer. Furthermore, the approach essentially involves artificially altering a design requirement to suit a particular design method. However, a designer should not have to alter a design requirement just to suit a particular design approach. Consider the example pdf presented in Figure 23.



a) slop stability constraint



b) slop stability constraint

Figure 22: pdfs for a) construction cost/time and b) slope stability (Pena-Mora & Li, 2001)

The acceptable design requirement is a design range of +/- A around the target FR performance value. The system pdf for the design solution under consideration lies partially within this design range. The shaded area represents the information content of this design. The important point to note is that the design is capable of meeting the design requirement with a probability of approximately 50%. To increase the importance of this FR however, Suh advocates tightening the design range, for example to +/- B. Now, the system pdf lies completely outwith this new, artificial design range: i.e., the design solution is not within the design range +/- B. Thus, essentially this design solution has an information content of 0, is now not able to meet the design requirement, and would be discarded by the designer, even though it does in fact meet the true design requirement (design range +/- A). In essence, the approach suggested by Suh can result in acceptable design solutions being unnecessarily discarded.

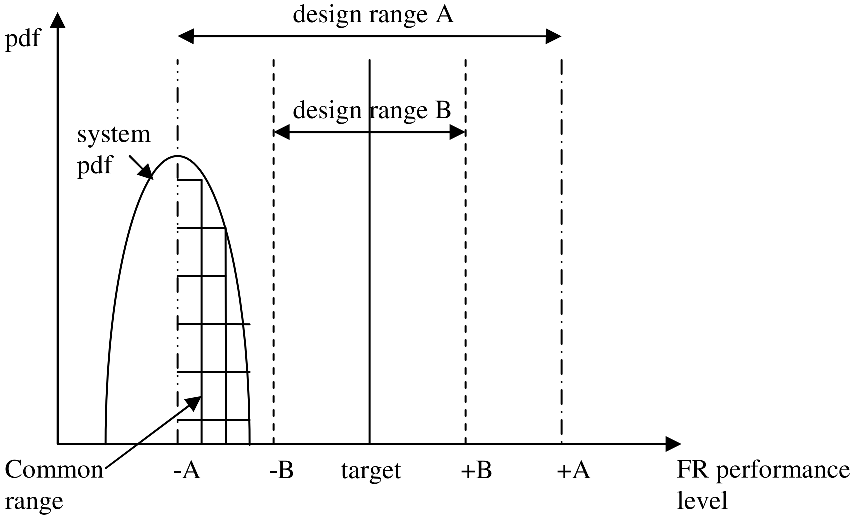


Figure 23: Tightening the design range

Thus, when considering the overall decision-making process within the axiomatic design framework, there are several issues to be addressed:

- All FRs and constraints are assumed to be equally important and there is no valid method for assigning relative importance to either FRs or constraints;
- Constraints assume a fairly limited role, and can be more actively incorporated into the decision making process to help guide design development;
- Axiom 2 is rarely used due to the problem of generating and validating pdfs for potential design solutions. Design evaluation often becomes reliant purely upon

the first axiom and hence the decision-making process becomes rather one-dimensional. A more encompassing method of evaluating designs would help the designer make the most appropriate design decisions.

2.4 Decision-based Design Using Utility Analysis (DBDUUA)

Section 2.3 argued that there was a need for a more encompassing decision making process within the axiomatic design framework, rather than evaluating designs purely in terms of the two axioms. Decision-based design using utility analysis (DBDUUA) is a design theory where the emphasis is on using a numerical technique to help the designer evaluate different design options (Gu et al., 2000; Tappea et al., 2001; Thurston, 1991). It attempts to provide a more quantitatively accurate numerical technique for making decisions than is possible with standard weighting techniques.

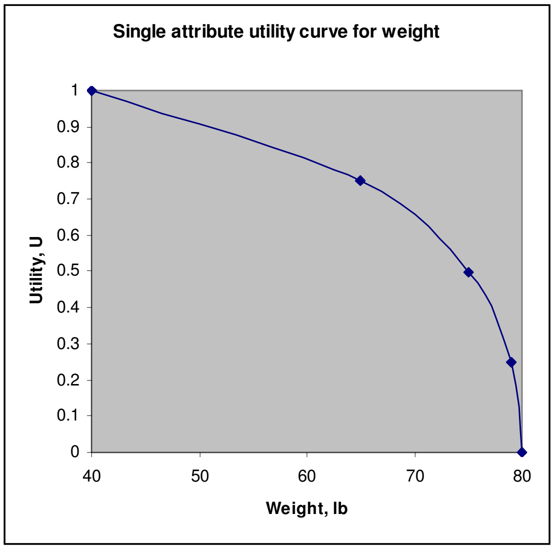


Figure 24: A Utility Curve

The significant advantage that utility analysis has over using standard linear weighting as the basis for evaluation is that it allows the use of non-linear preferences (see Figure 24) to assist decision making. It allows for the fact that a designer's preferences may change depending upon the particular value that an attribute has. Generally speaking an objective might be to limit the weight attribute of a fixture to a certain value. In Figure 24 the target is a fixture weight of 40 lbs. Weights above this are considered, up to a maximum of 80 lbs. However once the weight exceeds 70 lbs or so, then the worth of that particular fixture begins to drop of quite dramatically.

Thus it provides greater freedom with which to express preferences. Figure 25 illustrates the difference between the standard weighting techniques, axiomatic design, and DBDUUA in terms of how accurately each approach can represent a designer's preference. A design range has been specified around a target performance attribute. According to axiomatic design principles, as long as a design performs within the specified design range then the designer has no varying preference. Essentially, it makes no difference if the design performs at the target value or at either end of the design range and a black-and-white view of the world is assumed.

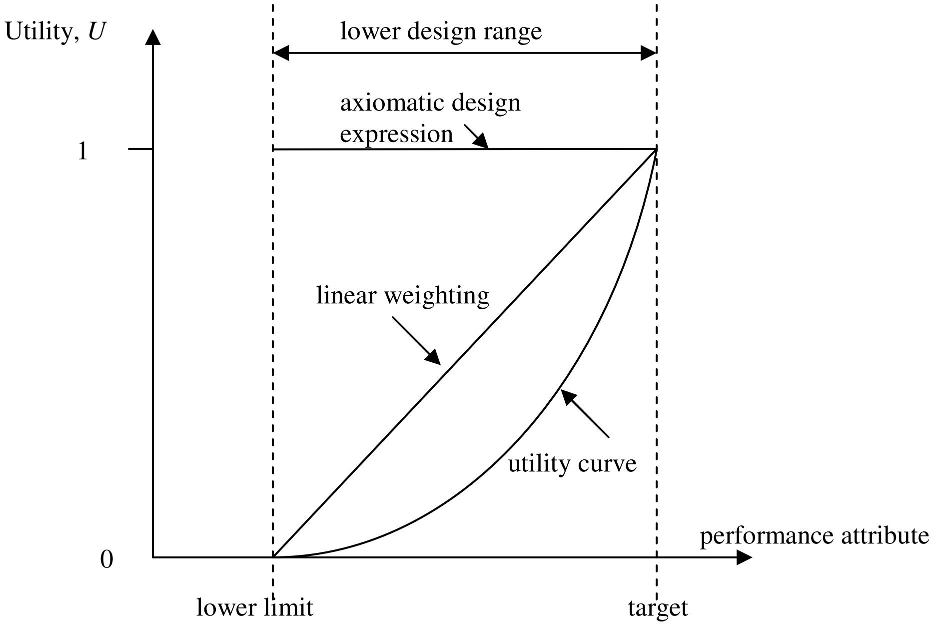


Figure 25: Expressing a designer's preferences

Linear weighting allows the designer to say that the closer to the target value a design option gets, the more highly the designer rates that design: i.e., the higher its utility.

However, only a linear relationship between utility and performance is possible. DBDUUA however provides the designer with an opportunity to fully express a preference. The utility curve can assume any shape, whither be it linear, quadratic, logarithmic, exponential or indeed any curved or linear form. Thus, it is a powerful tool with which to express a designer's preferences.

The process adopted for utility analysis is to determine the utility curve for each performance objective and then combine all the calculated utilities using the following multiplicative (Thurston, 1991):

$$U(X) = \frac{1}{K}\left[\left[\prod_{i=1}^{n}\left(Kk_iU_i\left(x_i\right)+1\right)\right]-1\right]$$

$U(X)$ = overall utility of the complete set of performance objectives X;
x_i = performance level of each attribute i;
X = set of attributes ($x_1, x_2, \ldots, x_n$);
k_i = assessed single attribute scaling constant, i.e. the importance of each attribute relative to the others
$U_i(x_i)$ = assessed single attribute utility value
$i = 1,2,\ldots,n$ attributes;
K = scaling constant.

Figure 26: Determining the Overall Utility of a Design Case

K is obtained by normalizing $U(X)$ in the standard way:

$$1+K = \prod_{i=1}^{n}\left(1+Kk_i\right)$$

The key tasks are to generate the single FR utility curves and the assessed single attribute scaling constants. The utility curve $U_i(x_i)$ expresses the worth of varying levels of each attribute in isolation. The scaling factor k_i relates to the tradeoff between attributes the decision maker is prepared to make. Both are created through the decision maker answering a series of lottery questions, an example of which is presented in Figure 27. The process of generating utility curves and scaling constants is detailed in Chapter 4, but essentially involves asking the designer to choose between two imaginary designs that are identical in every respect, other than their attribute performance values and the probability of each design of achieving these values. The process is repeated by altering the probability value until it is such that the designer cannot make a choice between the two designs. This probability value is then one point on the utility curve. The process is repeated for other performance values of the attribute until sufficient points on the utility curve have been plotted.

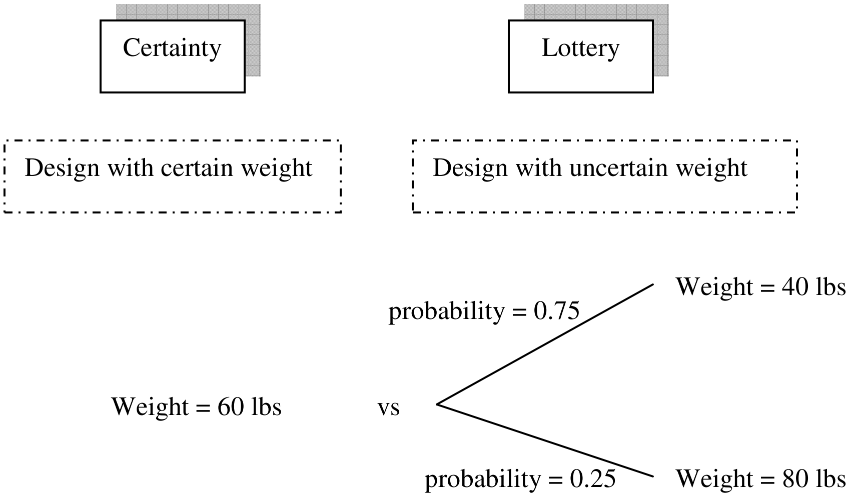


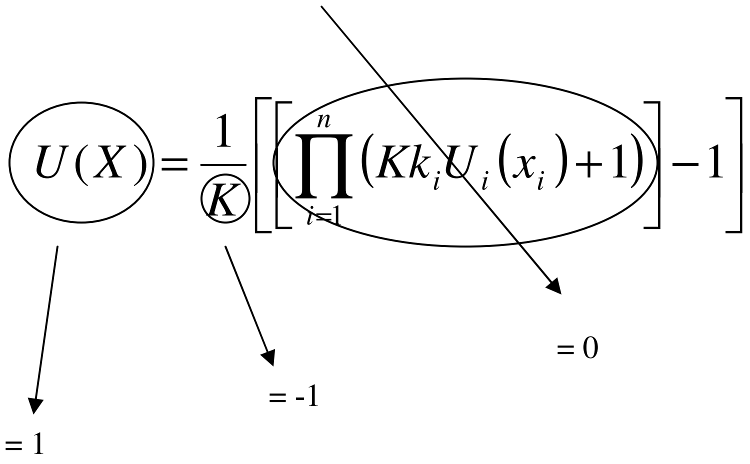
Figure 27: An example of a lottery question

There are two drawbacks to using DBDUUA which have prohibited its widespread use in the engineering community. The first drawback is the substantial time and effort involved in generating a single utility curve (Thurston, 2001). Therefore designers are prepared to make a tradeoff and use a less expressive technique such as weighting purely because it is simpler to use.

Secondly, as a result of the calculation of the total utility (*U(X)*) being based upon a multiplicative expression, *U(X)* always tends to a value of one when a high number of attributes (empirically more than six) are used. Thus it is impossible to distinguish between designs options. High numbers of attributes result in two consequences:

- the normalizing constant of *K* tends to a value of one, and;

- the utility returned for a design tends to one 1 because the multiplicative expression tends to zero. The expression *[Kk$_i$U$_i$(x$_i$)+1]* always has a value between 0 and 1. Multiplying a high volume of numbers that have a value within this range will result in the product tending towards zero. The net effect of this therefore is that *U(X)* always tends to one for a high number of attributes, as illustrated in Figure 28.



$$U(X)=\frac{1}{K}\left[\left[\prod_{i=1}^{n}\left(Kk_iU_i\left(x_i\right)+1\right)\right]-1\right]$$

Figure 28: The Effect of a High Number of Attributes Upon Calculated Utility

Overall the following considerations need to be addressed when implementing and using DBDUUA:

- the task of generating utility curves and scaling constants is a rather thankless one that requires considerable time and effort from the designer. The significant problem is simply the excessive iteration involved. Thus some means of simplifying this process is required;
- the method is not particularly useful when more than approximately six design attributes are considered. When more attributes are considered the calculated utility tends to one, thus some method of handling large numbers of design attributes must be developed.

2.5 Summary

To summarize the findings of this literature review, there are several challenges that stand out with regard to fixture design. The first of these relates to the design of individual units, such as locating and clamping units. Much of the work that has been performed thus far in the CAFD field has concentrated on developing units that satisfy a particular functional height requirement. Little effort though has been directed towards determining the structure of these units based upon a clear understanding of the functions that they must perform, for example with respect to providing a desired stiffness. Secondly, the integration of CAFD systems remains as issue, particularly in terms of repairing designs that fail testing in the verification phase. Aspects such as deciding where the responsibility lies for fixing designs and also how to fix designs have yet to be addressed. Thirdly, few CAFD approaches fully define the fixturing problem. There are many requirements fixtures need to satisfy ranging from obvious ones such as locating accuracy and secure workholding, to others such as assembly time, loading time, tool positioning, and so on.

With regard to CBR, indexing of design cases is a problematical issue. No formal method for defining case indexes exists and it is generally left to the experience of the designer to determine what indexes should be used. A poor understanding or definition of the design requirement is directly related to inadequate indexing. If the requirements of a fixture design problem can be adequately formalized, then it seems likely that these requirements can be used, if not directly then at the least as a guide, to determine the indexing attributes.

Chapter 3 – Research Objectives and Methodology

Chapter 2 presented a review of various CAFD and general design techniques, outlining for each approach areas in which further research work was required. This chapter summarizes the findings of the literature review by stating the objectives of this dissertation. Subsequently the methodology adopted to achieve those objectives is presented in section 3.2.

3.1 Research Objectives

Section 1.4 listed the high level objectives of this research, and this section expands upon these aims. There are two standpoints from which the objectives can be viewed. One is from an application based standpoint that lists objectives with respect to the CAFD field. The second considers objectives resulting from a commitment to use CBR, axiomatic design, and decision-based design using utility analysis as a means of achieving the application based objectives.

The goals with respect to computer-aided fixture design are:

- Concentrate on developing an approach for assisting the unit design phase of fixture design. The aim is to generate complete fixture designs that fully detail the physical structure of the locating/clamping units based upon an understanding of the required function of each unit.
- Develop a CAFD method that is able to generate a comprehensive formulation of a fixturing requirement based upon the following design considerations:
    - workpiece geometry;
    - workpiece design tolerances;
    - workpiece stability;
    - fixture unit stiffness;

    - fixture cost;
    - fixture usability;
    - fixture component collision;
    - fixture weight.
- Develop a CAFD method that can generate solutions to satisfy the requirements listed in this comprehensive formulation.
- Develop a CAFD method that integrates setup planning, fixture planning, unit design, and verification into a single design tool. This integration should be such that:
    - the output from one design phase can be accepted and understood by the following phase;
    - it should be possible to repair outputs from design phases if they fail during testing. This aspect of integration is largely limited to the unit design and verification stages of design whereby if a unit fails testing, then the unit can be passed back to the unit design phase where the design is either repaired or deemed un-repairable. If a repair is not possible then alternative solutions should be sought within the unit design phase of the design process and subsequently verified.
- Develop a software implementation that demonstrates the operation of the CAFD methodology.

To achieve the above goals a commitment was made by the author to use CBR due to the experiential nature of fixture design (Kumar, 1995). Specifically the role of CBR is to assist the unit design stage and it is therefore the primary means by which locating and clamping units are generated. To make effective use of CBR, the following objectives need to be satisfied.

- Due to the problem of inseparability within CBR, a formal method for determining or criteria for choosing the indexing attributes of a design case needs to be identified.

- Given the limitations of basing retrieval upon attribute similarity, adaptation knowledge underpins the retrieval method in this CAFD approach. For an effective implementation of adaptability-based retrieval, the following goals are established:
    - Develop an adaptability-based retrieval method that is computationally feasible and has a well-defined control mechanism to restrict navigation of the search space.
    - Develop specific criteria for managing the size of the case base to ensure that it contains sufficient levels of useful knowledge but is not so large that retrieval becomes computationally demanding.
    - Develop criteria for evaluating cases on the basis of their adaptability.

Objectives have been listed that declare the need for a comprehensive formulation of a fixturing problem and the need to develop a thorough technique for determining the indexing attributes of a design. To address these issues, the concept of axiomatic design requirement decomposition is used. However, the limitations of the evaluation mechanisms used in axiomatic design lead to the creation of the following two objectives.

- Develop a method of evaluating designs within the axiomatic design framework that allows for the fact that not all FRs are equally important, rather than relying exclusively upon the two axioms.
- Provide a mechanism within axiomatic design that will allow constraints to assume a more proactive role within the design decision-making process.

A common objective listed for CBR and axiomatic design is to provide a means for evaluation. With this is mind the utility analysis approach used in decision-based design using utility analysis is used within the CBR framework as the basis for making decisions. However, its implementation is not without difficulty leading to the formulation of the following two minor objectives.

- Simplify the process of determining utility curves and scaling constants that must be generated during utility analysis. The aim is essentially to reduce the amount of time taken to generate the curves.
- When large numbers of attributes are involved, the utility tends to a value of 1, making it difficult to discern which designs are more favourable than others. The goal is to develop a technique whereby utility analysis can be used in designs in which a large number of attributes are being considered.

3.2 Proposed Approach

To achieve these objectives, the Computer-Aided FIXture Design methodology (CAFixD) is proposed. One of the primary objectives of CAFixD is to generate the individual fixture units that combine to form a complete fixture. Initially the design requirements for these units need to be defined and then the units can be designed based upon those requirements. To develop the design requirement, axiomatic design decomposition is used. The thoroughness of this technique allows the comprehensive formulation of the fixturing requirement in the form of a list of FRs for which DPs can be subsequently obtained. To support the generation of these FRs, the CAFixD method includes various techniques for analysing the design problem. Most notably these involve analysing the tolerances and machining forces on a workpiece.

Upon completion of the FR list, DPs are then sought which satisfy the FRs. Some of the DPs (for example locating points) are calculated directly whereas others are physical entities, such as locating and clamping units. These are generated using a CBR approach in which previous examples of units are retrieved and adapted. Within the CBR model, axiomatic design requirement decomposition provides a thorough indexing mechanism for design cases to alleviate the problem of inseparability. Adaptability-based retrieval recalls cases from the library in a two step process. Initially, to restrict the search area a vetting stage identifies cases that are qualitatively able to satisfy FRs: i.e., these cases have the correct type of FRs (e.g., they may exhibit a stiffness in the correct direction) but may not satisfy the FR quantitatively (e.g., the may have a stiffness value too low for the current design requirement). Cases that survive this vetting stage are then evaluated on the basis of the modifications required to quantitatively satisfy the FR.

This analysis is performed by implementing adaptation strategies and subsequently evaluating the effect of these strategies. The adaptation strategies contain knowledge that allows them to instigate repairs, test them, and then evaluate the effectiveness of a repair. These adaptation strategies are able to identify all physical changes that would have to be made to a DP to allow it to satisfy a particular FR. They can also identify when strategies may fail. In this way, these strategies support the objective of integrating the unit design and verification stages of fixture design together.

It is likely that more than one design solution will be repairable (and possibly repairable in a number of ways), and utility analysis is used to evaluate different candidate DP/adaptation strategy combinations that have resulted in successful repairs. Global constraint attributes, such as cost, weight, assembly time, etc., play a major role in this process. Preferences for each of these constraints are defined in the form of utility curves and utility analysis used to evaluate which DP/adaptation strategy results in a complete fixture design that best matches these design preferences.

To help control the search through the case library, a maintenance mechanism is proposed that evaluates knowledge held in the library and expels knowledge that it considers to be of little value. The basic criterion for deciding which knowledge is useful or not is based upon usage. Knowledge that is regularly retrieved during the recall process is considered useful knowledge, whereas knowledge rarely retrieved is considered expendable and subject to possible expulsion from the case library.

Two objectives were raised with regard to the use of utility analysis. The first objective related to simplifying the generation of design preferences. To achieve this utility curve reuse is supported by allowing the recall and modification of existing curves. This partially simplifies the utility curve generation process. In terms of the second objective, a grouping approach is adopted when determining the utility of a design with a high number of attributes. This prevents the utility multiplicative from always tending to zero.

Finally, to demonstrate the operation of the CAFixD methodology a software implementation is developed using Microsoft Visual C++ and a workbook design package (Tidestone Formula 1). A particular advantage of using the workbook design package is that it offers considerable potential for passing information between the different design phases.

Chapter 4 – Proposed Design Methodology

This chapter describes the CAFixD approach that has been developed to satisfy the objectives detailed in chapter 3. The method is based upon a CBR model in which previous design cases, most notably individual locating and clamping units, are retrieved from a case library and adapted to meet a new design requirement. Section 4.1 acts as an introductory overview to the CAFixD method. The indexing mechanisms that are of great importance in a CBR tool are detailed in section 4.2 and thereafter the retrieval approach is described in section 4.3. Section 4.4 briefly reviews the underlying ethos of the method.

4.1 CAFixD Overview

Overall, the method (Figure 29) decomposes the design problem into a series of smaller problems, searches the case base for a solution to each individual problem, and then reconstitutes the individual solutions to form one complete solution. During retrieval, emphasis is given to evaluating the adaptability of design cases.

The approach is similar to that adopted by a human designer, who would initially generate a conceptual design solution, and subsequently fill in the details of that solution during a detailed design stage. In the proposed methodology, a conceptual design solution is initially retrieved from case library 1, and then case library 2 is used to fill in the details of this conceptual design. In this fashion, case library 1 corresponds to conceptual design and case library 2 corresponds to detail design. Case library 1 is used to support the setup and fixture planning stages of fixture design, whereas case library 2 supports the unit design stage.

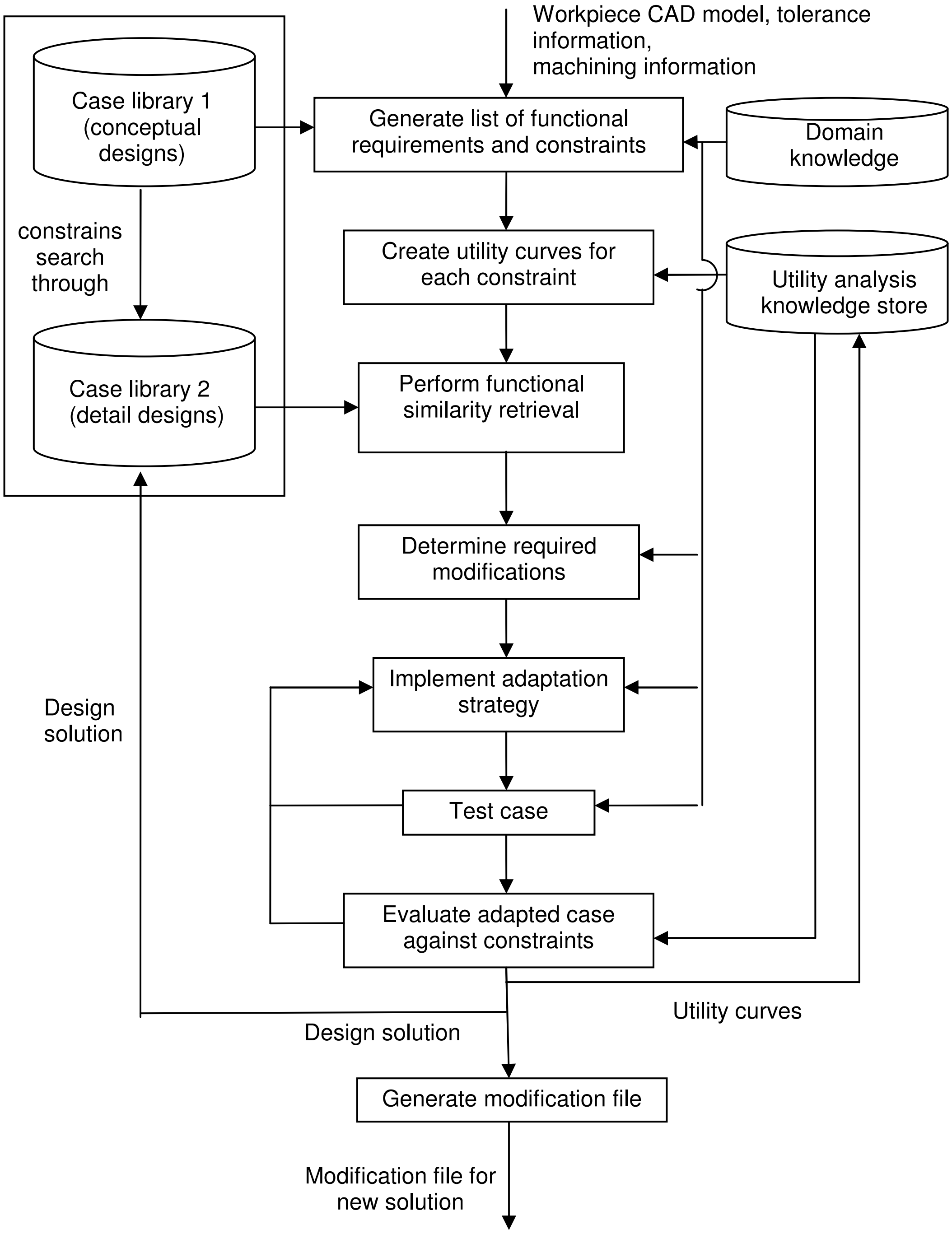


Figure 29: The fixture design methodology

The external inputs to CAFixD are:

- the workpiece geometry;
- the workpiece design tolerances;
- the machining information;
- the design preferences.

The output is a new fixture design in the form of a modification file that lists the required changes that must be made to the retrieved design cases.

Initially, workpiece and machining information are processed to determine a suitable conceptual design for the fixture. The key task during this stage is to assign locating and clamping surfaces upon the workpiece. Based upon the nature of these surfaces an appropriate conceptual fixture design can be retrieved from case library 1. This conceptual model identifies the number of locating and clamping units required and the design is then refined by developing the specific functional requirements (FRs) for each of these units through an analysis of the workpiece geometry, tolerances, and machining force information. Not all of these requirements can be automatically formulated and thus the designer may have to specify certain additional FRs if they are desired. This issue is discussed in greater detail in section 4.2.3.

The user must also specify a number of global constraint attributes, such as fixture cost or assembly time, that apply to the fixture design as a whole and record design preferences for each of those constraint attributes. These preferences are represented in the form of utility curves that are subsequently used to guide the retrieval process in which suitable units are retrieved from case library 2 to satisfy the FRs generated during the conceptual design stage.

This retrieval is a two stage process. An initial vetting stage is used to identify the cases potentially capable of satisfying a particular FR. Generally possible solutions are sought for each FR individually, but if this is not possible then solutions are sought that satisfy a number of FRs. Normally these cases will have to be adapted to meet the design FRs. The retrieved solutions are re-evaluated based upon the effect that the required adaptations will have on the ability of the design to satisfy the design preferences expressed for the global constraint attributes.

In this adaptability-based stage of the retrieval process the next task is to identify the type of adaptation that is necessary: e.g., is it necessary to adapt a unit's stiffness or clamping force. Secondly possible strategies that can perform the adaptation are identified. There may be one or more means of adapting a case and some strategies may be more suited to a particular design situation than others. Therefore each adaptation strategy is implemented and the subsequent performance of the design evaluated relative to the preferences expressed for all global constraints. The candidate case having an adaptation strategy that returns a design most in keeping with these preferences is chosen as the retrieved case with which to satisfy the FR being considered. This process is then repeated for each FR until all have solutions.

The new amalgamated design is presented as the final output in the form of a list of physical modifications that must be made to the retrieved cases. Also, the new adapted design cases chosen as the final solutions for each FR are added to the case library for possible future use. Due to the high levels of computation involved in the adaptability-based retrieval phase, case library 2 is subject to maintenance to prevent it becoming too large. The criteria for maintaining the library are largely based upon the number of times a case is successfully retrieved. Those cases whose retrieval success is below defined criteria levels are subject to deletion from case library 2.

During the design process, the domain knowledge store is used to support the FR generation and adaptability-based retrieval tasks. The utility analysis knowledge store contains previously stored design preferences which can be recalled and edited by the user, and these curves are the primary means against which design cases are evaluated during the adaptability-based retrieval stage.

4.2 Indexing Design Cases

Axiomatic design principles are used to determine the indexing of both design cases and their solutions, as illustrated in Figure 30. Indexing is not based upon choosing “surface” attributes that describe a design problem but rather, cases are indexed according to a deeper understanding of their role in a design solution. The more obvious “surface” customer attributes (CAs) are the workpiece geometry, design tolerances, and machining information. These are processed to generate a list of FRs that explicitly state the functions that the fixture design must perform. These functions relate to three main areas of the design requirement. These are ensuring accuracy of location, exhibiting sufficient stiffness to withstand the machining and clamping forces, and satisfying a number of additional ergonomic requirements.

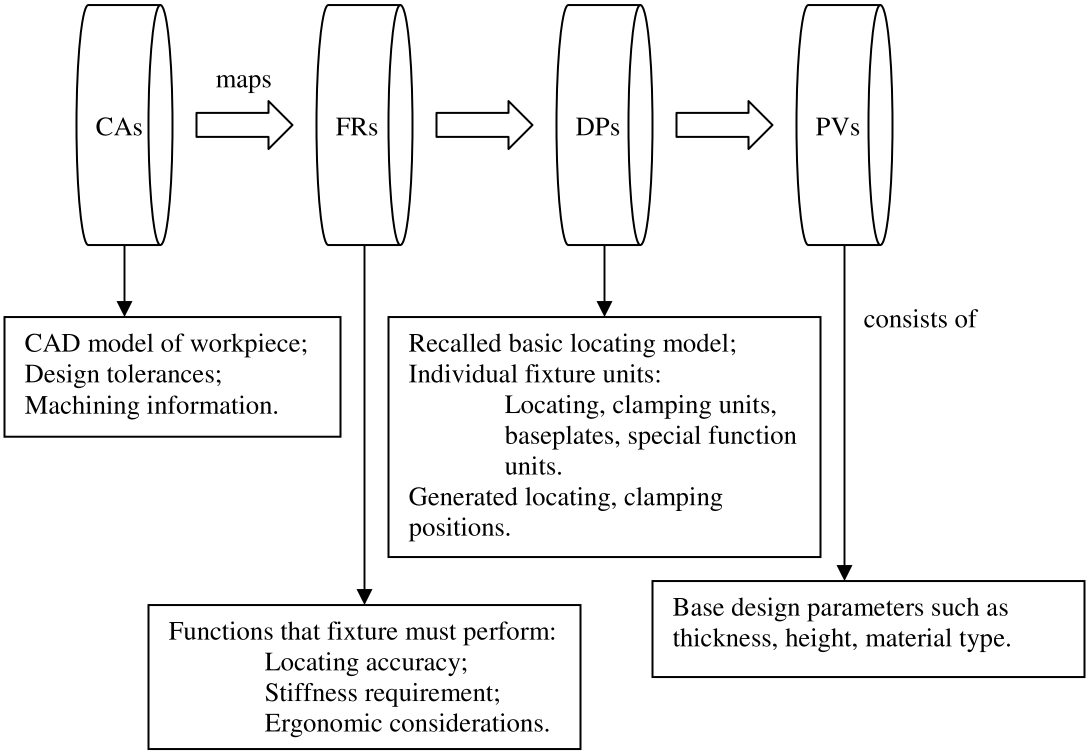


Figure 30: Axiomatic design domains applied to fixture design

The FRs map onto design parameters (DPs), which are the solutions used to satisfy the FRs. These DPs include those design cases retrieved from the case libraries, whether they be conceptual models retrieved from case library 1 or specific locating/clamping units, baseplates, and locator types that are recalled from case library 2. However not all DPs are generated from existing cases in the case base. Other forms of DPs are generated from the workpiece geometry and include solutions such as locating directions, locating and clamping surfaces, and locating and clamping coordinates. These DPs in turn can be used to partially guide the retrieval of cases from the second case library.

Parameter variables (PVs) are base parameters used to achieve the DPs. It is important to note that PVs are not always required. For example when the DP is a workpiece surface then no PV is attached to this DP because it is not possible to alter the workpiece in any way. Rather PVs are generally reserved for those parts of the fixture that have a physical structure. Typical examples include clamping units, base plates, and locating units. The PVs are the individual parameters of the unit structure that can be manipulated to result in a change of performance of the DP. In essence these PVs are the means of modifying a design case to satisfy a FR: i.e., they are modified by the adaptation strategies to achieve a certain level of functional performance. A typical example would be a locating unit for which a specific stiffness is desired. This stiffness can be controlled through parameters such as the thickness, width, or material properties of the unit. These parameters are the PVs.

4.2.1 The Design Case Libraries

The high-level design of the case library is presented in Figure 31. The case base consists of two libraries. Case library 1 is related to fixture planning. It stores conceptual fixture designs in terms of their locating principles. The second case library holds the individual units that constitute the fixture design. Examples include locating units or clamping units. The approach CAFixD adopts is to navigate through case library 1 to retrieve a conceptual design, before proceeding to the second case library to retrieve appropriate fixture units. Thus, the output from case library 1 constrains the search through case library 2 as only units that can be used in the retrieved locating principle are considered for retrieval. The case libraries do not hold the knowledge detailing which units can be used in particular conceptual designs. Rather, this knowledge is held in the domain knowledge base.

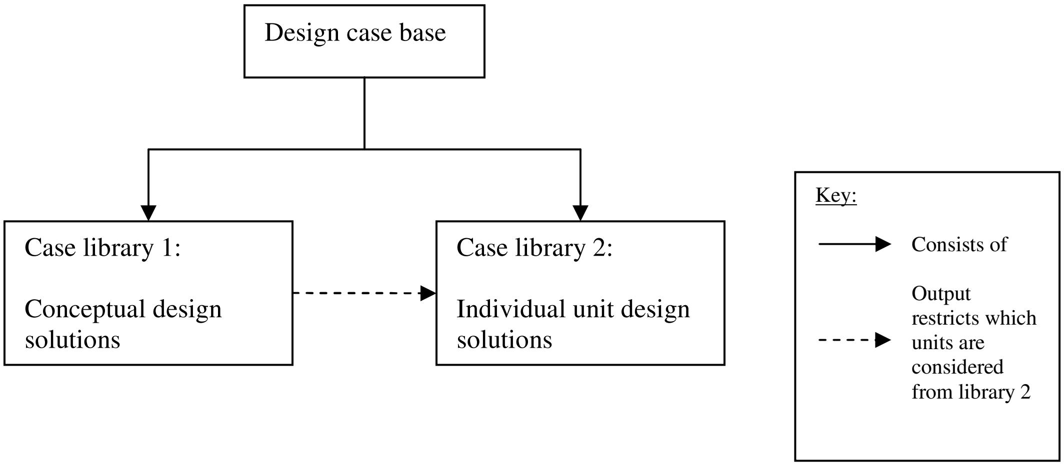


Figure 31: The design case base

4.2.2 Case Library 1

The structure of case library 1 is presented in Figure 32. It contains cases that are conceptual in nature: i.e., they contain information relating to locating principles in terms of locating methods and locating point distributions. Each conceptual design is capable of restraining the required six degrees of freedom (three of which are linear whilst the remainder are rotational).

There are 3 basic locating methods: plane, pin-hole, and external profile locating. In plane locating only planar surfaces are used for locating purposes. Pin-hole locating subdivides into short shaft locating and long pin locating. One plane surface is used for primary locating and one inner cylindrical surface for secondary locating in the short shaft variation. For long pin locating one inner cylindrical surface is used as the primary locating surface to secure four degrees of freedom. External profile locating subdivides into V-block and V-pad locating. In V-block locating an external cylindrical surface is used to perform primary locating, whereas in V-pad locating an external cylindrical surface is used to perform secondary locating. In such cases two V-pads can be used to secure the four degrees of freedom in the same manner as V-block locating.

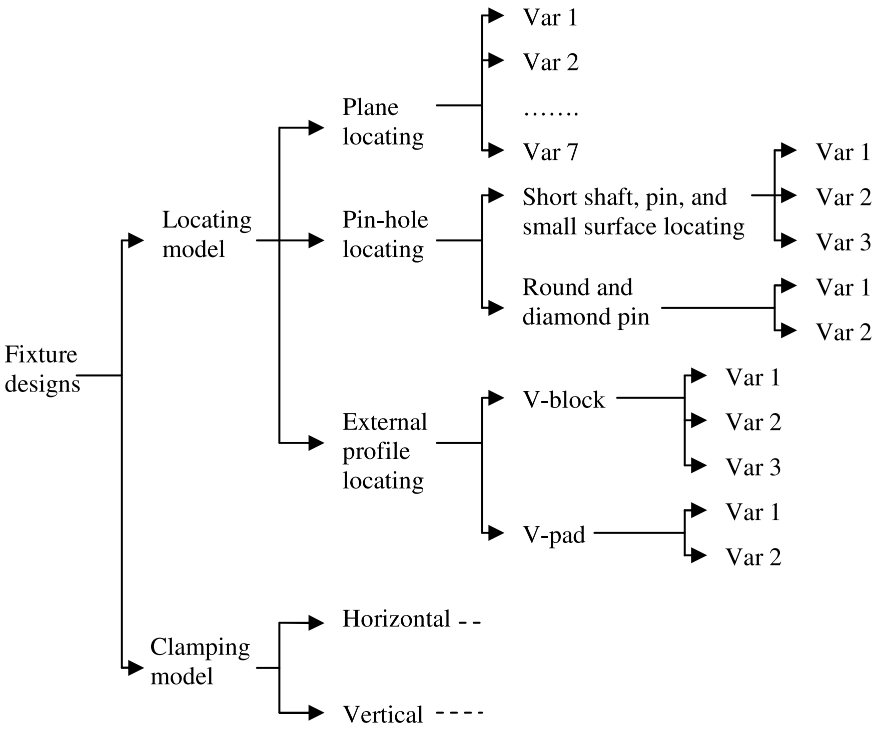


Figure 32: Case library 1 - conceptual design solutions (Rong, 1999)

For each method, there are subsequent decompositions and refinements of the root locating method. Plane locating (3-2-1) has seven variations, as illustrated in Figure 33. The first variation is locating with an edge bar and a parallel bar in the bottom surface, which is equivalent to three points in the vertical direction and two points in the horizontal direction. The tertiary locating is performed by one additional point. The second variation has two parallel bars supporting the large bottom planar surface, which is equivalent to three locating points. The secondary and tertiary locating surfaces are the two side surfaces. The two secondary locators need not be one the same planar surface, but must act in the same direction.

Variation 3 has three locators on the bottom planar surface with secondary and tertiary locating identical to variation 2. The three primary locators must act in the same direction, but need not be on the same planar surface. Variation 4 has locating with an edge bar supporting the bottom and side surface of the workpiece, which is equivalent to four locating points (two are horizontal, two are vertical). An additional supporting point is used in the primary locating direction and another one used for tertiary locating.

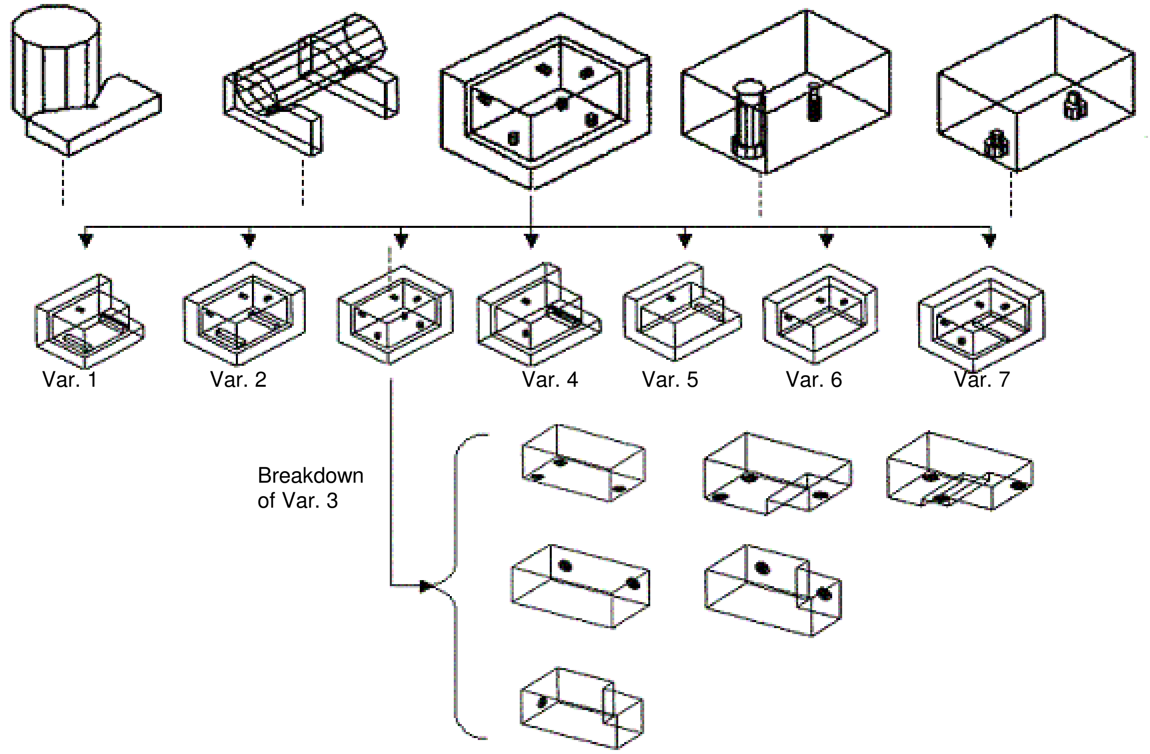


Figure 33: Decomposition of conceptual 3-2-1 locating solutions

The fifth variation has primary locating performed by the bottom planar surface being in direct contact with the fixture baseplate. This is equivalent to three locating points. Secondary locating is performed by a side-bar. Variation 6 has the same primary locating arrangement as Variation 5, but secondary locating is performed by two individual points rather than a side-bar. Variation 7 has two bottom planar surfaces performing the primary locating, one of them directly in contact with the workpiece and equivalent to two locating points. The secondary locating is provided by two points (that do not need to be on the same planar surface), whilst a solitary locating point performs the tertiary locating function.

The locating points do not always need to act upon the same surface. They need only act in the same direction. Thus, the primary locating points in the Variation 3 can act upon the same surface, or two locators can act on one surface and the remaining point on another. Alternatively, the locating points can all act on different, parallel surfaces.

As the design solution proceeds, the CAFixD method supports the identification (during the setup planning stage) of surfaces that will be used for locating in a particular setup. The nature of these surfaces determines the conceptual models that can be considered as a basis for the fixture solution. For example if all the locating surfaces are planar in nature then one of the plane locating variations will be chosen. If the primary locating surface is a hole, then one of the pin-hole locating variations will be chosen. Within each of these basic types there are a range of subsequent variations of which any number may be applicable. The selection of which particular variation to proceed with is driven by rule evaluation which gradually attempts to refine the possible locating models.

Initially the locating surfaces are evaluated using the following set of rules which determine the basic type of locating model:

If (primary_locating_surface is "Plane") Then (Conceptual_Design is Plane_Locating)
If (primary_locating_surface is "Hole") Then (Conceptual_Design is Pin_Hole_Locating)
If (primary_locating_surface is "Cylinder") Then (Conceptual_Design is Ext_Profile_Locating)

Further rules are invoked to narrow the range of conceptual solutions considered. For example checks can be performed to determine if there are any workpiece surfaces that result in an interference occurring between any of the locating faces (see Figure 34). If there is an interfering surface then this precludes the possibility of housing the two locators for those faces on a common locating unit since a collision results between the fixture and the workpiece. It is possible to use a common locating unit, but such a design is somewhat redundant as the unit essentially acts as a secondary baseplate upon which auxiliary individual locating units have to be placed (Figure 35).

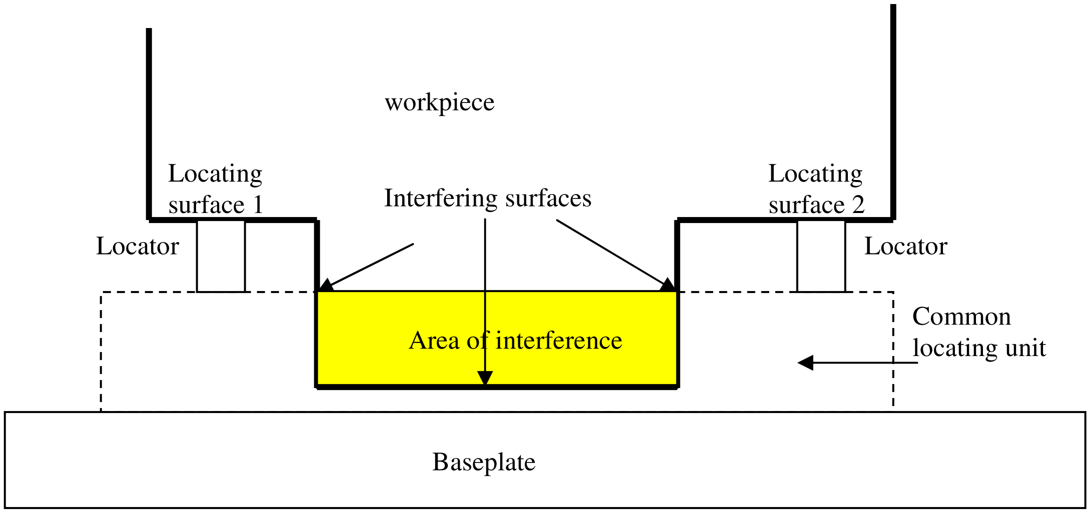


Figure 34: An interfering surface between locating points

If such an interference does exist then only variations three and four of the plane locating models are possible solutions so the following rule is invoked to limit the potential conceptual model:

If (interfering_surface_1/2 is YES)

Then (Conceptual_Design is Plane_Var_3 OR Plane_Var_4)

If similar interference is found to occur between the first and third primary locating points then variation three is the only possible solution. If there is no interference then both variations are feasible. Other tests can be made to determine if the locating surfaces are all at the same height. If all locating surfaces are at the same height relative to the baseplate of the fixture then it is possible to use common locating units. If they act at different heights then the problem of design redundancy is encountered again due to the common unit acting as an auxiliary baseplate.

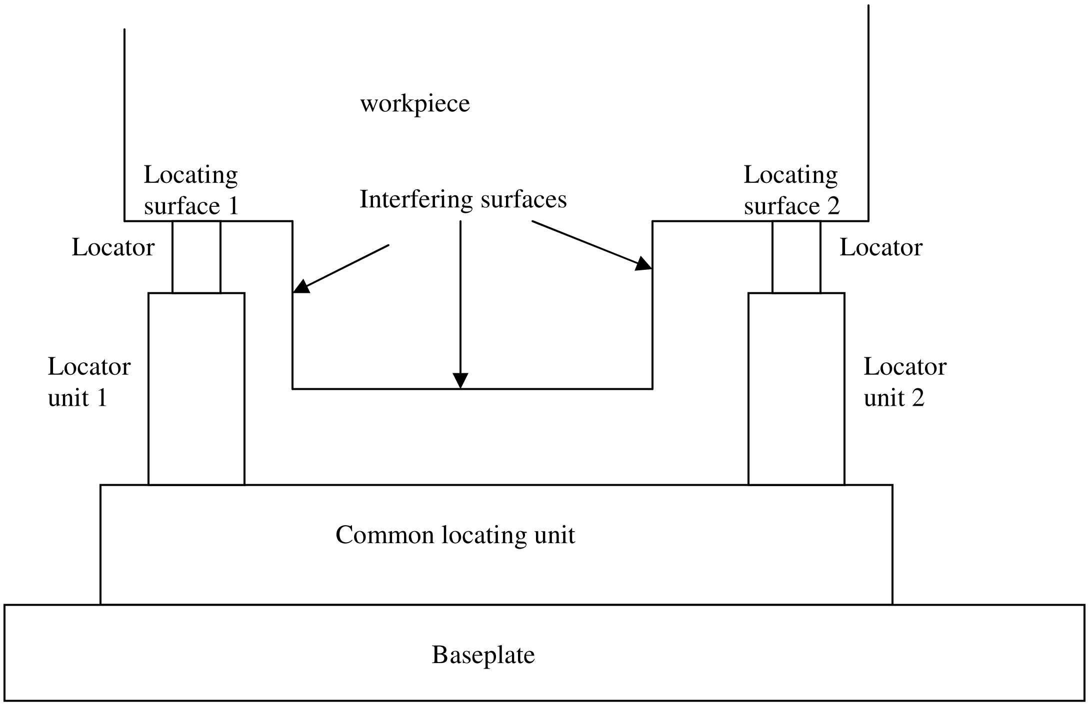


Figure 35: A redundant common locating unit

An important point to note from this discussion is that more than one plausible conceptual model may be retrieved from the case library. There is no need to pick one over the other at this stage. Rather they are all carried through into the remaining stages of the design task and full fixture designs can be generated for each model by retrieving suitable units from case library 2 as per the standard retrieval process detailed in section 4.3. The conceptual model resulting in the most suitable design (as determined by the results of the retrieval process) would then be ultimately chosen as the final solution, along with the generated fixture units.

Once at least one conceptual design has been found in case library 1, the search for a design solution proceeds to the second case library, where appropriate individual fixture units can be retrieved for modification. Before doing so however, the functional requirements (FRs) for the units must be specified. To assist this task, “skeleton FR sets” are attached to each variation of case library 1.

4.2.3 FR Decomposition

Skeleton FR sets list all the functions of which a fixture for any particular locating model may have to be capable, and the type of solution (DP) used to satisfy each FR. This skeleton is subsequently refined by processing workpiece, tolerance, and machining data, and from accepting user input. A partial decomposition of the skeleton FR set for plane locating, variation three is presented in Figure 36. FRs are grouped into three main categories. One group deals with the locating accuracy requirements, the second with the stability requirements of the fixture, and the third deals with ergonomic issues related to fixturing. The DPs used to satisfy the FRs are detailed in Figure 37. A full list of FRs and DPs for variation three of plane locating can be viewed in Appendix A.

The first two groups are the simplest to handle in terms of automating their generation. The locating principle determines the number of units in the fixture design. For the third variation of plane locating there are six individual points of location and for each locating point a locating unit is required. A clamp must act against each locating point thus six clamping units are required. The first group of FRs concerns accurate location of the workpiece, which in itself subdivides into locating the workpiece and constraining the six degrees of freedom ($FR_{1.1}$), and ensuring the correct accuracy of location ($FR_{1.2}$). $FR_{1.1}$ decomposes into two groups of FRs. $FR_{1.1.1}$ decomposes into six FRs that ensure each degree of freedom is constrained by specifying the direction that each locator must act in, and the corresponding DPs relate to surfaces on the workpiece that have the correct orientations to satisfy the DoF FRs ($DP_{1.1.1}$). $FR_{1.1.2}$ decomposes into six FRs that require contact to be established between the locators and the workpiece to constrain the six DoFs. The corresponding DPs are the locating coordinates and these contact points must fall on the surfaces specified in $DP_{1.1.1}$.

FR$_{1.2}$ is concerned with controlling the accuracy of location and decomposes into three groups of FRs. FR$_{1.2.1}$ defines the need to ensure the accuracy of location at a particular locating point. The corresponding DPs are the locating units that act at each point. These DPs must provide the required accuracy of location. FRs 1.2.2 and 1.2.3 take account of the machine tool accuracy and the irregularities of the workpiece surface that the locator will act upon. The corresponding DPs are tolerance allowances that are incorporated into the analysis performed to determine the allowed tolerance for each locating unit in FR$_{1.2.1}$. This process of tolerance assignment is explained in greater detail in section 4.2.3.1.2.

- FR$_1$ – Locate workpiece to required accuracy
    - FR$_{1.1}$ – Locate the workpiece
        - FR$_{1.1.1}$ – Control six degrees of freedom (6 FRs)
        - FR$_{1.1.2}$ – Provide contact between locator and workpiece (6FRs)
    - FR$_{1.2}$ – Control accuracy of location
        - FR$_{1.2.1}$ – Locate workpiece to required drawing tolerances (6FRs)
        - FR$_{1.2.2}$ – Compensate for machine tool misalignment (6FRs)
        - FR$_{1.2.3}$ – Compensate for surface variations at fixture/workpiece interface (6FRs)

- FR$_2$ – Stabilize workpiece deflection during machining and clamping
    - FR$_{2.1}$ – Hold workpiece in situ during machining
        - FR$_{2.1.1}$ – Provide clamping forces against each locator (6 FRs)
        - FR$_{2.1.2}$ – Control fixture unit deflection to within design tolerances (12FRs)
        - FR$_{2.1.3}$ – Provide clamping orientation (6FRs)
        - FR$_{2.1.4}$ – Provide clamping coordinates (6FRs)
    - FR$_{2.2}$ – Provide extra support for large workpieces

- FR$_3$ – Satisfy certain ergonomic considerations
    - FR$_{3.1}$ – Prevent damage at the fixture/workpiece interface
        - FR$_{3.1.1}$ – Prevent damage to the workpiece from the fixture
            - FR$_{3.1.1.1}$ – Prevent surface damage to workpiece from locator contact (6 FRs)
            - FR$_{3.1.1.2}$ – Prevent surface damage to workpiece from clamping contact (6 FRs)
        - FR$_{3.1.2}$ – Prevent damage to the fixture from the workpiece
            - FR$_{3.1.2.1}$ – Prevent surface damage to locator from workpiece contact (6 FRs)
            - FR$_{3.1.2.2}$ – Prevent surface damage to the clamp from workpiece contact (6 FRs)
    - FR$_{3.2}$ – Assist coolant flow during machining
        - FR$_{3.2.1}$ – Fixture units should be capable of chip shedding (12 FRs)
        - FR$_{3.2.2}$ – Direct coolant flow to specific workpiece features
    - FR$_{3.3}$ – Provide means of loading and unloading the workpiece from the fixture
    - FR$_{3.4}$ – Provide machine tool guidance to during machining
    - FR$_{3.5}$ – Error proof w/piece (3 FRs)

Figure 36: A partial FR skeleton set for 3-2-1 plane locating, variation 3

- DP$_1$ – Fixture locating arrangement
  - DP$_{1.1}$ – locating principle e.g. 3-2-1
    - DP$_{1.1.1}$ – locator/workpiece interface surface (6DPs)
    - DP$_{1.1.2}$ – workpiece/locator interface contact coordinates (6DPs)
  - DP$_{1.2}$ – Locator unit parameters
    - DP$_{1.2.1}$ – locator units with tolerances (6DPs)
    - DP$_{1.2.2}$ – tolerance allowance for machine tool (6DPs)
    - DP$_{1.2.3}$ – tolerance allowance for workpiece surface irregularities (6DPs)

- DP$_2$ – Fixture unit force capabilities
  - DP$_{2.1}$ – Clamping unit force capabilities
    - DP$_{2.1.1}$ – Clamping units (6DPs)
    - DP$_{2.1.2}$ – Clamping and locating units (12DPs)
    - DP$_{2.1.3}$ – Clamping surfaces (6DPs)
    - DP$_{2.1.4}$ – Clamping coordinates (12DPs)
  - DP$_{2.2}$ – External support units

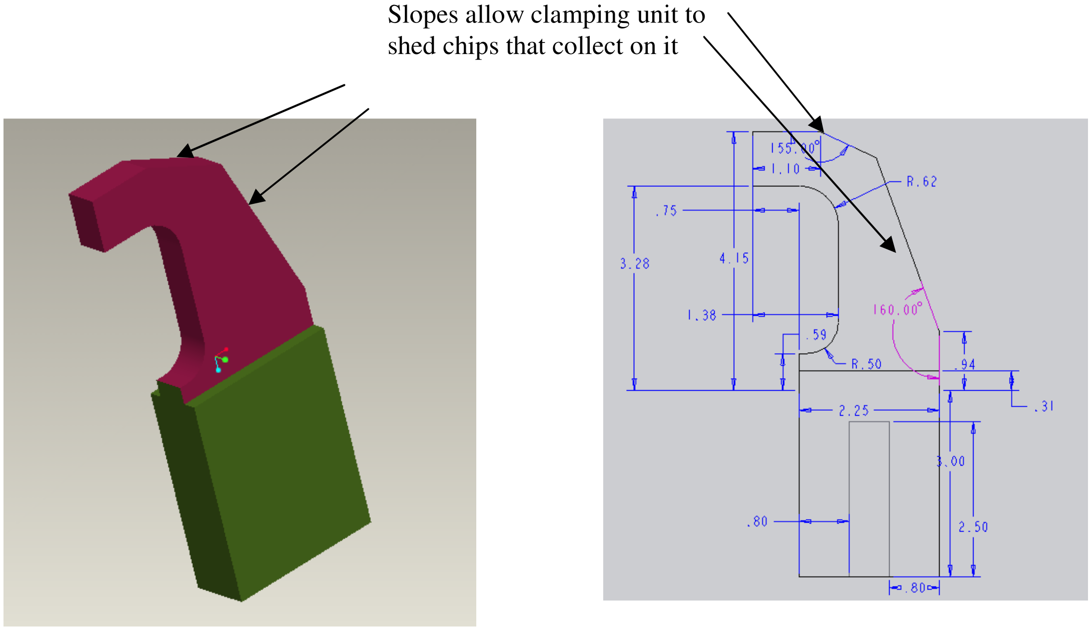
- DP$_3$ – Ergonomic design features
  - DP$_{3.1}$ – Fixture/workpiece interface parameters
    - DP$_{3.1.1}$ – Fixture interface parameters
      - DP$_{3.1.1.1}$ – Contact area at workpiece/locator unit interface (6DPs)
      - DP$_{3.1.1.2}$ – Contact area at workpiece/clamping unit interface (6DPs)
    - DP$_{3.1.2}$ – Fixture hardness parameters
      - DP$_{3.1.2.1}$ – Locating surface area contact hardness (6DPs)
      - DP$_{3.1.2.2}$ – Clamping surface area contact hardness (6DPs)
  - DP$_{3.2}$ - Coolant flow channels
    - DP$_{3.2.1}$ – V-channels on fixture units (12DPs)
    - DP$_{3.2.2}$ – Coolant directing units
  - DP$_{3.3}$ – Workpiece loading/unloading mechanisms
  - DP$_{3.4}$ – Tool guide units
  - DP$_{3.5}$ – Interference pin arrangement (3DPs)

Figure 37: The matching design parameters for the partial FR skeleton set

The second group of FRs (FR$_2$) is concerned with the ability of the fixture to both exert and withstand forces. The main FR (FR$_{2.1}$) ensures that the fixture is able to withstand the machining forces so that location accuracy is maintained. It subdivides into four FRs, one of which states the necessary clamping force that must be exerted on the workpiece (FR$_{2.1.1}$). As six clamps are required for variation three plane locating, then FR$_{2.1.1}$ decomposes into six FRs each of which specifies the clamping force requirement at a particular clamping point. The corresponding DPs are clamping units capable of generating the required forces (DP$_{2.1.1}$). FRs 2.1.3 and 2.1.4 specify the directions that the clamping forces must act in, and the corresponding DPs are the workpieces surfaces on which the clamps act ($DP_{2.1.3}$) and the clamping coordinates ($DP_{2.1.4}$). $FR_{2.1.2}$ states the required stiffness of the locating and clamping units. The DPs of these FRs are the physical fixture units. These DPs are the same as those used to satisfy $FR_{1.2.1}$ (locating units) and $FR_{2.1.1}$ (clamping units). Thus, although independent solutions are sought for each FR in keeping with the first axiom of axiomatic design, this is not always possible. $FR_{2.2}$ is a special case FR where for large workpieces it may be necessary to provide some additional support.

In terms of developing a software implementation of the CAFixD method, FR_1 and FR_2 can potentially be generated automatically by means of an analysis of the workpiece and the machining information. The procedure for doing this is detailed in section 4.2.3.1. However the third group of FRs cannot be treated in this way and the user would have to specify which ones apply. FR_3 is related to ergonomic considerations and subdivides into five FRs. The first deals with ensuring that damage is not suffered by the workpiece or the fixture at the fixture/workpiece contact points. Thus the locators and clamps should not damage the workpiece and vice-versa. To prevent damage of the workpiece surface ($FR_{3.1.1}$) the locating and clamping areas ($DP_{3.1.1}$), of which there are twelve in total, can be increased to reduce the contact pressure. To prevent damage to the locators and clamps ($FR_{3.1.2}$) the hardness of their contact areas ($DP_{3.1.2}$) can be increased.

$FR_{3.2}$ is concerned with controlling coolant and chip flow during machining. One of the FRs to which it decomposes ($FR_{3.2.1}$) states that fixture units should be able to shed chips: i.e., chips should not accumulate on fixture units. The corresponding DPs are the same twelve locating and clamping units used to satisfy FRs. The geometry of these units controls the chip shedding capability as only units with slanted corners are capable of performing this function, as illustrated in Figure 38. $FR_{3.2.2}$ states a requirement for coolant to be directed along a specific path. The corresponding DP is a physical unit along which the coolant can flow, such as a tube or a special additional unit in the fixture that houses a channel for the coolant to flow along.



Slopes allow clamping unit to shed chips that collect on it

Figure 38: A clamping unit with chip shedding ability

The third FR ($FR_{3.3}$) specifies that special arrangements are required to assist loading and unloading of the workpiece from the fixture. Possible DPs are specific types of disappearing locator pins or ejector mechanisms that allow release of the workpiece more quickly than removal by hand. The fourth FR ($FR_{3.4}$) relates to providing special structures that will guide the cutting tool towards specific areas or features of the workpiece. Fixtures that have such devices are normally referred to as jigs.

The final FR is designed to ensure error-proofing. This means that some physical means should exist on the fixture to ensure that the workpiece cannot be inserted incorrectly. Depending on the workpiece, it is sometimes possible to insert a workpiece into a fixture incorrectly yet still have it make solid contact with the locators. Obviously if the orientation is not corrected then the workpiece will not be manufactured correctly. To ensure that a workpiece is not inserted in such a fashion, $FR_{3.5}$ decomposes into three requirements demanding the provision of some means to prevent the workpiece being inserted with the incorrect orientation. Standard DPs for this requirement are strategically placed interference pins on the fixture that ensure the workpiece will not rest on the locators if wrongly inserted. Three FRs are specified to ensure correct orientation around the *x, y,* and *z* axes. Correspondingly three pin positions are required to act as DPs.

4.2.3.1 Selecting and Refining the Skeleton FR Decomposition

To generate a list of FRs for a particular design solution, there are two main stages that need to be completed. These are selection of an appropriate skeleton FR set and refinement of the chosen skeleton.

Selecting a FR skeleton set is based upon workpiece geometry and the design datum surfaces, and consists of two subtasks:

1. the directions of location must be determined using the design tolerances, and;
2. workpiece surfaces need to be chosen that provide the appropriate directions required for locating. The surface type of each locating surfaces dictates the type of conceptual model that can be retrieved from case library 1.

Refining a FR skeleton set subdivides into five main tasks.

1. Initially determine the coordinates of each locating point.
2. For each of these locating points the allowed variation in their position must be calculated. This allowed variation is the maximum tolerance allowed for each locating point that still allows the design tolerances to be achieved during machining. The first step in this process is to perform a sensitivity analysis to determine which design tolerances are the most sensitive to variations in position of each locating point. These design tolerances will be used to drive the remainder of the process.
3. Perform a tolerance analysis to determine the allowable variation of each of the locating positions.

4. Perform a tolerance assignment in which the allowed tolerance of each locating position is divided up amongst the various contributors to this tolerance.
5. Perform a force/stiffness analysis to determine the required stiffness at each locating and clamping point.

4.2.3.1.1 Selecting a Skeleton FR Set

As indicated above, choosing a skeleton FR set is driven by two factors – the workpiece geometry and the design tolerances. To obtain the locating directions, the workpiece features that are to be machined must be identified. Subsequently the tolerance information associated with these features is analysed to obtain the relevant datum surfaces. The directions of these surfaces dictate the locating directions because these surfaces are used as the machining datums. Once the locating directions have been chosen, then the locating surfaces must be specified. Although the design datum surfaces are normally used for locating, it is also possible to use other surfaces in conjunction with these datum surfaces. The reason for doing this is that using other surfaces may offer specific advantages, such as increased workpiece support. Once the locating surfaces have been selected, a suitable locating model can be retrieved from case library 1 based upon the nature of these surfaces: i.e., are they cylindrical or plain, etc.

To determine the locating directions, the workpiece tolerances must be analysed. Geometric tolerancing is used in the CAFixD method. Specifically true position, parallel, and perpendicular tolerances are supported and the conventions for representing each type are illustrated in Figure 39. At this stage the design datum surfaces listed in the tolerance specifications for a workpiece are the most important piece of information. Each of the design datums is a surface on the workpiece. Each of these surfaces has a particular orientation, and the locating directions will be chosen from these orientations. The number of times that each datum surface is referenced by a design tolerance is recorded, as illustrated in Table 4. This table lists design datums taken from a workpiece, and the features for which these design datums apply.

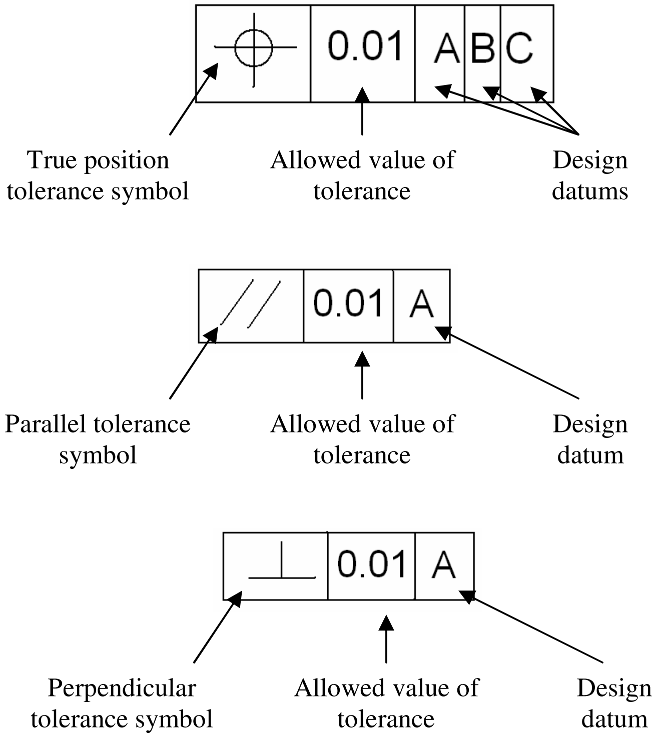


Figure 39: True position, parallel, and perpendicular tolerance specifications

Initially the primary locating direction is determined. Typically this is derived from the machine tool type and the machining operations that the workpiece will undergo. Primary location, as a rule, acts in the same direction as the normal of the machine tool table. The workpiece must therefore be arranged such that the spindle of the machine tool can perform the specified machining operations. For example if a hole is to be drilled in a workpiece and the machine is a vertical machine center, then the workpiece must be orientated such that the axis of the desired hole is in alignment with the spindle of the machine. Similarly if a surface is to undergo face milling then the workpiece must be oriented such that the surface normal is parallel to the spindle. In these circumstances the workpiece orientation during machining can be set and the potential surfaces for primary locating determined from surfaces that are directly exposed to the machine table (Figure 40).

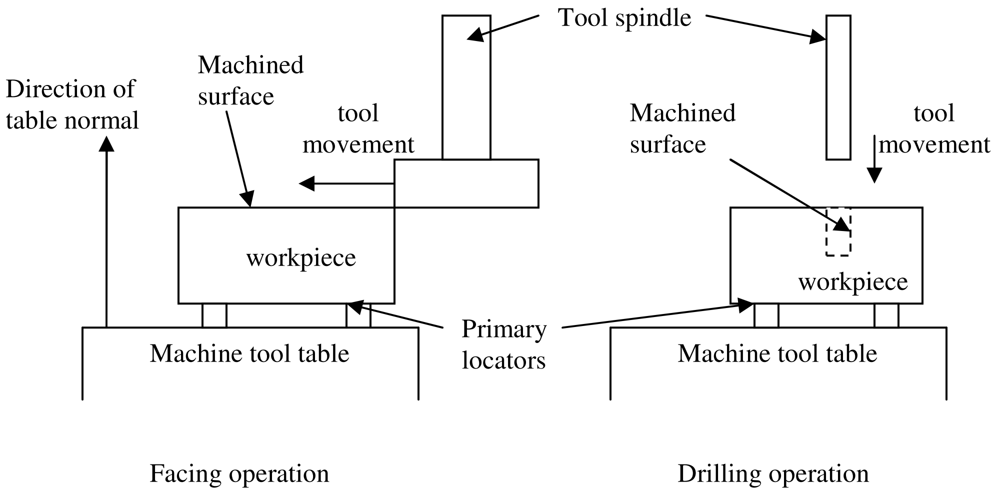


Figure 40: Determining the primary locating direction

The secondary and tertiary directions of location cannot normally be determined this way, but a possible list of orientations will exist from the analysis of the design datums. If more than two remaining options exist then the most commonly used datums and their orientations are selected as the possible candidates. Of those orientation directions that have been discarded, it is important to note that the features that use these orientations in their design datums cannot be machined in this particular setup. These features are identified and recorded, and when the current setup is complete the CAFixD method then repeats the solution process but only for the remaining features that could not be machined in the current setup. This repeats until the required number of setups has been generated in which all features can be machined according to their design datums. This is the manner by which CAFixD supports multiple setup planning. For example, Table 4 presents a list of design datums taken from a workpiece, and the features for which these design datums apply.

Datum surface	Datum orientation	Features with this datum	Number of times datum referenced
A	1,0,0	T,R,S,U	4
B	0,1,0	T,R,S	3
C	0,0,1	T,R,S	3
D	0,0,-1	U	1

Table 4: Design datums and multiple setup planning

There are four possible orientation possibilities – (1,0,0), (0,1,0), (0,0,1), and (0,0,-1). Only three of these possibilities are required for a particular setup. Assuming that (1,0,0) and (0,1,0) have been chosen as the primary and secondary locating orientations by the methods previously described, the remaining task is to determine whether to use (0,0,1) or (0,0,-1) as the direction of tertiary location. (0,0,1) is referenced by more design features than (0,0,-1) as features T, R, and S use it as one of their design datums, whereas (0,0,-1) is referenced only once by design feature U. Thus (0,0,1) is chosen as the tertiary orientation for the current setup. Feature U is removed from consideration in further stages of the design solution for this setup, but once a fixture design has been designed for the current setup, a fixture for a second setup to machine feature U is designed. Checks are also made to ensure that the three chosen directions of location are mutually perpendicular and that all six degrees of freedom are constrained. The CAFixD method can determine if the DoF constraint is satisfied or not, but if an error is found then CAFixD cannot as yet fix the design. The inherent assumption made is that the design datum information is correct and complete.

The CAFixD method is limited at this time to considering only planar faces for locating. For any particular orientation of location, a number of faces may be capable of providing location and a decision must be made on which combination of faces to use. The criteria for making such decisions with regard to primary locating are twofold and involve picking the combination of surfaces that provides:

- the largest location area, and;
- the location triangle that is closest to an equilateral triangle.

Typically, at least one of the points must lie on the design datum surface. Ideally all three would but the above criteria determine if the design datum in combination with other surfaces should be used to provide locating. Consider for example the situation presented in Figure 41. Design datum A acts as the surface upon which at least one of the locators must act. Possible surfaces upon which locators *P*2 and *P*3 can act are surfaces E, F, and G. Locator *P*3's function is to prevent rotation around the *y* axis, and *P*2's is to prevent rotation around the *x* axis. To determine the maximum triangular area of location, surfaces furthest apart are selected. Potential surfaces for *P*3 are datum A, E, F, and G. E offers the greatest distance between the two locators and is therefore chosen as the surface for locator *P*3. For *P*2, the choices are also A, E, F, and G. In terms of surfaces that are furthest apart then the candidate locating faces can be narrowed down to a choice between E and F. Then, the position of locator *P*3 is held steady whilst that for *P*2 is varied across the range of possible values as indicated in Figure 41. Calculated for each position are the triangular locating area and a measure of how equilateral the triangle. The measure of how equilateral a triangle is can be calculated by taking the ratio of each side to the other and summing the three ratios (Figure 42). The more equilateral a triangle is, the closer the sum of the ratios is to three. The combination of surfaces is chosen that provides the largest triangular area and the largest value of $measure_{equilateralism}$.

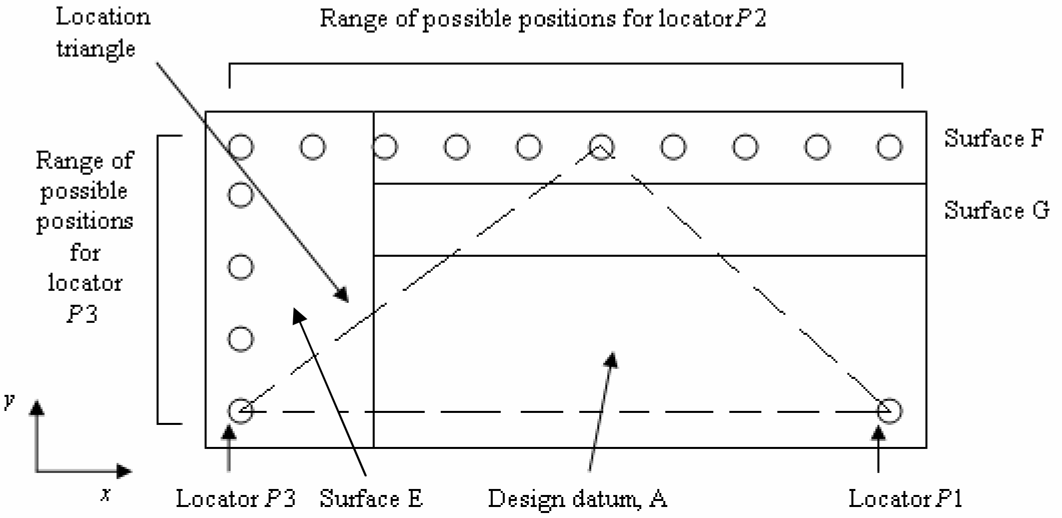
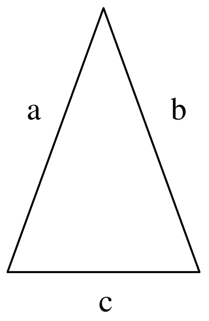


Figure 41: Choosing locating faces



Ratios are (smallest length value acts as the denominator):
ratio_ab = a/b
ratio_bc = b/c
ratio_ac = a/c

$measure_{equilateralism}$ = ratio_ab + ratio_bc + ratio_ac
For an equilateral triangle, $measure_{equilateralism} = 3$.
For a non-equilateral triangle, $measure_{equilateralism} < 3$

Figure 42: Determining how equilateral a triangle is

A similar is adopted to determine the secondary and tertiary directions of location and their surfaces. The orientation of secondary locating is determined by choosing the combination of faces that provide the greatest location length (secondary locating requires two locators only). At the end of this process both the locating surfaces and the locating coordinates are known.

Once the locating surfaces are obtained then the skeleton FR set can be retrieved from case library 1 and subsequently refined. Simple rules select the relevant FR skeleton by evaluating the type of surfaces selected for locating purposes. For example if all surfaces are planar, the plane 3-2-1 locating models are applicable. The rules for selecting a model have been discussed in section 4.2.2 and interested readers are referred back to that section. The retrieved model can now be refined by entering the locating surfaces and coordinates into the FR set. Recalling the FR and DP sets from Figure 36 and Figure 37 respectively, then $FR_{1.1}$ and $DP_{1.1}$ can be completed. $FR_{1.1}$ decomposes into two groups of FRs the first of which ($FR_{1.1.1}$) lists the orientation of each locating point, and the relevant DPs ($DP_{1.1.1}$) are the locating surfaces that provide the required orientation. The second group of FRs $FR_{1.1.2}$) states the need to contact the workpiece at this point for which the relevant DP are the coordinates of each locating point. Figure 43 presents a sample of updated FR and DP sets.

FR_1 – Locate workpiece to required accuracy
    $FR_{1.1}$ – Locate the workpiece
        $FR_{1.1.1}$ – Control six degrees of freedom (6 FRs)
            $FR_{1.1.1.1}$ – Control DoF along the *y* axis
            ……..
            $FR_{1.1.1.6}$ – Control DoF around the *z* axis

        $FR_{1.1.2}$ – Provide contact between locator and workpiece (6FRs)
            $FR_{1.1.2.1}$ – Contact workpiece with locator *P*1
            ……..
            $FR_{1.1.2.6}$ – Contact workpiece with locator *P*3

DP_1 – Fixture locating arrangement
    $DP_{1.1}$ – 3-2-1 locating principle variation 3
        $DP_{1.1.1}$ – locator/workpiece interface surface (6DPs)
            $DP_{1.1.1.1}$ – Surface A
            ……..
            $DP_{1.1.1.6}$ – Surface E

        $DP_{1.1.2}$ – workpiece/locator interface contact coordinates (6DPs)
            $DP_{1.1.1.1}$ – Coordinates (10,1,1)
            ……..
            $DP_{1.1.1.6}$ – Coordinates (1,1,1)

Figure 43: Updating the FR and DP skeleton sets (sample values only)

4.2.3.1.2 Completing the Skeleton Set for FRs 1 and 2

The remaining tasks are to complete the locating accuracy and stability FRs. This process revolves around an analysis of the design tolerances existing on the features of the workpiece. Specifically, a sensitivity analysis is performed to determine which workpiece feature is most sensitive to the rotations caused by locator pairs. The allowed tolerance at each locating point is then determined using the design tolerances of the most sensitive features, and finally the allowed tolerance at each locating point is split up and divided amongst the various contributors to the variation in location position.

The CAFixD method supports true position (Figure 44), perpendicular, and parallel (Figure 45) tolerances. The objective of the sensitivity analysis is to complete the table presented in Table 5, which details the features most sensitive to locating point variation.

Each combination of locators in a particular locating plane results in a shift in two of the three directions, x, y, and z. For the example presented in Figure 46, locators $P1/P3$ will produce a rotation around the z axis that results in a shift in the x and y directions. Basic geometry is used to determine the magnitude of these shifts which is then related to the allowed design tolerance for that feature to reveal the sensitivity of the design feature to the locating point variation.

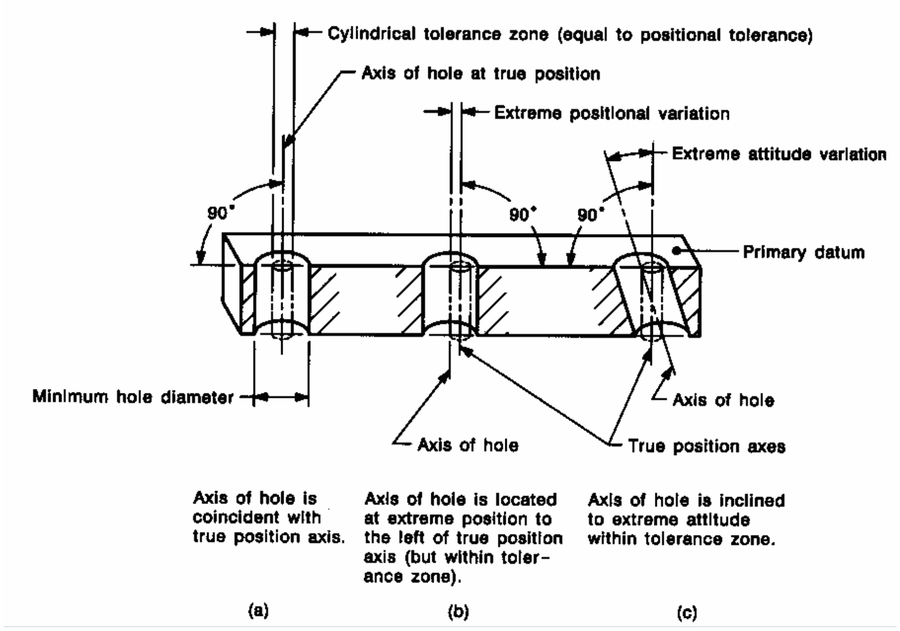
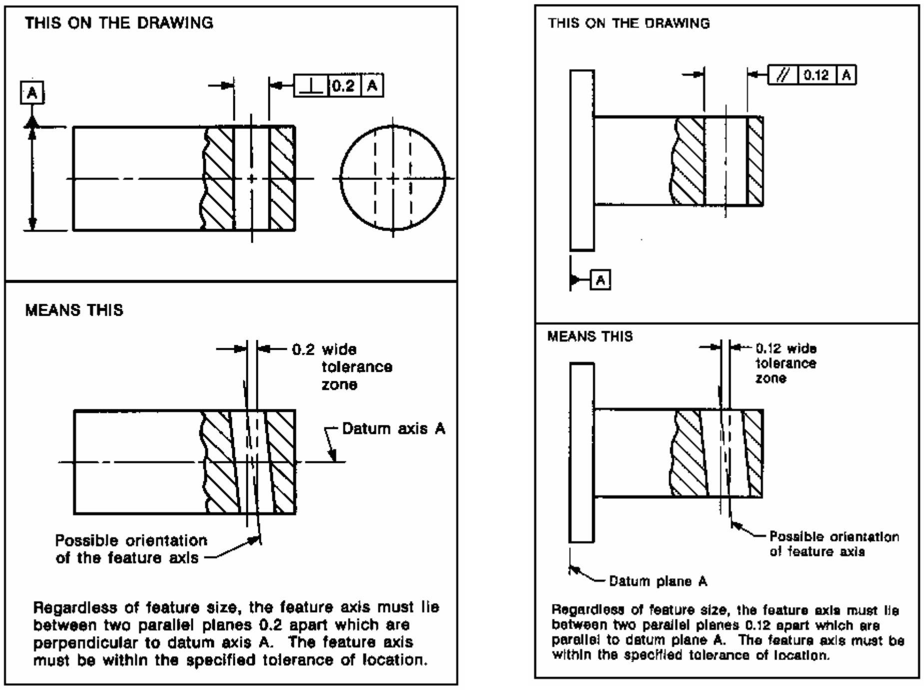


Figure 44: Definition of true position tolerance (ASME,1994)

The general procedure for each machined feature being considered for a specific setup is as follows.

1. Determine the type of feature: e.g., machined plane, hole etc.
2. Determine the type of tolerance the surface must satisfy, and its magnitude.
3. Recall the locating points and their orientation.
4. Determine the shift of each feature (the Δz, Δx, and Δy shifts) induced by the locator tolerances. The interaction of pairs of locators are used to determine this: i.e., $P1/P2$, $P1/P3$, $S1/S2$ where $P1$, $P2$, and $P3$ are the first, second, and third primary locators, and $S1$ and $S2$ are the first and second secondary locators.

5. Calculate the sensitivity of the feature tolerance to the locator tolerances by comparing the shifts to the design tolerance.
6. Compare the sensitivity to the entries already in the table. If the sensitivity is higher then replace the relevant entries in the table for the locator pair being considered.
7. Repeat steps 1 to 6 for each machined feature.



a) b)

Figure 45: a) Perpendicular and b) parallel tolerance definitions (ASME,1994)

Consider the example presented in Figure 46, where the *P*1 and *P*3 locators interact to create a rotation of the workpiece around a center point CP_{xy}. This causes a shift in the positions of two holes (*H*18 and *H*19), both of which are subject to a true position tolerance. Initially, the centre point between *P*1 and *P*3 in the *XY* plane can be generated using the coordinates for these two locating positions:

$$CP_{xy} = [(x_{P1} + x_{P3})/2, (y_{P1} + y_{P3})/2]$$

	Locating pair $P1/P2$			Locating pair $P1/P3$			Locating pair $S1/S2$		
	Feature	Tole-rance	Sensi-tivity	Feature	Tole-rance	Sensit-ivity	Featu-re	Tole-rance	Sensitiv-ity
Max Δx/tol shift									
Max Δy/tol shift									
Max Δz/tol shift									

Table 5: The sensitivity analysis table

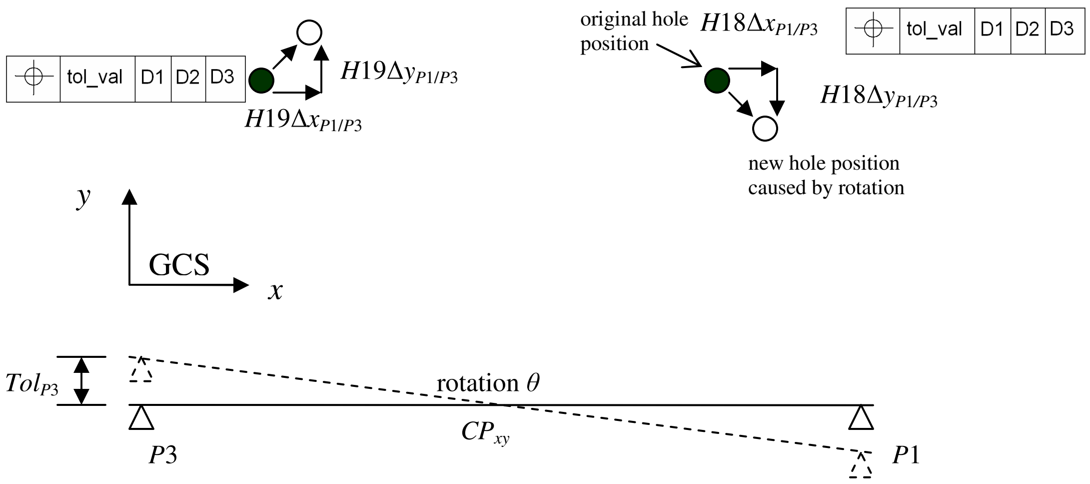


Figure 46: Performing the sensitivity analysis

An angle of rotation is assumed, the size of which is unimportant. It is important however to apply the same angle of rotation to all features. The standard equations for determining the new coordinates of a point rotated an angle θ about an origin (McMahon & Browne, 1993) are employed to obtain the new positions of holes 18 and 19 in the XY plane, where the center point (CP_{xy}) acts as the origin. Thus, for hole 18:

$$H18x_{P1/P3}' = (H18x - CPx_{xy})\cos\theta - (H18y - CPy_{xy})\sin\theta$$
$$H18y_{P1/P3}' = (H18x - CPx_{xy})\sin\theta + (H18y - CPy_{xy})\cos\theta$$

where:

$H18x$ = original *x* coordinate of hole 18;

$H18y$ = original *y* coordinate of hole 18;

$H18x_{P1/P3}'$ = new *x* coordinate of hole 18 relative to center point *CP*;

$H18y_{P1/P3}'$ = new *y* coordinate of hole 18 relative to center point *CP*;

CPx_{xy} = *x* coordinate of center point between locators *P*1 and *P*3;

CPy_{xy} = *y* coordinate of center point between locators *P*1 and *P*3;

θ = assumed angle of rotation.

The resultant shifts in the *x* (H18$\Delta x_{P1/P3}$) and *y* ($H18\Delta y_{P1/P3}$) directions are therefore:

$$H18\Delta x_{P1/P3} = H18x_{P1/P3}' - (H18x - CPx_{xy})$$
$$H18\Delta y_{P1/P3} = H18y_{P1/P3}' - (H18y - CPy_{xy})$$

There is no shift in the *z* direction. The sensitivity of a feature to the tolerance variation is:

$$Sensitivity\_x = \Delta x / tol\_val$$
$$Sensitivity\_y = \Delta y / tol\_val$$
$$Sensitivity\_z = 0$$

where *tol_val* is the true position design tolerance. These values would then be evaluated against those figures already entered in the shaded areas of Table 5. If the sensitivity of the current feature is greater than the table entries then the table is updated with the new feature identification, sensitivity value, and tolerance type. A similar process is used to determine the sensitivity of features with perpendicular and parallel tolerances. However the shift is calculated slightly differently. For any surface *ID* subject to a parallel tolerance, the shift is the sum of the magnitudes of the shifts at each end of the surface, as illustrated in Figure 47. Thus:

$$S\_ID\Delta y_{P1/P3} = \sqrt{\left(S\_IDEndy_{P1/P3}' - S\_IDStarty_{P1/P3}'\right)^2}$$

where:

$S\_IDStarty_{P1/P3}'$ = new *y* coordinate of start of surface ID relative to center point *CP*

$S\_IDEndy_{P1/P3}'$ = new *y* coordinate of end of surface ID relative to center point *CP*

The sensitivity of this surface tolerance is then determined by:

$$Sensitivity\_y = S\_ID\Delta y_{P1/P3} \,/\, tol\_val$$

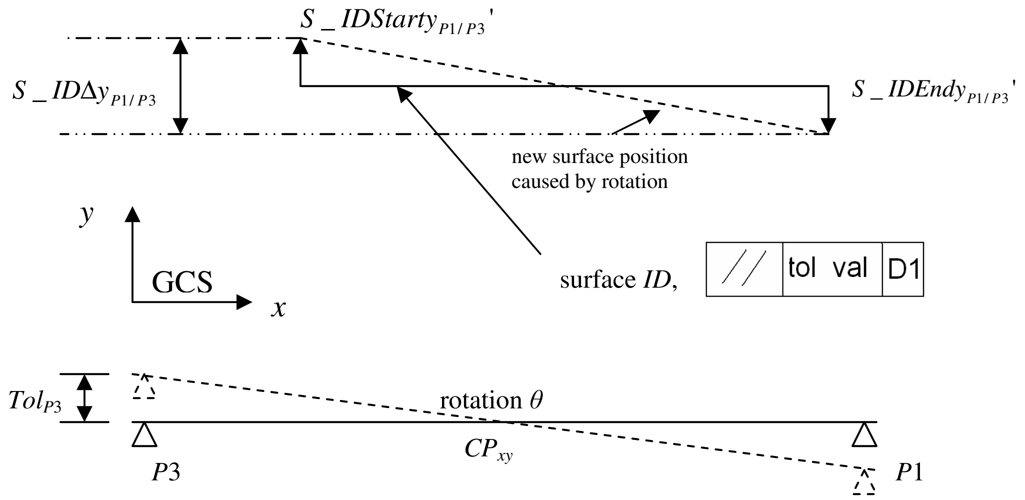


Figure 47: Performing a sensitivity analysis for a parallel tolerance

Upon completion of the sensitivity analysis, the solution can proceed to calculating the allowed location position variation at each locating point. The basic steps in this process are as follows.

1. For each locator pair, the most sensitive tolerance direction is identified.

2. Determine the type of tolerance, its value, and the sensitivity.
3. Recalculate the shift caused in the relevant direction by the locator pair.
4. Determine the final tolerance allowed for that feature in the current direction.
5. Estimate the allowed angle of rotation using the sensitivity value.
6. Calculate the shift caused by this estimated angle.
7. Refine the estimated value of the allowed angle of rotation.
8. Calculate the allowed tolerances for the locating point pair.

Locating point	***P*1**	***P*2**	***P*3**	***S*1**	***S*2**	***T*1**
Tolerance, Δ						

Table 6: The allowed variations, Δ, at each locating point

At the end of the tolerance analysis, the tolerance table presented in Table 6 will be complete. For each locating point the table specifies the allowed variation of each locating point position. The first step is to recall from the sensitivity analysis table the most sensitive feature for each locator pair. The original shift (caused by the assumed angle of rotation used during the sensitivity analysis) is recalculated by multiplying the sensitivity by the allowed design tolerance, *tol_val*:

$$\text{Original shift, } \Delta_{axis} = Sensitivity * tol\_val$$

Then the allowed tolerance in a particular direction for a feature must be specified. This varies depending on the tolerance type but for a parallel tolerance on a planar surface, the allowed value is equal to the value quoted for the design tolerance of a feature. Determining the allowed angle of rotation caused by locating tolerances, θ_{tol}, is a two stage process. Initially, an estimate of this angle, $\theta_{estimate}$ is obtained using the sensitivity value from the sensitivity table:

$$\theta_{estimate} = (tol\_val \,/\, \Delta_{axis}) * \theta_{sens}$$

where θ_{sens} is the assumed angle of rotation used during the sensitivity analysis. $\theta_{estimate}$ is only an estimate of the allowed angle of rotation. To check its accuracy, the angle has to be fed back into the equations used to determine the shift in position of a surface caused by a rotation during the sensitivity analysis. The resultant shift, Δ_{axis}', is then compared to the allowed design tolerance to determine the similarity (*Similarity*) between the two:

$$Similarity = \Delta_{axis}' / tol\_val$$

The desired value of *Similarity* is 1: i.e., Δ_{axis}' is equal to the design tolerance. This will rarely be the case for the first estimate of $\theta_{estimate}$. The reason for this is that the relationship between the rotation and the shift of interest is not linear in nature, but rather is a function of the *sine* of the angle change, as illustrated in Figure 48. However, when dealing with very small rotations normally encountered during tolerance analysis the estimate for $\theta_{estimate}$ is a good starting point from which to refine the actual allowed value of rotation caused by a pair of locating points, θ_{tol}. Refinement occurs by altering the value $\theta_{estimate}$ until the similarity condition is satisfied. This value is the allowed rotation caused by both the fixture error and the machine tool orientation error, $\theta_{tol+machine}$: i.e., when the similarity has a value of 1:

$$\theta_{tol+machine} = \theta_{estimate}$$

Once the similarity condition is satisfied the allowed rotation for a locator pair can be calculated by subtracting the rotational error associated with the machine tool from this value:

$$\theta_{tol} = \theta_{tol+machine} - \theta_{m/c\_rot}$$

where θ_{m/c_rot} is the accuracy of the machine tool around the particular axis of interest. This piece of data is included in the machining information that is one of the inputs required in the CAFixD method. The next stage is to use θ_{tol} to determine the allowed tolerances at each locating position, for example at locating points $P1$ and $P2$ (Tol_{P1} and Tol_{P2}). The assumption made is that each locating point within a pair is assigned the same tolerance allowance (i.e., $Tol_{P1} = Tol_{P2}$). Since all angles of rotation are now known, the allowed tolerance values for each locating position can be computed simply from geometry, as illustrated in Figure 49.

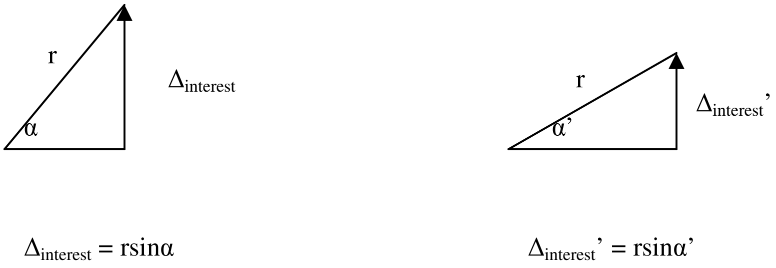


Figure 48: Effect of varying an angle upon shift of interest

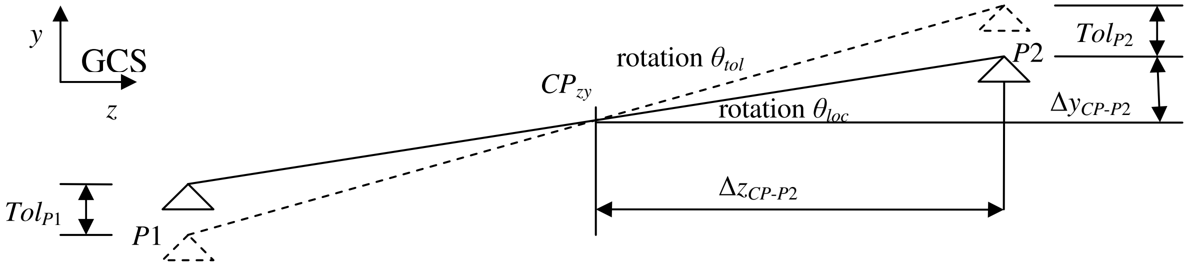


Figure 49: Calculating the tolerance allowed at each locating position

θ_{tol} = angle of rotation caused by locating point tolerance

θ_{loc} = angle of rotation caused by different y coordinates of locating points

θ = overall angle of rotation = $\theta_{loc} + \theta_{tol}$

$Tol_{P2} = Tol_{P1}$ = allowed tolerance for each locating point

From geometry:

$$\tan \theta_{loc} = \Delta y_{CP\text{-}P2} / \Delta z_{CP\text{-}P2}$$

$$\tan \theta = (\Delta y_{CP\text{-}P2} + Tol_{P2}) / \Delta z_{CP\text{-}P2}$$ where

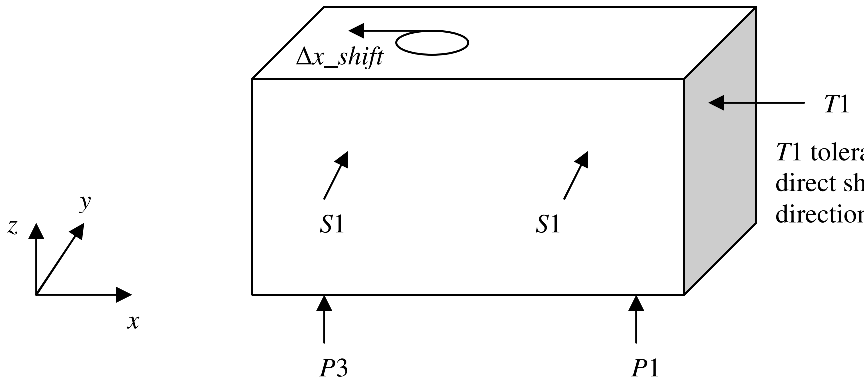
$$Tol_{P2} = (\tan\theta * \Delta z_{CP\text{-}P2}) - \Delta y_{CP\text{-}P2}$$

$$\Delta \text{ for point } P2 = Tol_{P2}$$

$$\Delta \text{ for point } P1 = Tol_{P1}$$

The value of Δ for a particular locating point can then be entered into the tolerance table (Table 6). It is important when performing the tolerance analysis to be aware that tolerances can be affected by a number of locating point combinations. For example if the hole in the block presented in Figure 50 has a true position tolerance, then locator interactions $P1/P3$ and $S1/S2$, as well as the locating point $T1$ tolerance all cause a shift in the x direction. During the tolerance analysis, in order to calculate the locating point tolerance it is therefore sometimes necessary to assume the ratio of contributions from each locating point source.

$S1/S2$ interaction causes a rotation around the z axis, resulting in a shift in the x direction, $\Delta x_{S1/S2}$



$T1$ tolerance results in a direct shift in the x direction, Δx_{T1}

$P1/P3$ interaction causes a rotation around the y axis, resulting in a shift in the x direction, $\Delta x_{P1/P3}$

$$\Delta x\_shift = \Delta x_{P1/P3} + \Delta x_{S1/S2} + \Delta x_{T1}$$

To aid the tolerance analysis, it may be necessary to assume allowed values for each contribution: e.g., $\Delta x_{P1/P3} = \Delta x_{S1/S2} = \Delta x_{T1}$

Figure 50: Design tolerances dependent upon several locating point pairs

Once the tolerance values for each of the locating points have been determined, the tolerance assignment process can begin. The actual variation in the locating position will be the combination of various effects, as governed by the following equation:

$$\Delta = \Delta_{loc} + \Delta_{surf} + \Delta_{m/c} + \Delta_{m/c\_rot} + \Delta_{disp} + \Delta_{clamp} + \Delta_{wp}$$

where:

Δ = total allowed tolerance at a particular locating point;

Δ_{loc} = tolerance of a locator at a locating point;

Δ_{surf} = tolerance of the locating surface at the locating point;

$\Delta_{m/c}$ = linear tolerance of the machine tool in the direction of location;

Δ_{m/c_rot} = rotational tolerance of the machine tool about an axis;

Δ_{disp} = tolerance allocated to displacement of locator or clamp during machining;

Δ_{clamp} = tolerance allocated to displacement of locators due to clamping forces;

Δ_{wp} = tolerance allocated to displacement/deformation of workpiece due to clamping and machining forces (assumed to be zero as the CAFixD method does not perform any analysis of workpiece deformation).

The objective of the tolerance assignment process is therefore to break down the calculated values of Δ for each locating point and assign a portion of Δ to each of the contributory factors. The tolerance table therefore needs to be updated to include the individual effects of these contributory factors, as illustrated in Table 7.

Generally speaking, Δ_{surf} and $\Delta_{m/c}$ are known and since Δ_{wp} is assumed to be zero, the above equation reduces to determination of Δ_{loc}, Δ_{disp}, and Δ_{clamp}:

$$\Delta - \Delta_{surf} - \Delta_{m/c} = \Delta_{loc} + \Delta_{disp} + \Delta_{clamp} + \Delta_{wp}$$

and the following heuristics are invoked (Boyes, 1999):

$$\Delta_{loc} = 0.6 * (\Delta - \Delta_{surf} - \Delta_{m/c} - \Delta_{wp})$$

$$\Delta_{disp} = 0.3 * (\Delta - \Delta_{surf} - \Delta_{m/c} - \Delta_{wp})$$

$$\Delta_{clamp} = 0.1 * (\Delta - \Delta_{surf} - \Delta_{m/c} - \Delta_{wp})$$

$$\Delta_{wp} = 0$$

Locating point	***P*1**	***P*2**	***P*3**	***S*1**	***S*2**	***T*1**
Tolerance (Δ)						
Δ_{loc}						
Δ_{surf}						
$\Delta_{m/c}$						
Δ_{m/c_rot}						
Δ_{disp}						
Δ_{clamp}						
Δ_{wp}						

Table 7: Updating the tolerance table to show all contributory factors

Upon execution of the tolerance assignment the FR skeleton can be refined further. From FR_1, the group of FRs related to controlling the accuracy of location can be specified. $FR_{1.2.1}$ states the locating accuracy required of each of the six locating units (Δ_{loc} values). The relevant DPs are the locating units that offer this level of locating accuracy. $FR_{1.2.2}$ states the machine tool errors that need to be accounted for and the relevant DPs are the allowances made for these errors when performing the tolerance assignment ($\Delta_{m/c}$ and Δ_{m/c_rot}). $FR_{1.2.3}$ states the need to account for the surface variations at the workpiece/fixture interface and again the relevant DPs are the allowances made for these errors when performing the tolerance assignment (Δ_{surf}). This completes FR_1 since $FR_{1.1}$ is fully specified before the tolerance analysis of the workpiece occurs.

FR_1 – Locate workpiece to required accuracy

  $FR_{1.1}$ – Locate the workpiece

    $FR_{1.1.1}$ – Control six degrees of freedom (6 FRs).....*completed earlier*

    $FR_{1.1.2}$ – Provide contact between locator and workpiece (6FRs) .....*completed earlier*

  $FR_{1.2}$ – Control accuracy of location

    $FR_{1.2.1}$ – Locate workpiece to required drawing tolerances (6FRs)

      $FR_{1.2.1.1}$ – Locate at location point $P1$ to an accuracy of Δ_{loc_P1} inches

      ……………

      $FR_{1.2.1.6}$ – Locate at location point $P3$ to an accuracy of Δ_{loc_P3} inches

    $FR_{1.2.2}$ – Compensate for machine tool misalignment (6FRs)

      $FR_{1.2.2.1}$ – Compensate for machine misaligment of along the y axis, Δ_{m/c_y}

      ……………

      $FR_{1.2.2.6}$ – Compensate for machine misaligment around the z axis, Δ_{m/c_rot_z}

    $FR_{1.2.3}$ – Compensate for surface variations at fixture/workpiece interface (6FRs)

      $FR_{1.2.2.1}$ – Compensate for surface variation at workpiece/$P1$ interface, Δ_{surf_P1}

      ……………

      $FR_{1.2.2.6}$ – Compensate for surface variation at workpiece/$P3$ interface, Δ_{surf_P3}

DP_1 – Fixture locating arrangement

  $DP_{1.1}$ –. 3-2-1 locating principle variation 3

    $DP_{1.1.1}$ – locator/workpiece interface surface (6DPs) .....*completed earlier*

    $DP_{1.1.2}$ – workpiece/locator interface contact coordinates (6DPs) .....*completed earlier*

  $DP_{1.2}$ – Locator unit parameters

    $DP_{1.2.1}$ – locator units with tolerances (6DPs)

      $DP_{1.2.1.1}$ – Locating unit with tolerance of Δ_{loc_P1} inches

      ……………

      $DP_{1.2.1.6}$ – Locating unit with tolerance of Δ_{loc_P6} inches

    $DP_{1.2.2}$ – tolerance allowance for machine tool (6DPs)

      $DP_{1.2.2.1}$ – Assignment of machine misalignment tolerance of Δ_{m/c_y}

      ……………

      $DP_{1.2.2.6}$ – Assignment of machine misalignment tolerance of Δ_{m/c_rot_z}

    $DP_{1.2.3}$ – tolerance allowance for workpiece surface irregularities (6DPs)

      $DP_{1.2.2.1}$ – Assignment of surface tolerance of Δ_{surf_P1}

      ……………

      $DP_{1.2.2.6}$ – Assignment of surface tolerance of Δ_{surf_P3}

Figure 51: Completing FR_1

One point to note is that the above techniques for performing the sensitivity and tolerance analysis assume that the shifts in location position caused by rotations of the workpiece are negligible. Consider Figure 52. When the locator pair *P*1 and *P*2 cause a rotation of the workpiece, this alters the position at which locator *S*1 contacts the workpiece. However this effect is neglected in the tolerance and sensitivity analyses. The above tolerance analysis is not intended to provide the final allowed tolerance deviations Δ for each locating point. It is intended however to provide an initial estimate for these values based upon an understanding of the critical design tolerances. These estimates can be refined by passing them on to another tolerance analysis approach, for example that of Hu's (2001) who considers all the combination effects. Hu determined the allowed locating deviations by starting from a standard deviation (0.001 inches for each point), measuring the position change of each workpiece feature and incrementing the locating deviations by 0.001 inches until the position changes of the features exceeded the design tolerances. The largest value of Δ that still allowed the design tolerances to be satisfied was chosen as the allowed locating deviation Δ. The purpose of the CAFixD tolerance analysis is to quickly provide an initial estimate for Δ which can be refined. This provides a more targeted approach to obtaining values for Δ rather than starting at a base value and incrementing Δ until the maximum value can be found at which the design tolerances can be attained.

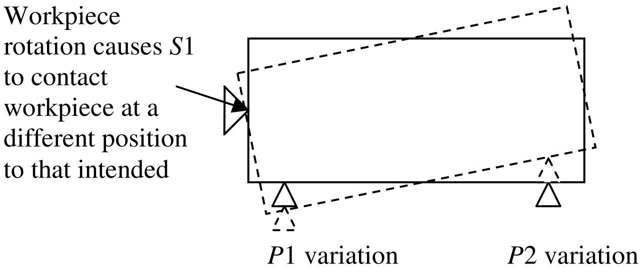


Figure 52: Changes in locating positions caused by workpiece rotations

The second group of FRs require some further analysis of the machining forces. The FRs that have to be specified are:

$FR_{2.1.1}$ – Provide clamping forces against each locator (6 FRs);
$FR_{2.1.2}$ – Control fixture unit deflection to within design tolerances (12FRs);
$FR_{2.1.3}$ – Provide clamping orientation (6FRs);
$FR_{2.1.4}$ – Provide clamping coordinates (6FRs).

With regard to $FR_{2.1.1}$ clamping force values are assumed. Much work has been done elsewhere with regard to calculation of clamping forces (Trappey & Liu, 1992; Liu & Strong, 2003) and is not repeated here. Much of the work related to stability has focussed on situations in which clamps act only against the vertical locating units and no clamps act against the horizontal units. Thus stability is only ensured if the frictional forces between the clamp and workpiece are greater than the horizontal forces experienced during machining. The CAFixD method however advocates that each locating point has a clamp directed against it and thus assuming the clamping or locating unit does not fracture then stability is assured.

The caveat made in the preceding argument stated that stability was ensured if the clamping or locating units do not fracture. $FR_{2.1.2}$ deals with the allowed deformation of units during operation. The allowed deformations are the values for Δ_{disp} and Δ_{clamp} calculated during the tolerance assignment. These deformations are not based upon the strength of the material used but simply upon the tolerance requirements of a particular workpiece. However the assumption is made that since the allowed deformations will be very small, there is no danger of the units undergoing fracture. In consequence of this assumption, the CAFixD method does not include a stress-fracture analysis of the fixture units, but concentrates solely upon calculating their deformation. $FR_{2.1.2}$ specifies the required stiffness at a locating or clamping point and this stiffness acts in the locating or clamping direction. The machining forces and their directions are specified in the machining information required as inputs in the CAFixD method. They are analysed to determine the maximum forces that act against the clamping and locating units, and the stiffness FR is derived using Hooke's Law (Grandin, 1991). For a locating unit:

$$\text{Locating unit stiffness} = \text{maximum force acting against unit} / (\Delta_{disp} + \Delta_{clamp})$$

$FR_{2.1.3}$ states the clamping directions that are required. These are derived from the locating units against which clamps must act. The direction of clamping is derived by reversing the direction of locating, thus the clamp orientation now acts against the locators. The DPs for this group of FRs are workpiece surfaces that have the required orientation. $FR_{2.1.4}$ states the need for the clamps to physically contact the workpiece and the associated DPs are the coordinates of the clamping points. As much possible a clamping position should be on the axis of location, but this may not always be possible, particularly with vertical clamps. When machining a workpiece, most of the cutting is performed on the top surfaces and this often limits the possibilities for vertical clamping. Thus if it is not possible to clamp on the ideal locating axis, then the closest available position is chosen. At the conclusion of this force analysis the FRs can be completed (see Figure 53).

Up to this point the CAFixD method has been supporting setup and fixture planning. Once the FRs have been fully developed, the unit design and verification stages begin in earnest. Some of the DPs discussed in the previous sections are generated through calculations (such as locating coordinates) and some are selected surfaces of the workpiece. However, other DPs are the physical structures within the fixture design, normally the locating and clamping units. These DPs are generated by retrieving previous examples from the second case library and modifying them to satisfy a particular FR or group of FRs. For these DPs, a further mapping is required in which the parameter variables (PVs) of the structures can be related to their ability to satisfy an FR. Details of these PVs are held in case library 2.

- FR$_2$ – Stabilize workpiece deflection during machining and clamping
    - FR$_{2.1}$ – Hold workpiece in situ during machining
        - FR$_{2.1.1}$ – Provide clamping forces against each locator (6FRs)
            - FR$_{2.1.1.1}$ – Provide clamping force of 50 lbs against locating point *P*1
            - …………………
            - FR$_{2.1.1.6}$ – Provide clamping force of 50 lbs against locating point *P*3
        - FR$_{2.1.2}$ – Control fixture unit deflection to within design tolerances (12FRs)
            - FR$_{2.1.2.1}$ – Exhibit locating stiffness at locating point *P*1 of 30000 lb/in
            - …………………
            - FR$_{2.1.2.12}$ – Exhibit locating stiffness at clamping point *P*3 of 30000 lb/in
        - FR$_{2.1.3}$ – Provide clamping orientation (6FRs)
            - FR$_{2.1.3.1}$ – Provide clamping force direction against locating point *P*1
            - …………………
            - FR$_{2.1.3.6}$ – Provide clamping force direction against locating point *P*3
        - FR$_{2.1.4}$ – Provide contact between clamping forces and workpiece (6FRs)
            - FR$_{2.1.4.1}$ – Contact workpiece with clamp acting against locating point *P*1
            - …………………
            - FR$_{2.1.4.6}$ – Contact workpiece with clamp acting against locating point *P*3
- DP$_2$ – Fixture unit force capabilities
    - DP$_{2.1}$ – Clamping unit force capabilities
        - DP$_{2.1.1}$ – Clamping units (6DPs)
            - DP$_{2.1.1}$ – Clamping unit with requisite clamping force acting *P*1
            - ………………………..
            - DP$_{2.1.6}$ – Clamping unit with requisite clamping force acting against *P*3
        - DP$_{2.1.2}$ – Clamping and locating units (12DPs)
            - DP$_{2.2.1}$ –Locating unit with requisite stiffness acting at locating point *P*1
            - ………………………..
            - DP$_{2.2.12}$ – Clamping unit with requisite stiffness acting against locating point *P*3
        - DP$_{2.1.3}$ – Clamping surfaces (6DPs)
            - DP$_{2.1.3.1}$ – Workpiece surface M
            - ……..
            - DP$_{2.1.3.6}$ – Workpiece surface F
        - DP$_{2.1.4}$ – Clamping coordinates (12DPs)
            - DP$_{1.1.1.1}$ – Calculated coordinates (1, 0, 10)
            - ……..
            - DP$_{1.1.1.6}$ – Calculated coordinates (6, 1, 23)

Figure 53: Completing FR$_2$ (sample values only)

4.2.4 The Decomposition of Case Library 2

The second case library contains information relating to individual fixture units, specifically their functions and their physical properties. The library contains locating units, clamping units, locator types, fixture base types, interference pins, coolant channelling devices, tool guide units, and workpiece loading and unloading mechanisms, all of which can be combined to create a complete fixture for a workpiece. Figure 54 presents a high level view of the case library. The hierarchy descends from each basic type of unit and each step down this hierarchy represents a refinement of the unit design.

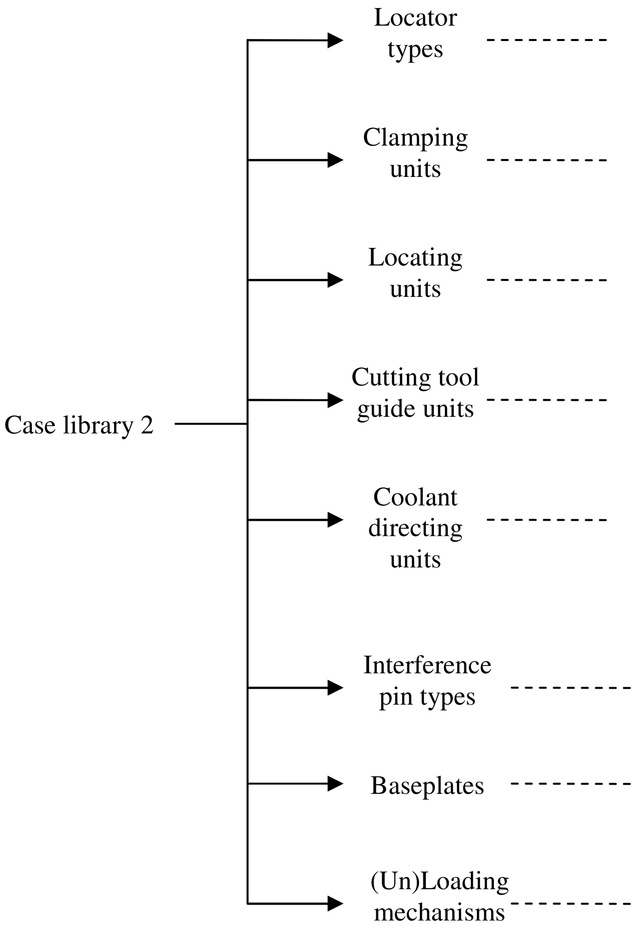


Figure 54: The high level view of case library 2

Figure 55 illustrates the decomposition of case library 2 for locating units. Initially the hierarchy descends on the basis of function: i.e., do they provide vertical or horizontal locating. Horizontal locators can be decomposed into two possible types, designated as HL01 (simple locating units) and HL02 (step-over locating units), both of which are illustrated in Figure 56. HL01 units can only be used in situations where no other face exists below and extends beyond the locating face (Figure 57b). When these conditions do not exist, HL02 units need to be used. In addition HL02 type units can be used in place of any simple locating unit, but a simple locating unit can only be used to replace a step-over unit if the workpiece geometry allows. Thus step-over units can be used in either of situations represented in Figure 57, but tower units are only suitable for Figure 57b.

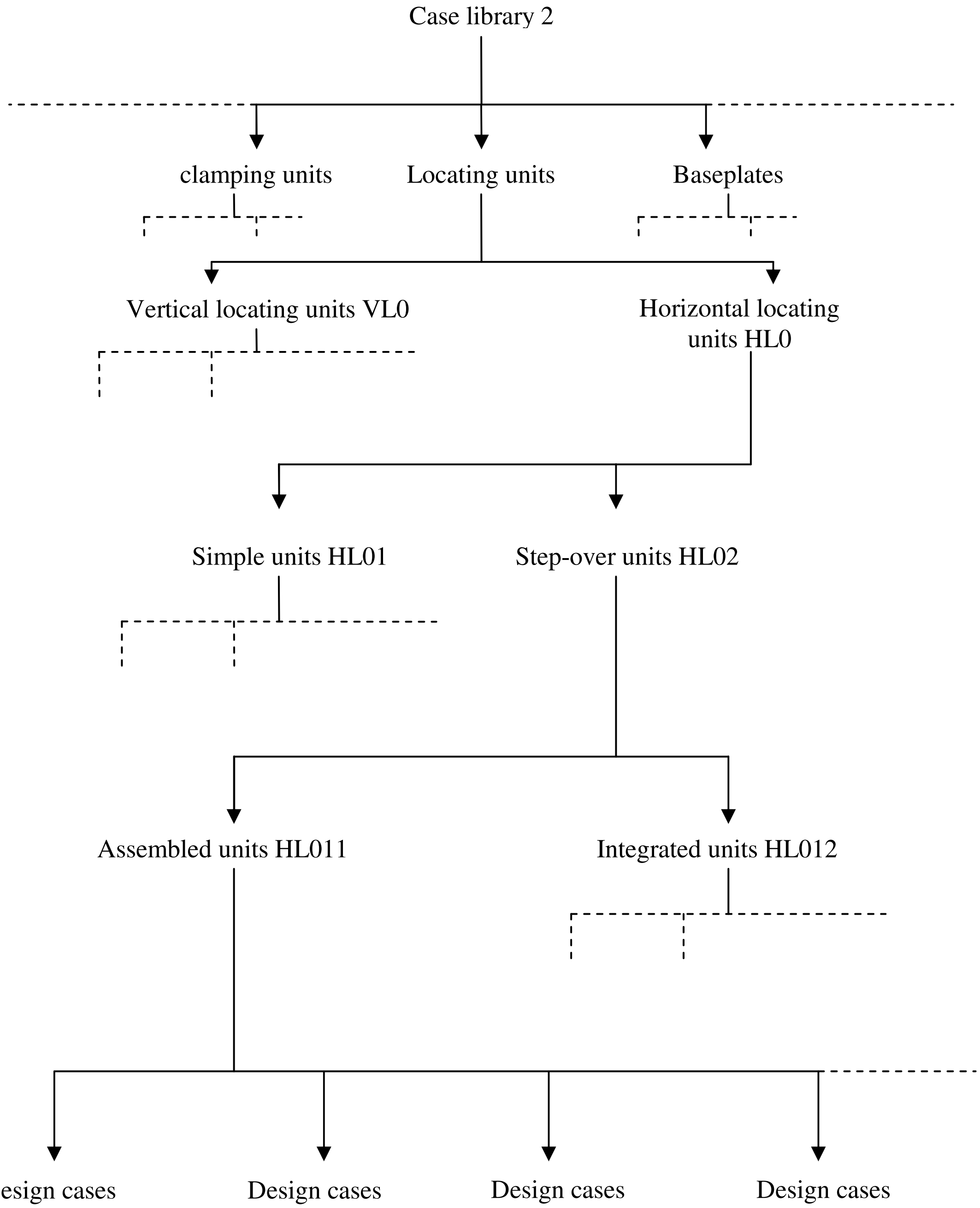


Figure 55: The decomposition of locating units in case library 2

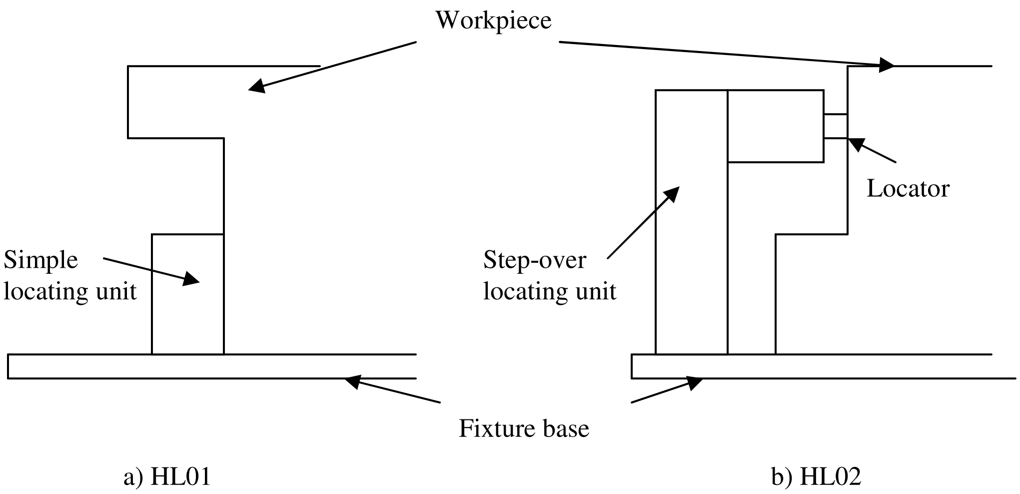


Figure 56: The Two Types of Horizontal Locators, HL01 and HL02

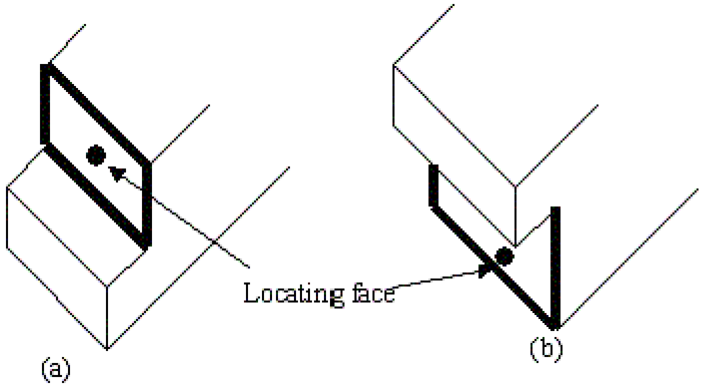
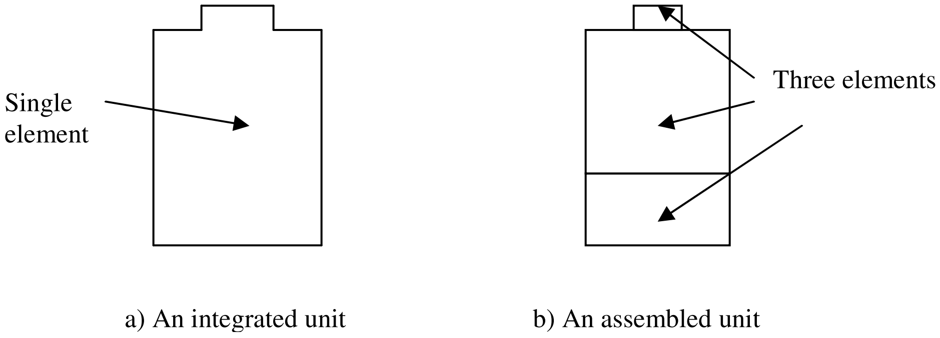


Figure 57: The Different Types of Horizontal Locating

Down to this point of the hierarchy, the decomposition has focussed on unit function: i.e., the situations in which they can be successfully implemented. Below that cases are arranged in terms of the adaptation knowledge required to modify them during the retrieval process. For example, step-over locating units can be decomposed into assembled and integrated units (Figure 58). Assembled units consists of a number of elements connected together whereas integrated units are one-piece structures in which the locator and support unit are one element together. During adaptation it is possible to change the locator of an assembled unit, but this is not possible with the integrated type since the locator and support unit are a solid, indivisible structure.



a) An integrated unit b) An assembled unit

Figure 58: Integrated and assembled locating units

The breakdown of the clamping unit hierarchy (Figure 59) follows a similar approach. Decomposition at the top of the hierarchy is initially based upon what type of clamping function units can perform: i.e., vertical or horizontal. Thereafter units are classified according to the adaptation knowledge used to modify them. This is based upon the manner in which units behave. For example magnetic clamps work on electro-magnetic principles, hydraulic clamps on fluid mechanic principles, and CAM clamps operate on the basis of wedge friction.

Strap clamps are considered as levers and they behave in accordance with applied mechanics. Considered loadings are bending and shear on the strap. Any strap clamp belongs to one of the three basic classes of levers, illustrated in Figure 60. For each of these classes the adaptation knowledge varies, most notably in the determination of the fulcrum (F) and work (W) force magnitudes and directions. Again these classes can be decomposed further. The third class of levers (VC013) can be decomposed into standard acting types, VC0132, and direct acting types, VC0131. VC0131 is a special class where L2 has a value of zero and the work force is applied directly onto the workpiece.

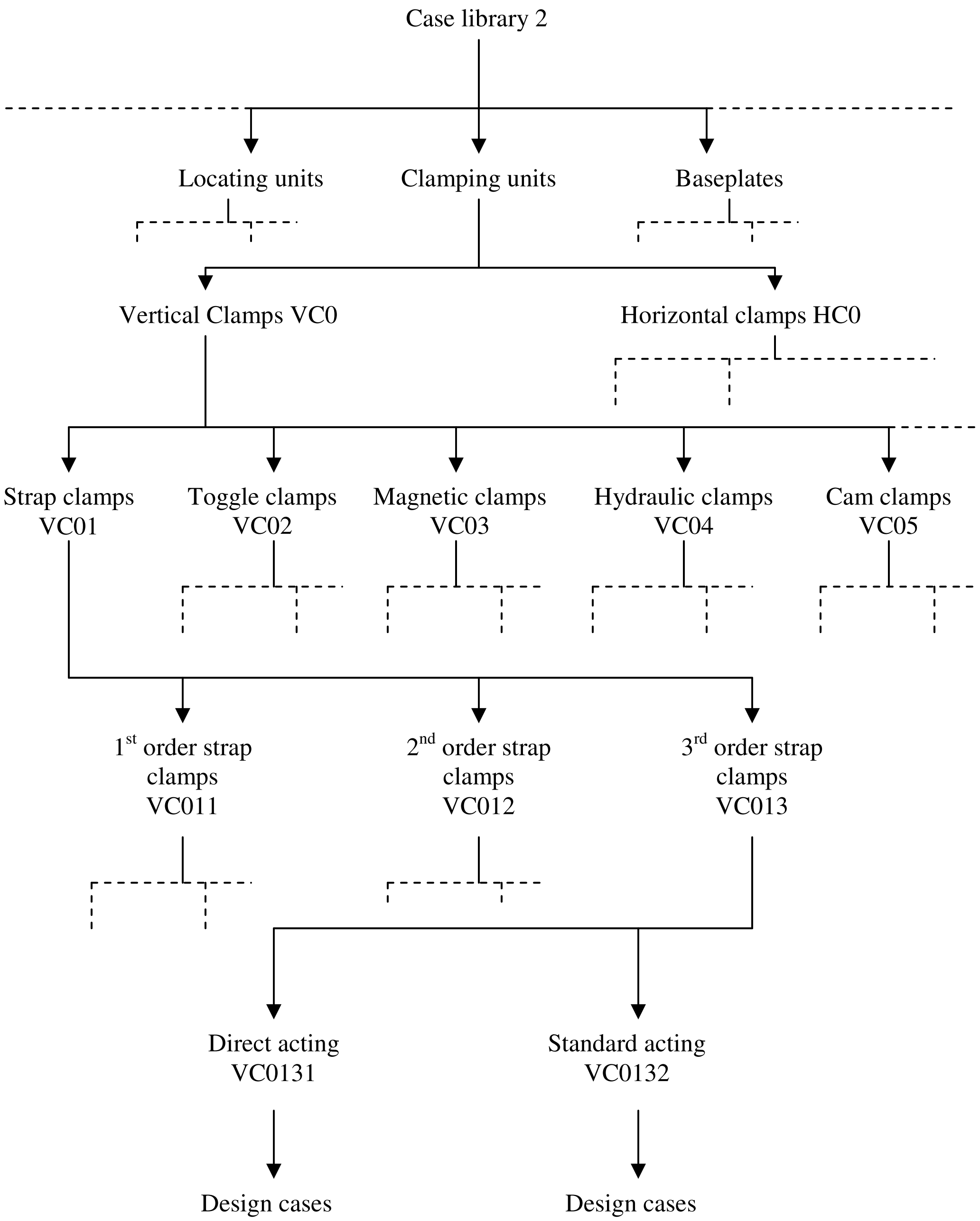
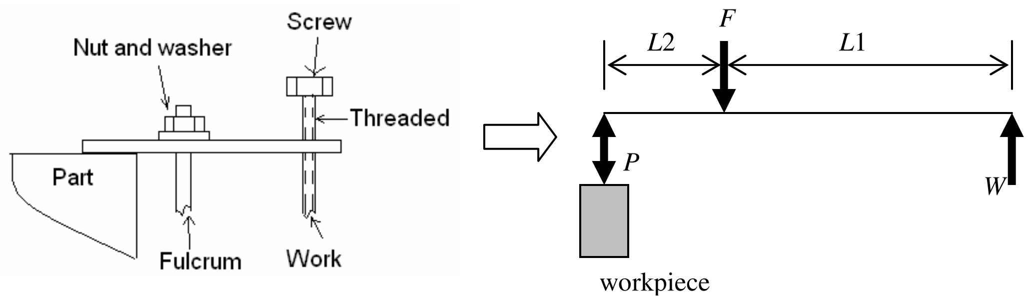
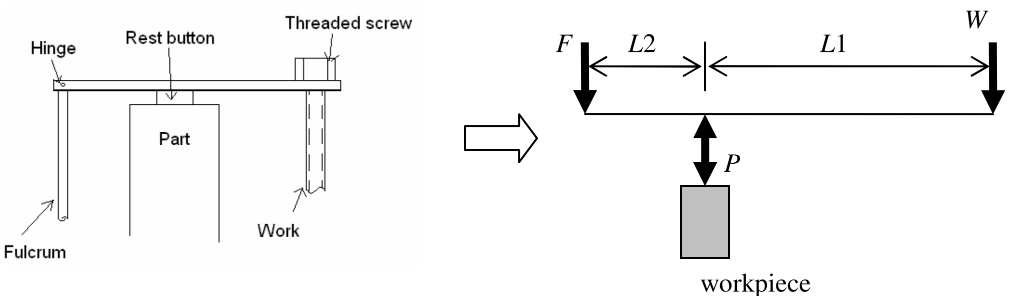


Figure 59: The decomposition of clamping units in case library 2

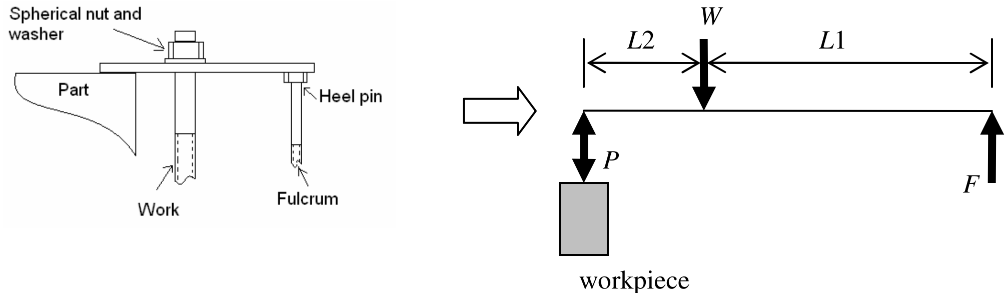
To each leaf of the case library are attached previous instances of units and situations in which they have been used. Specifically, this information consists of a list of the functional requirements the unit is capable of, its performance with regard to the global constraint attributes, and a breakdown of all the elements that combine to form the unit and their properties. A standard schema for the third order vertical clamping unit VC0132 (see Figure 61) is presented in Table 8.



a) First class lever action



b) Second class lever action



c) Third class lever action

Key:
W – work force (lb).
F – fulcrum force (lb).
P – clamping force on workpiece (lb).
$L1$, $L2$ – distances between forces P, W, and F.

Figure 60: The three strap clamp lever classes

Clamping unit attribute	Description
Class type	Class type within case library 2
Unit ID	Identifying name for unit
Stiffness FR performance	Unit stiffness (lb/in)
Clamping force FR performance	Unit clamping force (lb)
Acting height	Vertical distance of workpiece contact point from base of clamp (inches)
Chip shedding ability	Does the unit have a chip shedding ability?
Unit cost	Cost of unit ($)
Unit weight	Weight of unit (lb)
Loading time associated with unit	Time taken to load workpiece (mins)
Unit assembly time	Time taken to assemble the unit (mins)
Unloading time associated with unit	Time taken to unload workpiece (mins)
Force actuation	Means by which the work force (W) is produced
Total no. of elements	Total number of elements within the unit
No. of fulcrum elements	Number of elements in the fulcrum limb
No. or work elements	Number of elements in the work limb
No.of length BeamE1 elements	Number of elements in beam_elem1
No.of length BeamE2 elements	Number of elements in beam_elem2
Length of L1	L1 dimension (inches)
Length of L2	L2 dimension (inches)
(Work) L2 beam element	Beam element to which work limb connects
(Fulcrum) L1 beam element	Beam element to which fulcrum limb connects
C beam element	Beam element to which contact limb connects
Work limb max thickness	Maximum thickness in the work limb
Fulcrum limb maximum thickness	Maximum thickness in the fulcrum limb
Contact limb max thickness	Maximum thickness in the contact limb
Work element	Work element that contacts strap beam
Fulcrum element	Fulcrum element that contacts strap beam
Contact element	Contact element that contacts strap beam

Table 8: A schema for a clamping unit

Element attribute	Description
Element #	Element number
Limb element no.	Position of element within a limb
Structure type	Cross section type
Element type	Limb the element is situated in (i.e., work, fulcrum, beam)
Dist from end	Distance element is from the end of the limb (inches)
Length	Element length (inches)
Start CS b or radius	Element thickness at start of element (inches)
End CS b or radius	Element thickness at end of element (inches)
Start CS h or radius	Element width at start of element (inches)
End CS h or radius	Element width at endof element (inches)
Material mod	Material type
Height adjust	Is the element subject to a height adjustment if the acting height of the unit has to change?
Slot consideration	Is there a slot in the element?
Slot width	Width of slot (inches)
Available slot length	Length of slot (inches)
Connection to next element	What type of connection connects this element to the next element
No. of connections	How many connections there are to the next element
Offset distance	The position of the connections on the element cross section
Conn diameter	Diameter of the connections (inches)
Mated from	The element that this element connects from
Mated to	The element that this element connects to

Table 9: A schema for an individual clamping unit element

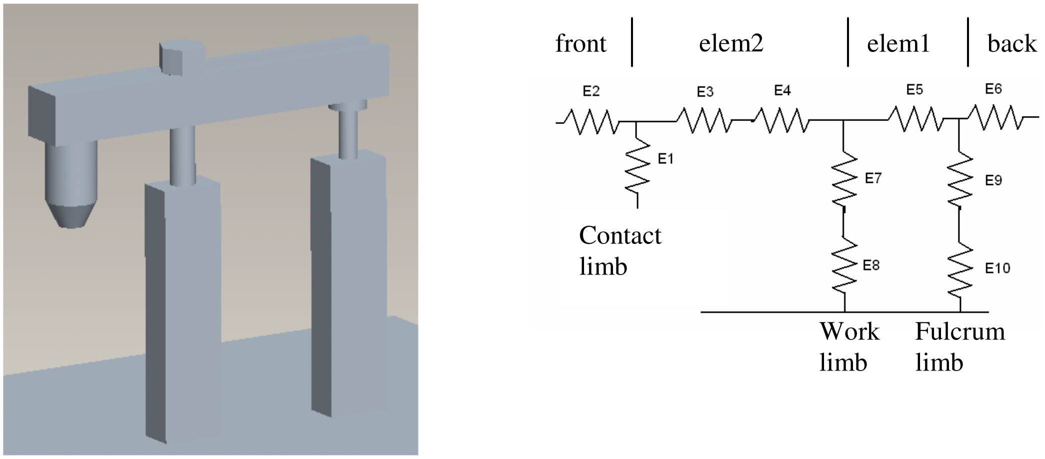


Figure 61: A third order vertical clamp and its equivalent element sketch

For each unit the schema details the number of elements within that unit, and decomposes that number into the number of beam, fulcrum, work, and contact elements. Elements that intersect with the main strap are also listed. For each element of the clamping unit a separate schema exists (Table 9) that specifies to which part of the structure they belong (fulcrum, work, contact, beam1, beam2), their position relative to other elements, their length and cross sectional properties, their material type, details of any slots that may exist in the element (this is a common feature of strap clamps), and details of connections to other elements. All of this information is used to guide the adaptability-based retrieval stage.

4.2.5 Learning Mechanism

One of the fundamental features of the CBR method is its learning capability. New knowledge is acquired and is then available for retrieval. In the CAFixD approach learning takes place in the second case library only. Case library 1 (containing conceptual models and FR/DP skeletons) is considered to be fairly complete in the respect that the most commonly used conceptual models already exist within the library and it is unlikely that a new design situation will require generation of a new conceptual model.

All learning therefore takes place within case library 2 and there are two aspects to the learning mechanism:

1. knowledge acquisition;
2. knowledge maintenance.

Knowledge acquisition relates to the addition of new knowledge to case library 2, which in practice is adding further examples of individual unit types such as instances of locating or clamping units. The simple approach adopted is to add to the library all units that are returned as design solutions at the end of the retrieval process. The only exception to this is if the same case already exists within the library. In such circumstances the case is not added.

Due to the computationally expensive nature of the retrieval process, it is necessary to restrict the search space navigated through during retrieval. One of the means by which this is achieved is to limit the size of case library 2. Much of the work to control the size of the case library falls within the remit of the knowledge maintenance mechanism (Figure 62), whose purpose is to determine which cases within the case library represent useful knowledge. At the bottom of the decomposition of case library 2 are different class types of units grouped together by behaviour, to which are attached specific examples: i.e., design cases. The mechanism attempts to ensure there is a sufficient number of cases ($case_{suff}$) for each class type so that a good spread of cases exists throughout the library. Library maintenance reduces to the task of identifying those cases that should be removed. There are two stages to this task. Initially, cases that are to be considered for maintenance are identified. Subsequently a measure of usefulness is calculated for each of those cases, and those with the lowest value are removed until the class type has the desired number ($case_{suff}$) of cases.

Individual cases are only subjected to maintenance if they have existed in the case library for a certain length of time. Time is measured in terms of how many retrieval operations a case has been involved in. To be considered for maintenance the case must have been involved in at least a minimum number of retrievals, $retr_{min}$.

A class type within the library consists of a quantity of cases (*cases*), which is comprised of a number of cases (*case_less*) that have been involved in less than $retr_{min}$ retrievals, and a number of cases (*case_more*) that have been involved in $retr_{min}$ or more retrievals. Thus for a class type *i*:

$$cases_i = case\_less_i + case\_more_i$$

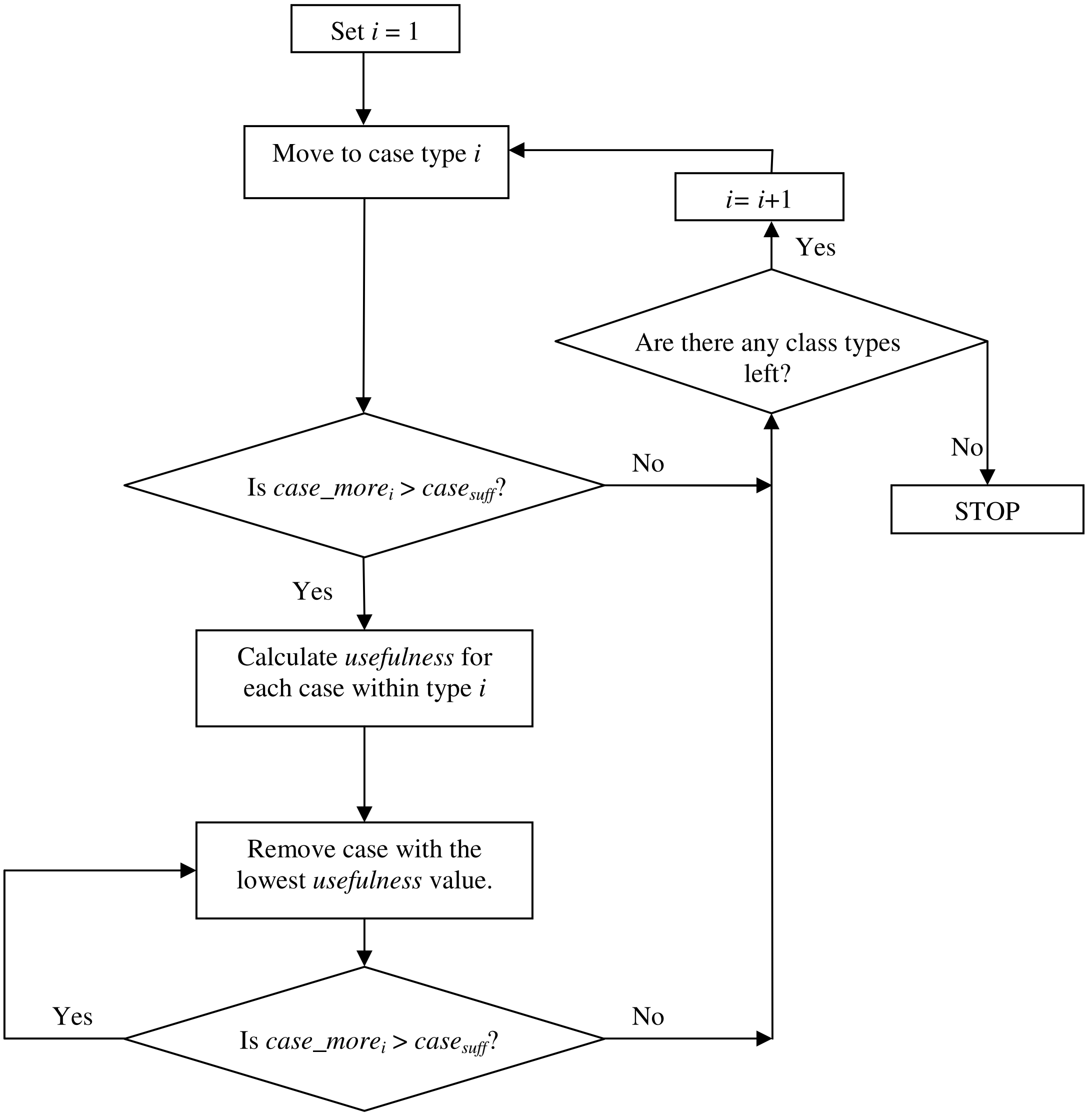


Figure 62: The library maintenance mechanism

Maintenance is performed for one class type at a time and only if *case_more* for that class type exceeds $case_{suff}$. Cases that have been involved in too few retrievals are left undisturbed so that their retrieval performance can be evaluated over a satisfactory period of time ($retr_{min}$). Once this period of time is complete, this performance is evaluated to determine how useful a case is.

Usefulness is measured in terms of how often a case is retrieved during the retrieval process. There are two stages to retrieval – the initial functional similarity-based step followed by the adaptability-based retrieval process. The measure of case usefulness is related to the number of times a case is successfully retrieved during design case recall using the following metric:

$$usefulness = \frac{w_{R1} * Use_{R1} + w_{R2} * Use_{R2}}{w_1 + w_2}$$

where:

usefulness = measure of usefulness

Use_{R1} = usefulness with regard to the first retrieval stage = the ratio of the number of times a case has been successfully returned by the first retrieval stage to the total number of vetting retrievals the case has been involved in;

Use_{R2} = usefulness with regard to the second retrieval stage = the ratio of the number of times a case has been successfully returned by the adaptability-based retrieval stage to the total number of adaptability-based retrievals the case has been involved in;

w_1 = weighting factor assigned to importance of Use_{R1};

w_2 = weighting factor assigned to importance of $Use_{R2.}$

For each particular type of unit, the cases with the lowest measures of usefulness are removed until *case_more* is equal to $case_{suff}$. Currently within the CAFixD method, the setting of values $case_{suff}$, w_{R1}, and w_{R2} is left to the discretion of the user.

4.3 Retrieval from Case Library 2

Retrieval is performed in two stages. Initially cases are vetted on the basis of functional similarity. Cases that survive this vetting process are subsequently subjected to adaptability-based retrieval in which the requisite modifications and means of implementing those modifications for each candidate case are identified. Cases that once modified are most in keeping with the design preferences are then used as the final solution for each FR or each groups of FR.

4.3.1 Functional Similarity-based Retrieval (Vetting Design Cases)

This is a vetting stage of retrieval in which the focus is on retrieving previous designs from case library 2 that are qualitatively capable of satisfying the FRs. Thus if a vertical clamping stiffness is required then cases are retrieved that can offer a vertical clamping stiffness. The quantitative value of stiffness that a potential candidate can provide is not important at this stage (such considerations are reserved for the adaptability-based retrieval process). The hierarchical decomposition of the second case library is arranged to facilitate this vetting stage as horizontal locating units are grouped together, as are vertical clamping units, vertical locators, and so on. Essentially the vetting retrieval navigates through the functional hierarchy of the case library and identifies feasible cases along the way. Once however it reaches the part of the library where decomposition is based upon adaptation knowledge then the vetting stage stops and makes no further decisions. Responsibility for moving the design process forward then passes to the adaptability-based retrieval module. Figure 63 illustrates the split in case library 2 for locating units.

The vetting module has a list of rules for each skeleton FR set that explain where, within the second case library, potential solutions exist that are qualitatively able to satisfy a particular FR of that skeleton set. Thus at the most basic level, if a horizontal locating requirement is specified for a plane locating 3-2-1 conceptual model then a rule will state that all horizontal locating units HL0 are feasible. This can be further refined by consideration of what surfaces lie below the locating surface, as described in section 4.2.4. Other rules which may be executed relate to the functions that are performed, such as whether chip shedding is a requirement. If so then only cases offering that capability are passed to the adaptability-based retrieval stage.

Another consideration is that for each skeleton the retrieval module knows which FRs have a common solution. For example the DP for a location tolerance FR required at a specific locating point is a locating unit with that desired tolerance. However that unit must also be able to satisfy the stiffness FR specified for that point. Thus during the vetting retrieval stage these groups of FRs satisfied by a common solution are identified and this is passed on to the adaptability-based retrieval stage.

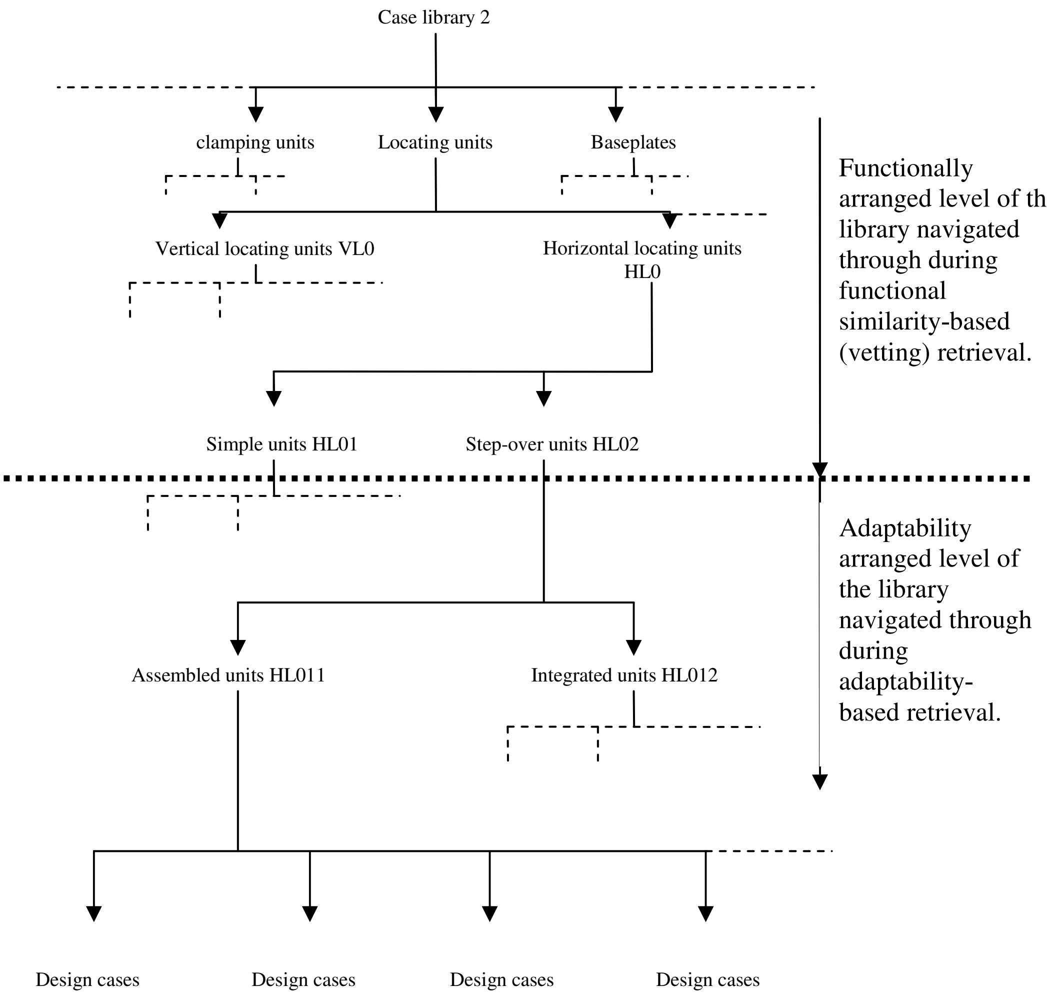


Figure 63: Functional and adaptation split within the locating unit section of case library 1

4.3.2 Adaptability-based Retrieval

Adaptability-based retrieval focuses on identifying how cases retrieved from case library 2 need to be adapted and then, once adapted, evaluating how well they satisfy the design preferences recorded in the utility curves for each global constraint attribute. At the end of the vetting stage, cases are qualitatively capable of satisfying FRs. However, they may not quantitatively satisfy a particular functional requirement. These cases need to be adapted until they can provide the desired performance. The main tasks of this part of the retrieval stage are.

- Define the relevant global constraint attributes.
- For each attribute define the design preferences in the form of utility curves.
- Identify and group together any FRs for which a common solution is required.
- For each FR or FR group, identify the candidate cases (DPs) returned by the vetting stage of retrieval.
- For each DP, determine if adaptation is required.
- If adaptation is required then identify the possible adaptation strategies.
- Implement each type of adaptation and check that the design requirement is satisfied.
- Once the design requirement is satisfied using a particular DP/adaptation strategy combination, the combination is evaluated against the design preferences expressed in the utility curves. The utility of each DP/adaptation strategy combination is calculated as a measure of how it satisfies the desired global constraint attribute performance values.
- return the DP/adaptation strategy combination with the highest utility as the solution for that FR or group of FRs.
- repeat for the next FR or group of FRs until all are satisfied.

Utility analysis is used to support decision making during this retrieval stage. It allows a numerical figure to be calculated that represents a measure of how well a design matches specified design preferences. This numerical figure makes the evaluation of different design solutions a reasonably simple matter as the solution with the highest utility is chosen as the final design.

4.3.2.1 Preparing for Utility Analysis

Before the utility analysis can be used for evaluation purposes, the design preferences must be defined. This is performed in four steps:

- define the global constraint attributes that solutions are to be evaluated against;
- specify the acceptable range of performance that is sought of a design for each of those attributes;
- generate the utility curve for each constraint attribute that specifies the utility of different values of performance within the accepted range;
- determine the scaling constant for each constraint attribute, which is a measure of the importance of one attribute relative to the others.

4.3.2.1.1 Defining Global Constraint Attributes and Their Acceptable Ranges

The CAFixD method supports six global constraint attributes, which are defined for a complete fixture design, but not the individual units of which a complete design is comprised. Each individual unit does however contribute towards a design's ability to satisfy these attributes. The global constraint attributes are:

- the cost of the fixture;
- the weight of the fixture;
- the time it takes to load a workpiece into the fixture;
- the time it takes to assemble the fixture;
- the time it takes to remove a workpiece from the fixture;
- the time it takes to disassemble the fixture.

For each of them the designer must specify an acceptable range of values. Two values are required, one of which is the ideal value for an attribute and the other which represents the worst case scenario that the designer is willing to accept. Once these values have been set the next step is to define the form of the utility curve that exists between these two limits. This curve expresses the design preferences within that range.

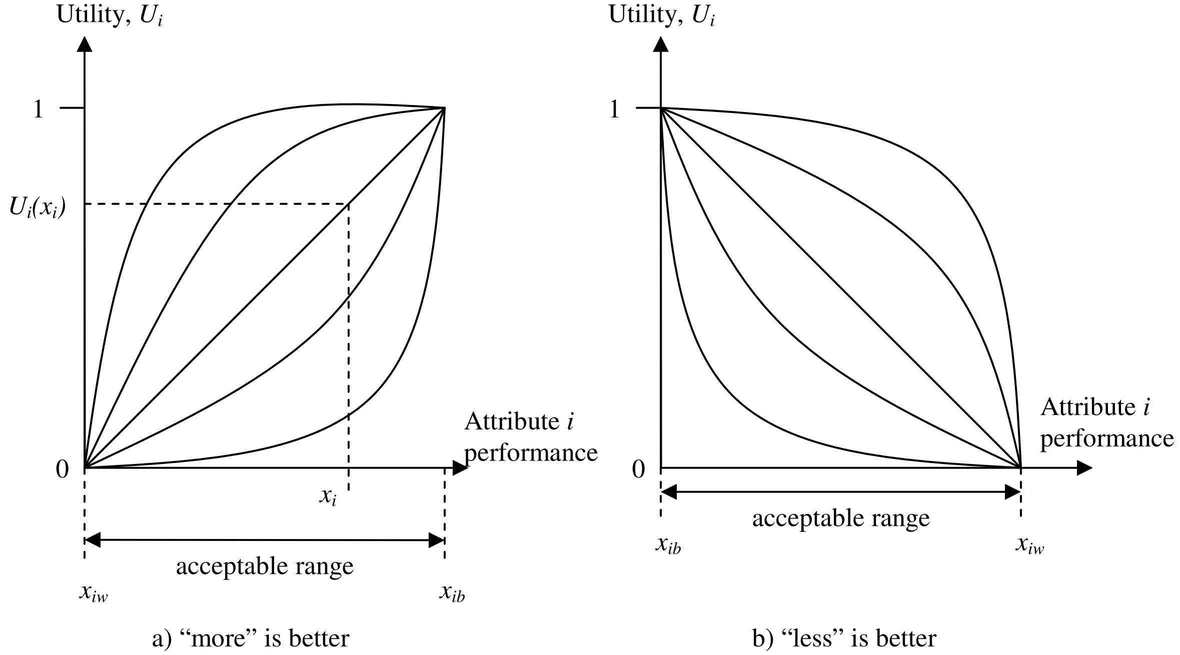
4.3.2.1.2 Generating Utility Curves

The utility curve can take any shape between these two limits depending upon whether less or more of some attribute performance value is desired or not, as illustrated in Figure 64. x_{ib} represents the optimum or best performance level x for attribute i. x_{iw} represents the worst performance level x for attribute i. $U_i(x_i)$ is the utility associated with a specific performance value x for attribute i.

Generally speaking an appropriate utility curve for cost (which generally should be kept as low as possible) would be similar to one of the curves presented in Figure 64b. If an attribute were speed and a high speed were sought then a curve similar to any of those in Figure 64a would be appropriate. Utility represents a measure of how well a particular performance value matches a design preference. 1 represents the most desirable option, 0 the least. Attribute performance values that lie outwith the acceptable range will have a performance value of either zero or one depending upon the curve type. In the case of Figure 64a, a performance value that lies to the right of the utility curve has a utility of one, and a performance value that lies to the left has a utility of zero. In the case of Figure 64b, a performance value that lies to the right of the utility curve has a utility of zero, and a performance value that lies to the left has a utility of one.

The key task is to determine the shape of the curve and this is performed using lottery questions, an example of which is presented in Figure 65. In this process a designer is presented with two designs that are identical in every respect bar their performance levels for a specific constraint attribute. One of the designs will be classified as a “certainty” in which a specific performance (somewhere within the acceptable range) will be achieved with a probability of 1 (100%). The second design will be a “lottery” whose performance will vary. The design will be capable of matching the most desirable performance value with a probability of p. However there is also a probability of $1-p$ that the attribute performance value attained will be the least desirable value previously specified by the designer. For each performance value of the “certainty” option, the value of p for the “lottery” option is altered until the designer is unable to choose between the “certainty” and the “lottery”. At this moment each design is considered to be equally useful. Thus the utility of the “certainty” is equal to the utility of the “lottery”:

$$\begin{aligned}U_i(x_i) &= pU_i(x_{ib}) + (1-p)U_i(x_{iw})\\ U_i(x_i) &= p(1) + (1-p)(0)\\ U_i(x_i) &= p\end{aligned}$$



a) “more” is better

b) “less” is better

Figure 64: A sample of possible utility curve shapes

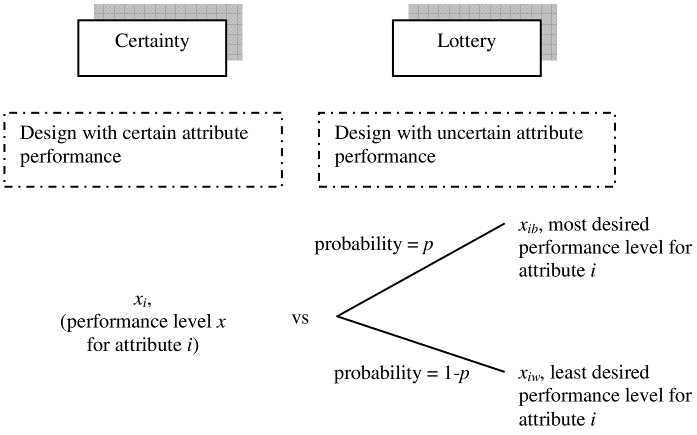


Figure 65: A sample lottery question

The value of p at which this moment of indifference is reached represents the utility of the "certainty" design's performance value, and this point is plotted on the utility curve as illustrated in Figure 66. This process is then repeated again for other "certainty" performance values x_i within the acceptable range to build up sufficient points from which the curve can be constructed.

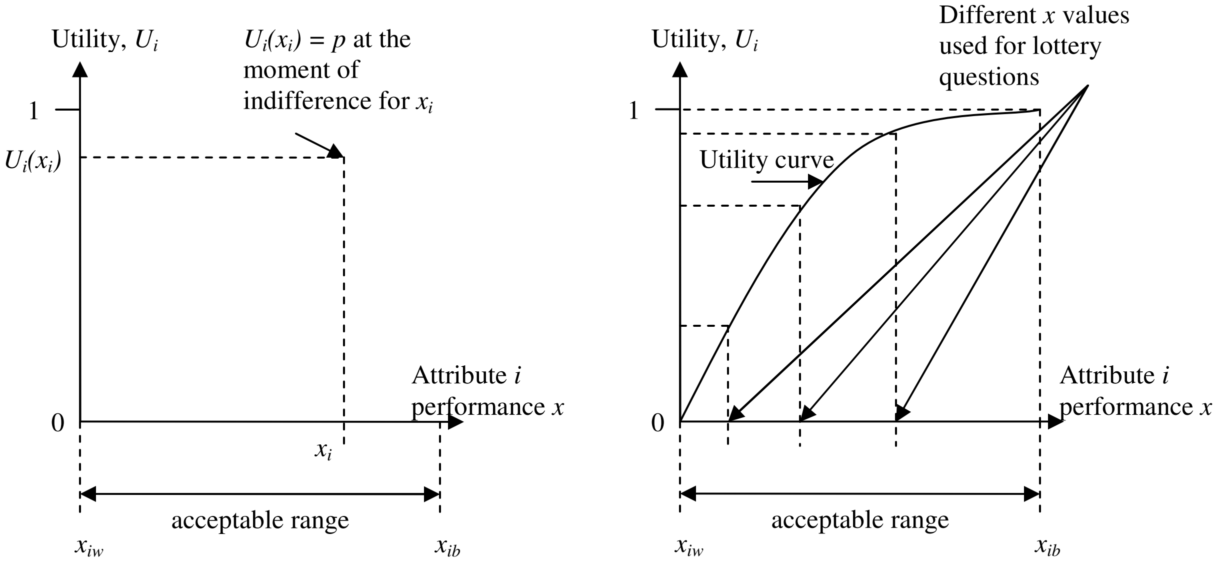


Figure 66: Generating a utility curve

To clarify the technique the following example is presented for determining a utility curve for the fixture cost constraint. Initially the least and most desired cost values are set. The most favourable is a cost of $0, and the worst case is deemed by the designer to be $80. Therefore the utility curve at this point assumes the form presented in Figure 67. The CAFixD method requires five points to determine the curve. The points at each end of the curve are already known so a further three are required. The acceptable range is divided into three equal segments and lottery questions are presented to the user to determine the utility of cost values $20, $40, and $60.

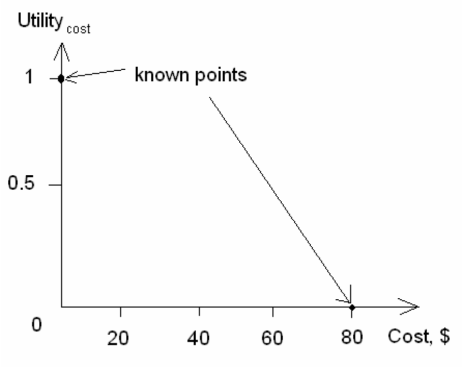


Figure 67: Creating a utility curve for cost

Initially the utility of a fixture design with a cost of $20 is determined. The lottery question illustrated in Figure 68 would be put to the designer.

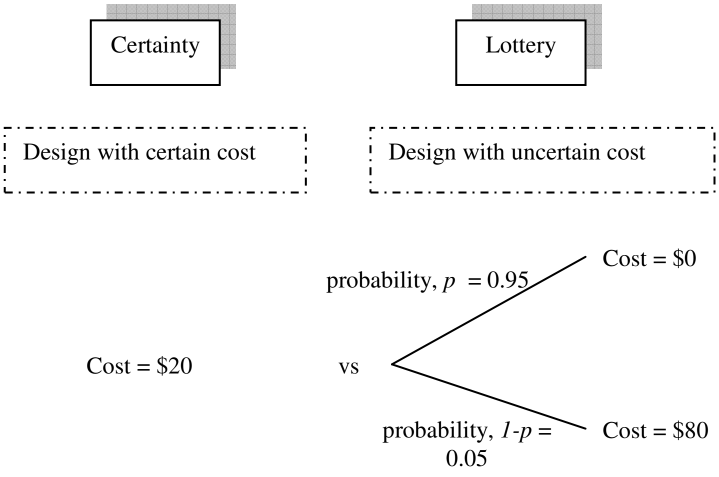


Figure 68: Lottery question used to determine the cost utility curve

The certainty is a design with a cost of \$20. The lottery represents a design which has a variable cost. There is a probability of 0.95 that the cost is \$0 but there is a 0.05 probability that it will be \$80. The designer is basically being asked to choose between the two designs. If a choice can be made between the two, then the value of p is altered until the designer is indifferent to either the "certainty" or the "lottery". At this moment of indifference, the value of p is used as one point on the utility curve. Thus if the designer was unable to choose between the certainty and lottery presented in Figure 68 then $U_{cost}(\$20) = 0.95$ and the curve would be updated (Figure 69).

$$U_{cost}(\$20) = 0.95 * U_{cost}(\$0) + (1-p) * U_{cost}(\$80)$$
$$U_{cost}(\$20) = 0.95 * 1 + 0.05 * 0$$
$$U_{cost}(\$20) = 0.95$$

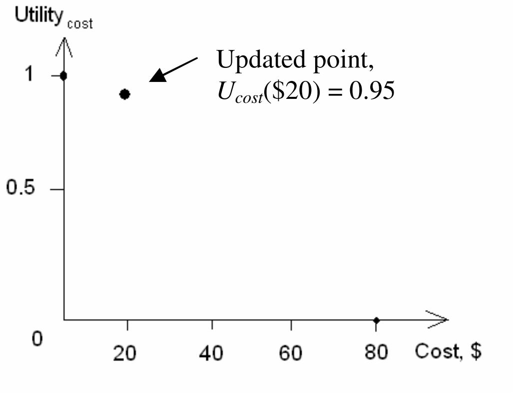


Figure 69: Updating the cost constraint utility curve

The process is then repeated to determine $U_{cost}(\$40)$ and $U_{cost}(\$60)$ and the curve (approximated as a cubic) can be generated from the five points held on the graph (see Figure 70).

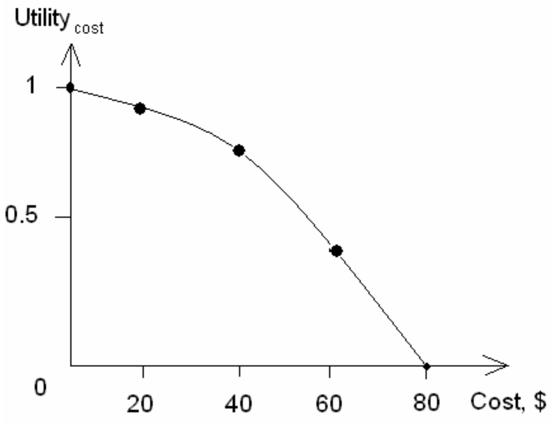


Figure 70: The completed utility curve for the cost constraint attribute

4.3.2.1.3 Determining a Single Attribute Scaling Constant, k_i

Single attribute scaling constants (k_i) represent the importance *k* of one constraint attribute *i* relative to the others, and similar to utility curves they are obtained using lottery questions. To determine the scaling constant for attribute *i*, the designer is presented with two design alternatives – the "lottery" and the "certainty". In the "certainty", the performance values of all attributes except *i* are set to their least desired values, x_w. The performance level of attribute *i* is set to its desired level x_{ib}. On the "lottery" side, the attribute performance value swings between the most desired values for all attributes (including *i*) with a probability *p* and the least desired values for all attributes with a probability of *1-p*. The designer is asked to choose between the two design alternatives based upon the differing attribute performance values. If a choice can be made, then the value of *p* is altered until the moment of indifference is reached and the designer expresses a preference for neither design. At this moment the utility of the design certainty and the design lottery are the same, thus:

$$U\left(x_{1w}.....,x_{ib}.......,x_{nw}\right)=pU\left(X_{b}\right)+(1-p)U\left(X_{w}\right)$$

$$U\left(x_{1w}.....,x_{ib}.......,x_{nw}\right)=p(1)+(1-p)(0)$$

$$U\left(x_{1w}.....,x_{ib}.......,x_{nw}\right)=p$$

where:

$U(X_b)$ is the utility of all attribute performance values at their most desired levels;

$U(X_w)$ is the utility of all attribute performance values at their least desired levels.

The scaling constant k_i is equal to the utility at this moment of indifference, which in turn is equal to p, thus $k_i = p$.

To clarify the procedure using an example, suppose that five constraints and their acceptable ranges have been defined for a fixture and are as summarised in Table 10. The objective is to determine the scaling constant for the cost constraint attribute. The lottery question illustrated in Figure 71 would be presented to the designer for consideration.

Constraint attribute	x_b (most desired performance level)	x_w (least desired performance level)
Cost ($)	0	80
Weight (lb)	0	30
Loading time (sec)	0	400
Assembly time (sec)	0	600
Unloading time (sec)	0	240

Table 10: The acceptable performance ranges for each constraint attribute

On the "certainty" side is a design which has the most desired cost but the least desired value of the remaining four constraint attributes. The "lottery" represents a design in which there is 0.95 probability that the values for all five constraint attributes will be at their most desired levels, but a 0.05 probability that they will all be at their worst. The designer is asked to choose between the two options and if a choice can be made then the value of p is altered until the moment of indifference is reached. At this moment the utility of the certainty is equal to that of the lottery, thus if the designer was unable to choose between the "certainty" and the "lottery" presented in Figure 71 then:

$$U(\$0_{cost}, 30\ \text{lb}_{weight}, 400\ \text{sec}_{load}, 600\ \text{sec}_{assem}, 240\ \text{sec}_{unload}) = 0.95 * U(X_b) + (1\text{-}p) * U(X_w)$$
$$= 0.95 * 1 + 0.05 * 0$$
$$= 0.95$$

where:

$U(X_b) = \$0_{cost}, 0\ \text{lb}_{weight}, 0\ \text{sec}_{load}, 0\ \text{sec}_{assem}, 0\ \text{sec}_{unload})$

$U(X_w) = \$80_{cost}, 30\ \text{lb}_{weight}, 400\ \text{sec}_{load}, 600\ \text{sec}_{assem}, 240\ \text{sec}_{unload})$

The scaling constant for cost, k_{cost} is therefore 0.95. This process is repeated for the remaining four constraints.

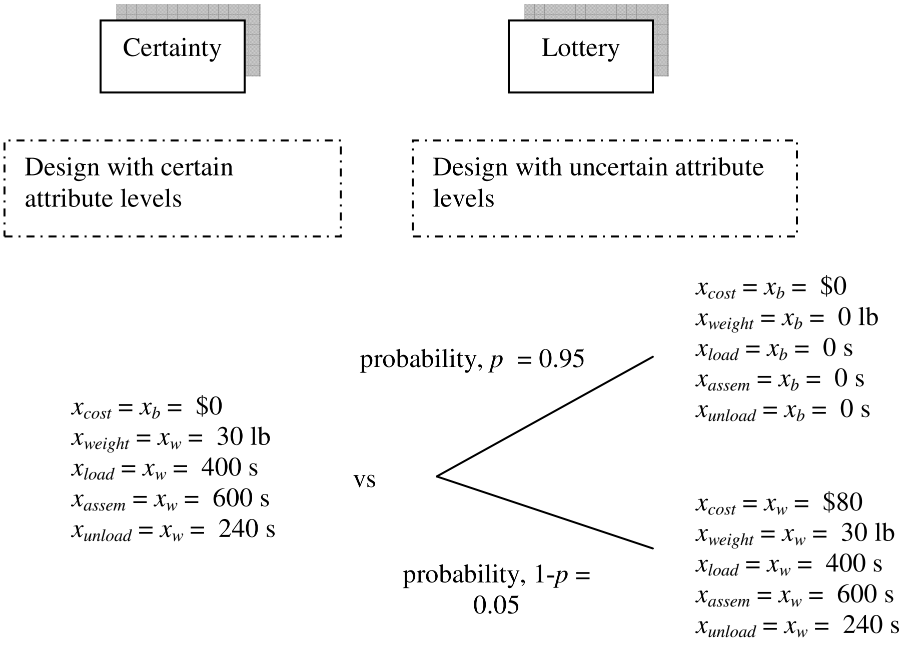


Figure 71: Lottery question used to determine the scaling constant for cost

When evaluating design cases during retrieval, each adapated design case will make its own contribution to the performance values for each of the constraint attributes. To assess how well a design case matches the design preferences the individual utility values for each of these constraints can be combined together to form a single overall utility for a complete set of constraint attributes. This utility, *U(X)* is then used to decide which design case and adaptation strategy to implement.

4.3.3 Evaluating Different Design Cases and Adaptation Strategies

The functional-similarity stage returns a number of cases for each FR or group of FRs, each of which can be considered for adaptation and subsequent implementation as the design case from which the final design solution can be generated. The objective is to retrieve the case that once adapted results in a fixture design most in keeping with the designer preferences. This boils down to picking the design that has the highest utility $U(X)_{max}$. Each DP, when adapted, may make a contribution to the performance of the fixture design with respect to each of the six constraint attributes: i.e., each adapted DP may have a cost, weight, assembly time, and so on associated with it and the DP that is subsequently chosen will be the one that results in a complete fixture design with the highest overall utility value. The tasks involved in this process are to:

1. generate a complete fixture design by randomly selecting candidate DPs such that all FRs are qualitatively satisfied (this design is used as a reference point from which to evaluate different adapted cases – see section 4.3.3.1);
2. calculate the performance values for each of the constraint attributes for this complete design;
3. go through this complete design and fix each FR in turn, thus initially select a FR (or group of FRs requiring a common solution) that needs to be satisfied;
4. identify the number of candidate DPs returned for that FR by the functional similarity-based retrieval stage;
5. identify the number of adaptation strategies, *n*, for a particular DP;
6. implement one of the adaptation strategies;
7. determine the new cost, weight, assembly time, loading time, unloading time, and disassembly time for the adapted case for this adaptation strategy;

8. incorporate these values into the overall cost, weight, etc., of the complete fixture design;
9. determine the overall utility of the new complete fixture design;
10. repeat steps 5 to 7 for each adaptation strategy;
11. compare the overall utility values for each adaptation strategy and select the strategy with the highest utility value $U_{max}(DP_{case\_id/n\_max})$ where *n_max* denotes the best adaptation strategy and *case_id* represents the DP identification;
12. repeat steps 4 to 9 for each candidate case for each FR or group of FRs;
13. compare the values of $U_{max}(DP_{case\_id/n\_max})$ for each DP and select the DP/adaptation strategy combination that returns the highest utility as the final design solution for that FR or group of FRs;
14. repeat steps 3 to 13 until all FRs are satisfied;
15. output the final design solution to the user.

The outputs of this retrieval stage are the completed unit and element schemas for each of the units that return the highest utility value for a particular FR. The schemas contain the details of the adapted cases.

4.3.3.1 Generating an Initial Design

The first stage of the adapatability-based retrieval process is to generate a complete fixture design that *qualitatively* satisfies the FRs. This complete fixture design provides a common reference point with which to compare all design cases and their adaptation strategies. An important point to note about this design is that is highly unlikely to satisfy the design requirement quantitatively (e.g., it will consist of the right type and number of units but the individual performance values for each of those units, such as clamping stiffness, will not be satisfactory), and the procedure adopted is to go through each FR in turn and implement adaptation strategies for each candidate DP. Once the DP has been fixed, the analysis can proceed to determining how well this repaired design satisfies the design preferences.

The output of the vetting stage is a list of possible DP solutions for each FR or group of FRs, as illustrated in Figure 72. The first step is therefore to obtain a complete fixture design solution by selecting a group of these DPs such that for each FR a DP exists in the fixture design that attempts to satisfy it. At this stage the DP does not have to quantitatively satisfy the FR. The simplest way to do this is simply to select the DPs that were returned first during the vetting stage (highlighted in Figure 72).

FR	Possible DP solutions			
$FR_{2.1.1.1}$ Provide clamping force of 50 lb against locator P1	VC0132C1	VC0132C2	VC021C3	VC022C1
$FR_{2.1.1.2}$ Provide clamping force of 50 lb against locator T1	HC022C1	HC022C2	HC022C3	HC021C1
$FR_{2.1.1.3}$ Provide clamping force of 50 lb against locator S1	HC022C1	HC022C2	HC022C3	HC021C1

Figure 72: A sample list of FRs and possible DP solutions

In case library 2, the details for each of these cases will be held in the standard case schema. Part of the information held in this schema (Figure 73) contains the functionality of the DP as well as its individual performance with respect to the global constraint attributes. Thus the overall fixture design attribute performance levels can be calculated by summing up the contributions from each individual unit used in the design. For example cost is equal to:

$$cost_{overall} = cost_{VC0132C1} + cost_{HC022C1} + cost_{HC022C1} + \ldots\ldots\ldots\ldots\ldots$$

Class type
Unit ID
Stiffness FR performance
Clamping force FR performance
Acting height
Chip shedding ability

Unit cost
Unit weight
Loading time associated with unit
Unit assembly time
Unloading time associated with unit

Figure 73: Part of the schema for a vertical clamp

In this way the cost, assembly time, etc., are calculated for the complete design. When each DP is subsequently adapted and evaluated, then the attribute performance values used for the initial design can simply be removed and replaced with the new values for the adapted DP and the overall utility of the design calculated.

4.3.3.2 Adapting Designs During Adaptability-based Retrieval

During adaptation, it is necessary to understand the relationships that exist between the FRs, DPs, and adaptation strategies. In terms of implementing an adaptation strategy, it is important to understand what parameters of a DP are affected by its implementation, what limitations exist on using a particular strategy (e.g., where it can be used), and what the effect upon the DP's ability to satisfy the design preferences is. To support the adaptation process, the CAFixD method relies on domain knowledge that it applies for specific FRs. This knowledge includes both the adaptation strategies themselves as well as knowledge regarding the FRs and DPs to which they are applicable. Domain knowledge also determines the effect that a particular adaptation strategy will have upon an individual DP's contribution to the performance values for each of the constraint attributes. Utility analysis is used to determine whether this is a beneficial or detrimental effect. A convenient representation of the adaptability-based retrieval process is a structure termed the “adaptation mapping layout“, an example of which is presented in Figure 74.

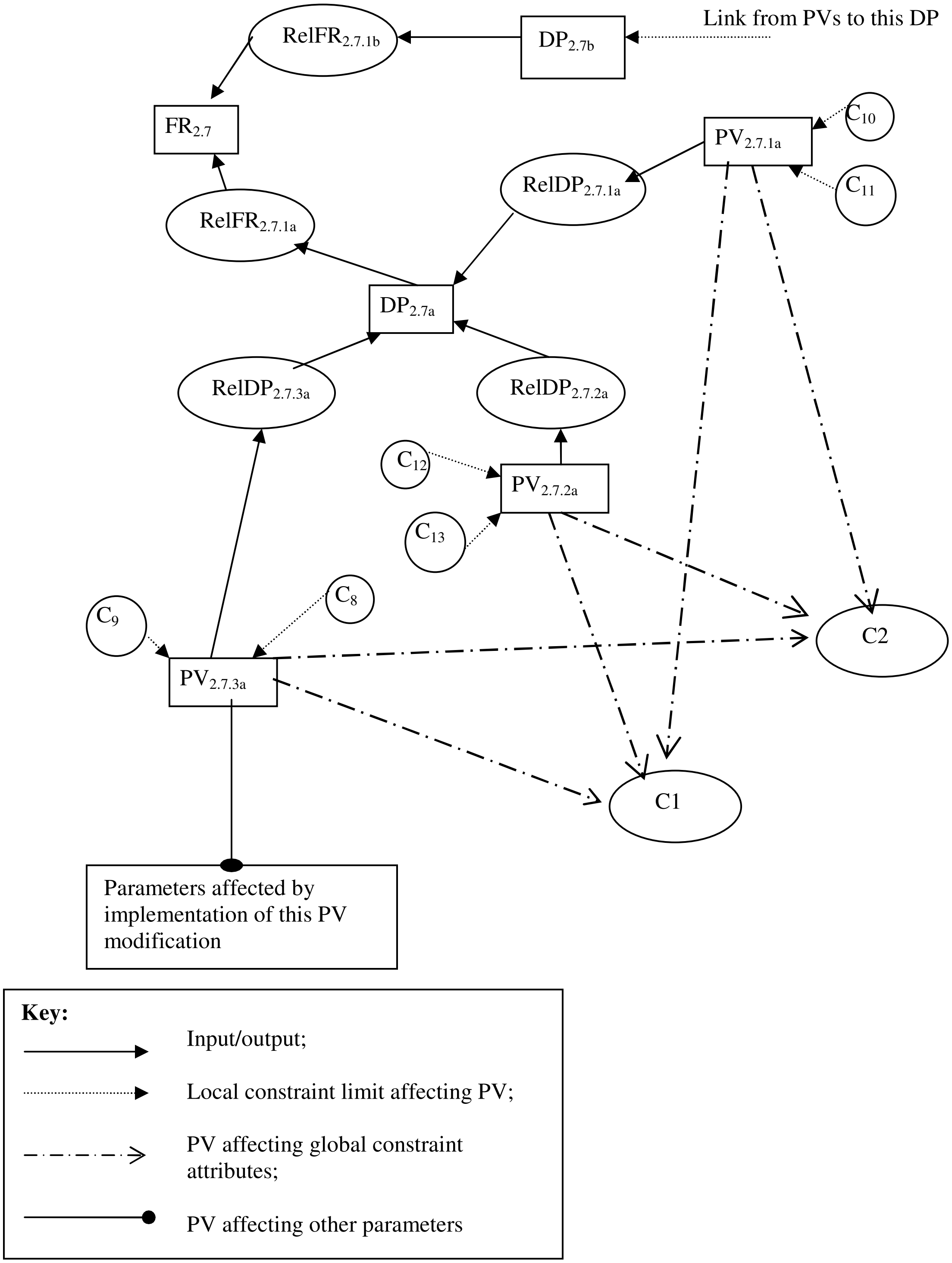


Figure 74: The adaptation mapping layout

Specifically this structure:

- outlines all candidate solutions (DPs) from which a design can be generated;
- shows how all of these candidate DPs can be adapted;
- provides a measure of how well a solution created from a particular DP and adaptation strategy combination satisfy the design preferences;
- shows the relationships between DPs and the functions they perform.

For each FR (e.g., $FR_{2.7}$ in Figure 74), there may be any number of possible DPs ($DP_{2.7a}$, $DP_{2.7b}$). The relationships between the FRs and DPs (RelFR) are qualitative and extend to ensuring that the DP can offer the type of FR that is required. A standard FR may be to provide a vertical clamping stiffness of 200E6 lb/in and the corresponding DP would be a clamping unit able to provide a vertical stiffness. If the vertical stiffness provided by the DP does not match the required value, then suitable adaptation strategies need to be identified and subsequently evaluated. These adaptation strategies modify a particular PV of a DP. PVs are general concepts such as DP thickness or material type. An adaptation strategy will change a PV using a statement such as *"Apply an increase of 0.5 inches to the thickness PV for* $DP_{2.7a}$". The task of actually implementating such a change to the elements within a DP can be fairly complex. Many elements within a DP may need to be modified to accommodate this PV change and adaptation strategies contain the details of the elements affected.

The nature of the RelDP relationships tends to be more complex than those that exist between the FRs and DPs and extends to understanding how the structure of a DP achieves its function. Essentially the relationships represent the behaviour of a DP. This understanding of the behaviour of DPs is used to determine the structural modifications necessary to achieve the desired FR. The role of the adaptation strategy is therefore to determine the PV change, implement it, and then test the revised DP to ensure that it works

Once an adaptation strategy has been successfully implemented the effect of the DP's contribution to the performance of the complete fixture design with respect to the design preferences can begin. The relationships between the parameters of the design and the global constraint attributes are known. That is, for each unit, relationships exist within the domain knowledge base that can be used to calculate an individual unit's cost, weight, etc. These calculated values can subsequently be incorporated into the constraint attribute performance values for the complete fixture design, allowing the overall utility of a particular DP and adaptation strategy combination to be obtained. This utility can then be compared with those of other DP/adaptation strategy combinations to ascertain the most preferred option: i.e., the DP/adaptation strategy with the highest utility.

When implementing an adaptation strategy, certain limitations may exist on what can be done and these are represented by the local constraints associated with the PVs. Simple examples are a limit on the number of materials that exist within the domain knowledge base, or a limit on the maximum dimensional modification of an element. For example, Figure 75 illustrates that the thickness of the horizontal element of the locating unit cannot be greater than 2*l* otherwise the element will collide with fixture base.

This form of collision detection is the main type of interference checking that the CAFixD method supports and it plays a particularly prominent role when evaluating how a DP should be changed when implementing an adaptation strategy. Specific adaptation strategies and issues arising from their invocation are discussed in section 4.3.3.2.1. The evaluation of different DP/adaptation strategy combinations is discussed in section 4.3.3.2.2.

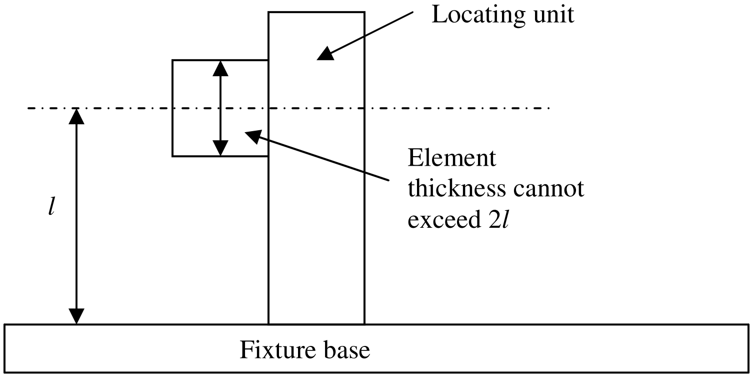


Figure 75: Local constraint limiting a dimensional change

4.3.3.2.1 Adaptation Strategies

Possible adaptation strategies are identified within the domain knowledge base by using simple rules. It is essentially a two stage process in which initially the type of FR is evaluated. Then the type of DP determines the possible adaptation strategies. Figure 76 represents a pseudo-code implementation of the process.

Upon initially determining the type of FR the search for the appropriate adaptation strategy is then driven by the type of DP being considered as a solution for that FR. For vertical clamps used to satisfy a clamping stiffness, three possible adaptation strategies exist. One alters the thickness of the components of the DP, the second their width, and the third the material properties of the unit components. Strategies have a modification module, a testing module, and a control module. The modification module makes the physical changes to a DP, which is then subjected to testing by the testing module. The control module evaluates the testing results to determine if a satisfactory stiffness has been attained. If not then the control module asks the modification module to modify the DP again, and it is the job of the control module to inform the modification module of the magnitude of the design change. The modification module manages the implementation of this change to the individual elements. This process is repeated until either a satisfactory solution has been achieved or the control module deems that the adaptation strategy is unable to produce a satisfactory solution. If the adaptation is successful then the modified design is subjected to the evaluation process presented in section 4.3.3.2.2. If the adaptation strategy is unable to produce a working solution then the retrieval process moves on to consider the next adaptation strategy for that DP.

```
If (FR is "vertical_stiffness") then
        If (DP is "strap_clamp") then
                If (DP is "strap_clamp_first_order") then
                        Adaptation strategy 1:          strap_thickness_adapt( )
                                Modification module:    alter_ thickness( )
                                Test module:            strap_clamp_first_order_disp_func( )
                                Control module:         dimension_control( )
                        Adaptation strategy 2:          strap_width_adapt( )
                                Modification module:    alter_ width( )
                                Test module:            strap_clamp_first_order_disp_func( )
                                Control module:         dimension_control( )
                        Adaptation strategy 3:          strap_material_adapt( )
                                Modification module:    alter_ material( )
                                Test module:            strap_clamp_first_order_disp_func( )
                                Control module:         material_control( )
                If (DP is "strap_clamp_third _order") then
                        Adaptation strategy 1:……….…………………………….
        If (DP is "toggle_clamp") then……………………….
If (FR is "vertical_clamping_force") then
        If (DP is "strap_clamp") then
                If (DP is "strap_clamp_first_order") then
                        If (Force_actuation is "thread") then
                                Adaptation strategy:            strap_torque( )
                                        Modification module:    torque_calc_first_order( )
                                        Test module:            torque_calc_first_order( )
                                        Control module:         torque_control( )
                If ( DP is "strap_clamp_second_order") then………………….
                If (DP is "toggle_clamp") then………………..
If (FR is "horizontal_stiffness") then……………………
```

Figure 76: Pseudo code representation of selecting adaptation strategies

Specific issues arise within the modification and control modules. During modification the interactions that can occur when modifying components within a fixture unit must be carefully managed. Difficulties within the control module relate to identifying when a strategy is likely to fail and how to generate an appropriate modification request for the modification module. Section 4.3.3.2.1.1 describes the modification modules in greater detail, section 4.3.3.2.1.2 the testing modules, and section 4.3.3.2.1.3 the control modules.

4.3.3.2.1.1 Modification Modules

The modification module implements the design change suggested by the control module. For example if the control module suggests a dimension change of 0.3 inches to the *alter_thickness( )* modification module, then it is the responsibility of the modification module to determine how the components within a DP must be changed to accommodate this amendment. During the implementation of an adaptation strategy an important point to note is the complex interactions that can arise when modifying a design case. To illustrate some of these difficulties a third order vertical strap clamp, as presented in Figure 77, will be considered. Changing the material of a unit poses no significant difficulty, thus discussion will be limited to complications that arise from implementing the modification modules *alter_thickness( )* and *alter_width( )*, which alter a unit's thickness and width respectively. Figure 78 and Figure 79 illustrate the directions in which thickness and width modifications are made.

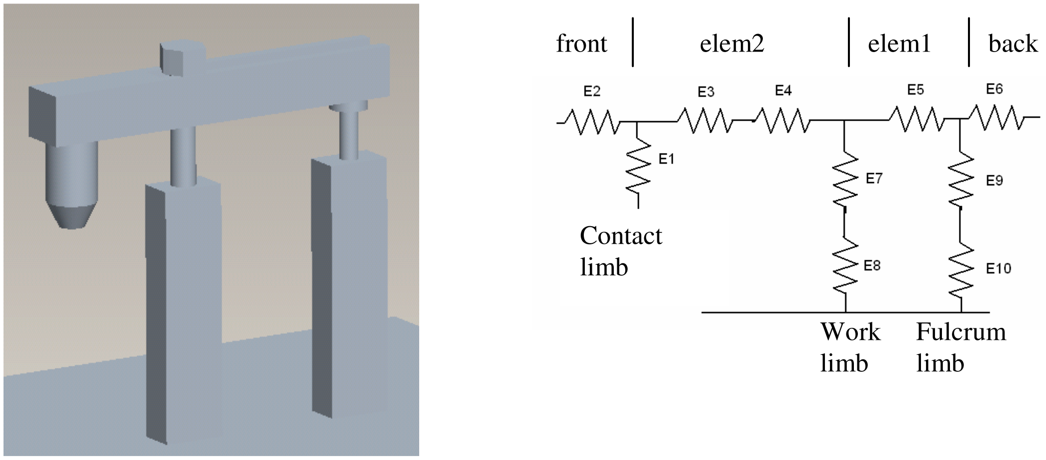


Figure 77: A third order vertical strap clamp and its element skeleton

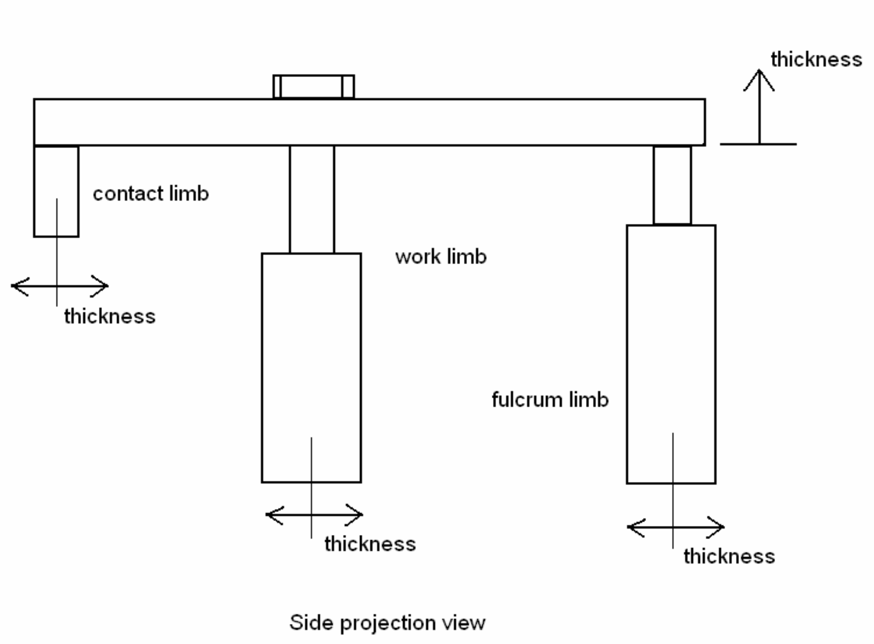


Figure 78: Thickness changes on a third order vertical strap clamp

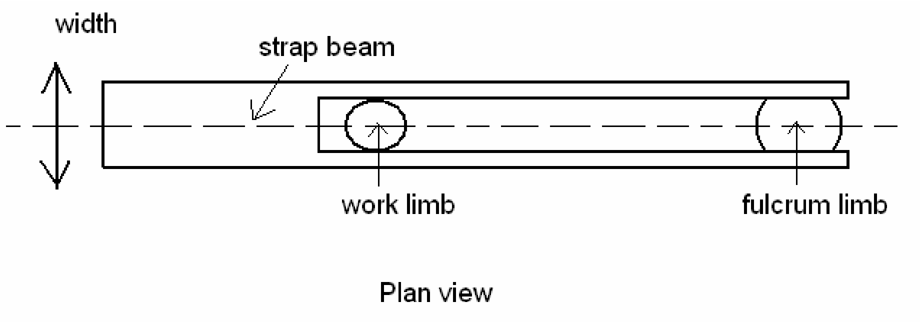


Figure 79: Width changes on a third order vertical strap clamp

Within case library 2, each unit is broken down into a number of manageable elements (for example E1, E2,…..E10 from Figure 77) to facilitate the stiffness analysis detailed in section 4.3.3.2.1.2. For each element the relevant details are stored in a standard element schema that is attached to the main unit schema. The unit and element schemas are recalled for convenience in Table 11 and Table 12. The greyed out entries relate to the performance of the unit as a whole and have been discussed previously in section 4.2.4. The areas of interest with regard to adaptation concern the description of the individual limbs and elements from which the unit is comprised.

The following information is provided about the limbs in the clamping unit schema.

- "Force actuation" – describes the manner by which the clamping force is produced. This is used to for calculating the loading and unloading time.
- "Total number of elements" – this the total number of elements the unit consists of and is used to control the number of times the testing module executes.
- "Number of fulcrum/work/beamE1/beamE2 elements" – this lists the number of elements that exist within each of the limbs of the unit. This information is used when changing the length and position of elements within each limb.
- The "(Work) L2 element", "(Fulcrum) L1 element", and "C beam element" entries list the elements from the beam that contact the work, fulcrum, and contact limbs respectively. This information is used to manage interactions that occur when modifying the width or thickness of the unit.

Clamping unit attribute	Description
Class type	Class type within case library 2
Unit ID	Identifying name for unit
Stiffness FR performance	Unit stiffness
Clamping force FR performance	Unit clamping force
Acting height	Contact point with workpiece is 3 inches from the base of the unit
Chip shedding ability	Does the unit have a chip shedding ability?
Unit cost	Cost of unit ($)
Unit weight	Weight of unit (lb)
Loading time associated with unit	Time taken to load workpiece (mins)
Unit assembly time	Time taken to assemble the unit (mins)
Unloading time associated with unit	Time taken to unload workpiece (mins)
Force actuation	Means by which the work force (W) is produced
Total no. of elements	Total number of elements within the unit
No. of fulcrum elements	Number of elements in the fulcrum limb
No. or work elements	Number of elements in the work limb
No.of length BeamE1 elements	Number of elements in beam_elem1
No.of length BeamE2 elements	Number of elements in beam_elem2
Length of L1	L1dimension (inches)
Length of L2	L2dimension (inches)
(Work) L2 beam element	Beam element to which work limb connects
(Fulcrum) L1 beam element	Beam element to which fulcrum limb connects
C beam element	Beam element to which contact limb connects
Work limb max thickness	Maximum thickness in the work limb
Fulcrum limb maximum thickness	Maximum thickness in the fulcrum limb
Contact limb max thickness	Maximum thickness in the contact limb
Work element	Work element that contacts strap beam
Fulcrum element	Fulcrum element that contacts strap beam
Contact element	Contact element that contacts strap beam

Table 11: A schema for a clamping unit (greyed out entries discussed in section 4.2.4)

- "Length of L1" and "Length of L2" are the lengths of beam elem1 and elem2 respectively. They are subject to possible modification and are subsequently used during the testing analysis to determine both the forces on the work, fulcrum, and contact elements, and the displacement of the beam when subjected to the machining forces.

- The “Work element”, “Fulcrum element”, and “Contact element” entries list the elements from each of these limbs that interface with the strap beam. This information is used to manage interactions that occur when modifying the width or thickness of the unit.
- The “Work limb max thickness”, “Fulcrum limb max thickness”, and “Contact limb max thickness” entries are the maximum thicknesses of the work, fulcrum, and contact limbs respectively. This information is used to help prevent limbs from colliding into each other during modification.

Element attribute	Comment
Element #	Element number
Limb element No.	Position along limb
Structure type	Cross section type
Element type	Limb the element is situated in)
Dist_from_end	Distance element is from the end of the beam segment (inches)
Length	Element length (inches)
Start thickness or radius	Element thickness at start of element (inches)
End thickness or radius	Element thickness at end of element (inches)
Start width or radius	Element width at start of element (inches)
End width or radius	Element width at end of element (inches)
Material mod	Material type
Height adjust	Is the element subject to a height adjustment if the acting height of the unit has to change?
Slot consideration	Is there a slot in the element?
Slot width	Width of slot (inches)
Slot length	Length of slot (inches)
Type of connection	What type of connection connects this element to the next element
No. of connections	How many connections there are to the next element
Offset distance	The position of the connections on the element cross section
Conn diameter	Diameter of the connections (inches)
Mated from	The element that this element connects from
Mated to	The element that this element connects to

Table 12: A schema for an individual clamping element

The following information is provided about the individual elements within each limb.

- “Element number” is an identification assignment ascribed to each element.

- “Limb element number” describes the position of the element relative to other elements within a particular limb.
- “Structure type” defines the cross sectional nature of the element (circular or rectangular). This information is primarily used during the testing phase, but for the critical elements that interact with the beam it is also used to help manage the interactions that occur between elements during modifications.
- “Element type” specifies whether the element belongs to the contact, work, fulcrum, beam elem2, beam elem1, front, or back limbs. This information is used during stiffness testing, and also during modification of element lengths.
- “Dist_from_end” is the distance of the start of an element from the end of the limb and is subject to change during modification. This is used for stiffness testing and for altering the position of elements during modification.
- “Length” is the length of the element and this is subject to change during modification. It is used during stiffness testing.
- “Start thickness” and “End thickness” are the start and end thicknesses of an element and are subject to change during modification. Rectangular and circular cross sections are supported, each of which can vary as illustrated in Figure 80. For circular cross sections, the start and end thicknesses are the start and end radii of an element.
- “Start width” and “End width” are the start and end widths of an element and are subject to change during modification. Rectangular cross sections can vary in a similar manner to that illustrated in Figure 80. For circular cross sections, this information is redundant as the start and end radii have already been specified.
- “Slot present”, “Slot width”, and “Slot length” detail any slots that may exist on the element. These are subject to change during modification, and are used during the testing phase.
- “Material type” lists the material from which the element is constructed. This is subject to change if the *alter_material( )* modification module is implemented.
- “Type of connection” lists the nature of the connection to the neighbouring element.

- The number of connections, their position (connections are usually positioned around the central axis of the element) and diameter are also listed. The diameter and position are subject to change during the modification process.
- The “Mated to” and “Mated from” entries list the elements to which the current element is connected.

Strap clamps work on the basis of a lever (Figure 81) in which a work force, *W*, is applied relative to a fulcrum point which in turn produces a force at the opposite end of the lever, *P*. *P* is the useful force exerted on some external body. The purpose of the stiffness analysis is to determine the displacement of the unit under machining loads. To perform a stiffness analysis it is necessary to specify the details of each element in the work, fulcrum, contact, and beam limbs. A finite element analysis is then performed to calculate the displacement of the unit in which the displacement of each element is calculated and then summed to ascertain the unit displacement.

During adaptation the dimensions of these elements may increase or decrease, thus their length, width, or thickness may change. Also their position within the structure maybe altered. Length changes may occur in the beam, fulcrum, and work elements. Width and thickness changes may occur in beam, fulcrum, work, or contact elements. The possible changes to each element are now described in greater detail.

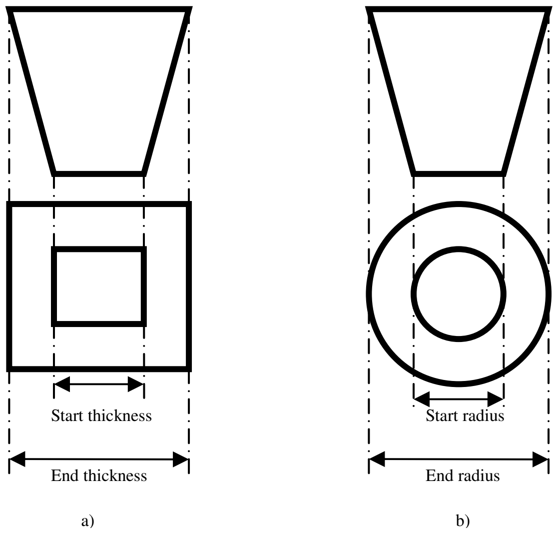


Figure 80: Start and end thicknesses for a) rectangular and b) circular cross sections

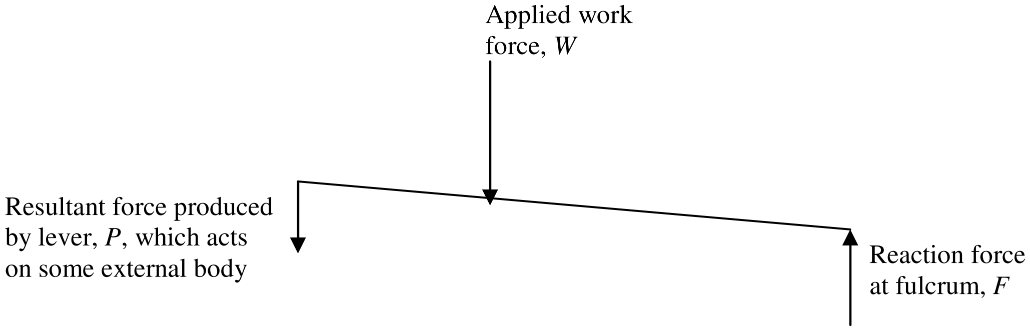


Figure 81: The forces in a lever arrangement

4.3.3.2.1.1.1 Modifying the Fulcrum, Work, and Contact Elements

The following information from the schema is used to support the changes in length of the fulcrum or work elements:

acting height, *h*;
number of fulcrum or work elements;
limb element number, *s_elem*;
distance from end, *d*;
length, *l*.

A standard fulcrum limb will take the form presented in Figure 82. If the acting height of the fulcrum needs to change for a new design then the values of l and d for each element will change (Figure 83). The new acting height is obtained from the FR that states the coordinates for this clamping point (the z coordinate is the relevant value). The new height is used to calculate the change in required length of each element, *delta_l,* and the new positions of each element d'. Thus:

$$\text{New acting height, } h' = z \text{ coordinate of clamping point}$$
$$delta\_l = (h' - h) / \text{number of fulcrum elements}$$

For element x, the dimension changes are:

$$l_x' = l_x + delta\_l$$
$$d_x' = d_x + (s\_elem_x - 1) * delta\_l$$

Thus for fulcrum element two (E2) in Figure 82:

$$l_2' = l_2 + delta\_l$$
$$d_2' = d_2 + (2 - 1) * delta\_l = d_2 + delta\_l$$

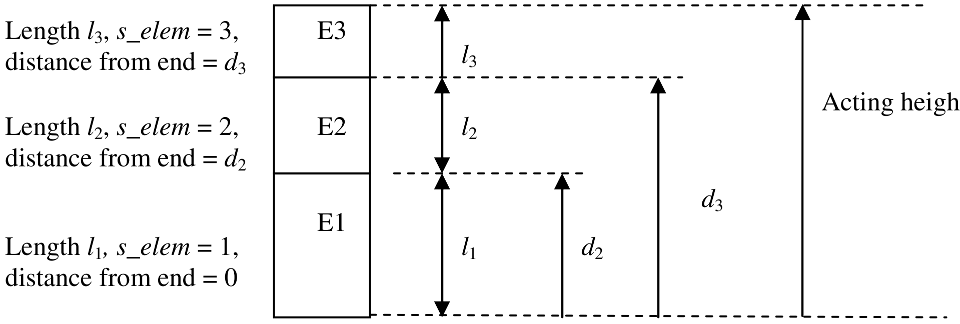


Figure 82: A standard fulcrum layout

The procedure is the same for the work limb, the sole exception being that the number of work elements replaces the number of fulcrum elements. The height of the contact element is not altered. It remains the same and only the fulcrum and work elements are modified to obtain the correct height of the unit. The height of these elements is altered to ensure that the clamp can contact the workpiece, but it is not used to control the stiffness of the unit although height does affect unit stiffness. The procedure adopted is to fix the height and then proceed to obtain the required stiffness of the unit. This can be achieved by altering the thickness, width, or material properties of the unit.

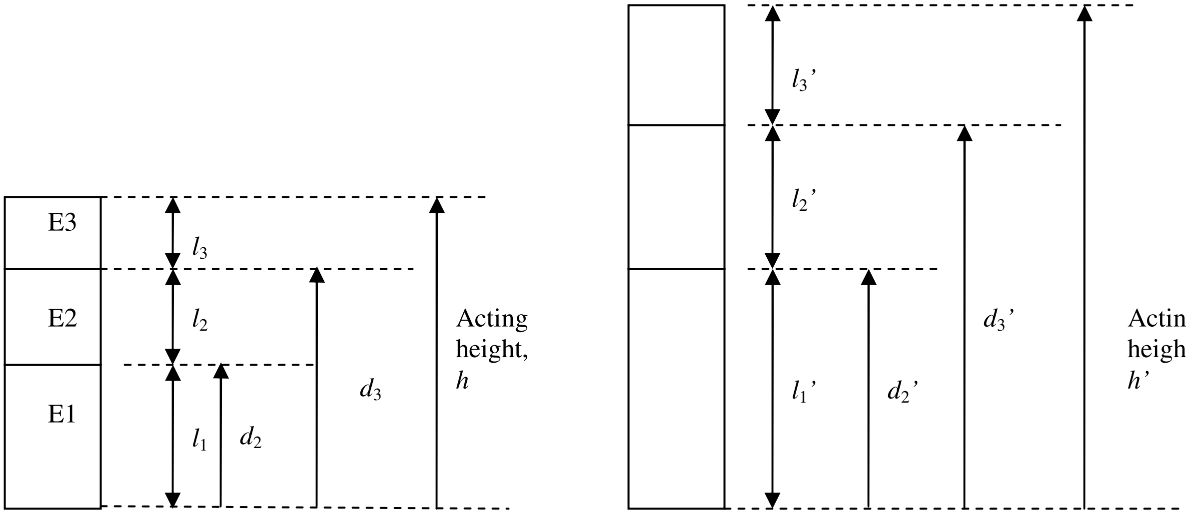


Figure 83: Altering the length of a fulcrum element

When altering the thickness or width of the fulcrum limb, the following information from the schema is required:

the starting thickness or radius of the element, *st_t*;
the end thickness or radius of the element, *end_t*;
the starting width or radius of the element, *st_w*;
the end width or radius of the element, *end_w*;
the fulcrum beam element (the element that connects to the strap beam);
the structure type.

Nominally when implementing the thickness adaptation strategy only the *st_t* and *end_t* values would be changed. However, it may be necessary to alter the width values as well depending on the structure type of the fulcrum beam element. The structure type of an element states whether the cross section of an element is rectangular or cylindrical in nature. If it is cylindrical in nature then it is also necessary to increase the width of the elements in the fulcrum block. Generally the connecting element will be a bolt that must fit inside the fulcrum element to which it attaches. Thus increasing the thickness of the bolt effectively means increasing the radius of the bolt. To accommodate this, the widths of the remaining fulcrum elements need to be increased, as illustrated in Figure 84.

This change is reflected in all the elements of the fulcrum. Similar considerations apply when modifying the contact and work elements of a clamping unit. A further issue regarding modification of these three types of limbs is ensuring that the dimension changes do not result in the units colliding with each other. This is only relevant when considering thickness changes which are applied across the central axis of each limb as illustrated in Figure 85. If the value of the thickness change δt is greater than the available distance between the work and fulcrum elements g then the units will collide. In such circumstances the option pursued is to increase the length of the beam elements until the units no longer collide.

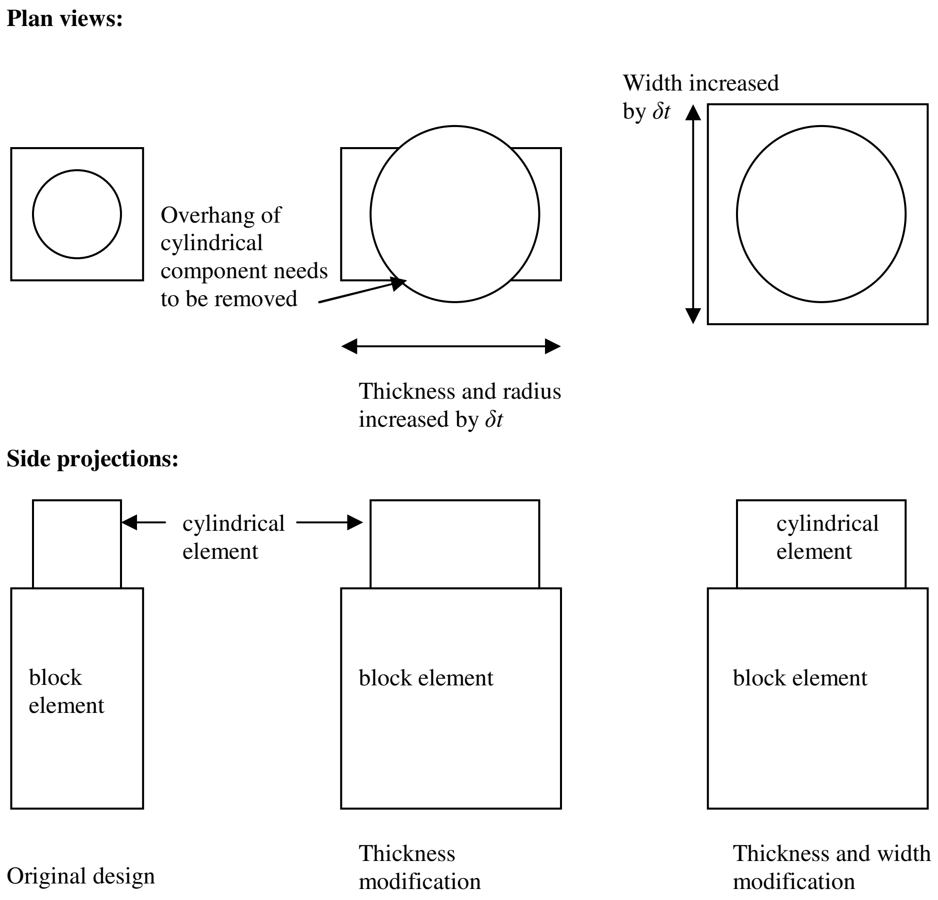


Figure 84: Modifying fulcrum components

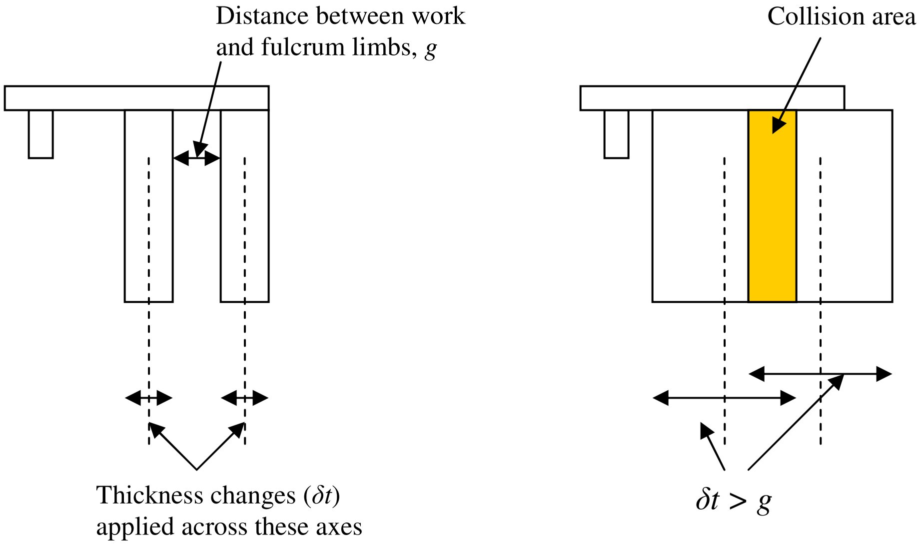


Figure 85: Collisions between fulcrum and work limbs

4.3.3.2.1.1.2 Modifying the Beam Elements

The beam itself is split into two main limbs, as illustrated in Figure 86. Beam elem2 represents the portion of the beam existing between the work and the contact limbs, and beam elem1 the portion existing between the work and fulcrum limbs. When the occurrence of a collision between two limbs exists, then the relevant beam length is increased until the limbs do not interfere with each other. In the case of the example presented in Figure 85, $L1$ would be increased by at least δt.

In practice straps are one piece components. However for the purposes of stiffness analysis it is necessary to split this single real component into a number of imaginary components connected together. Already the beam has been split up into limbs elem1 and elem2 but further subdivisions are often required to allow the stiffness analysis. Consider for example the plan view of a normal strap beam, as presented in Figure 87.

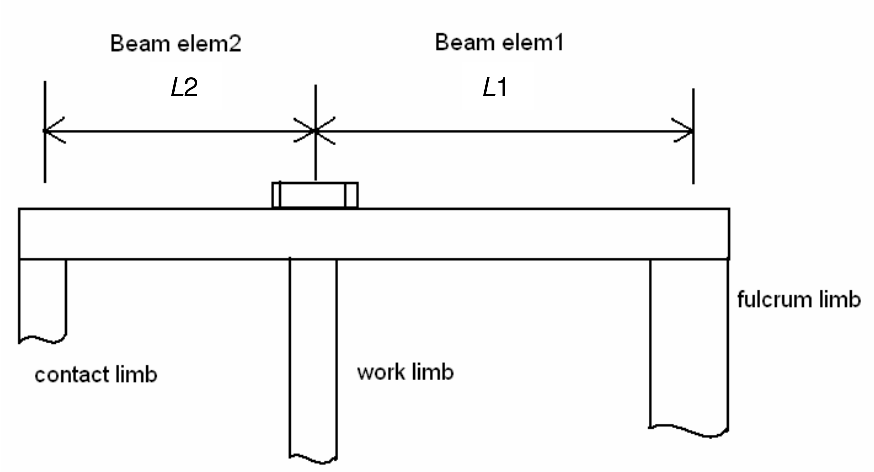


Figure 86: Splitting up the strap beam (side projection view)

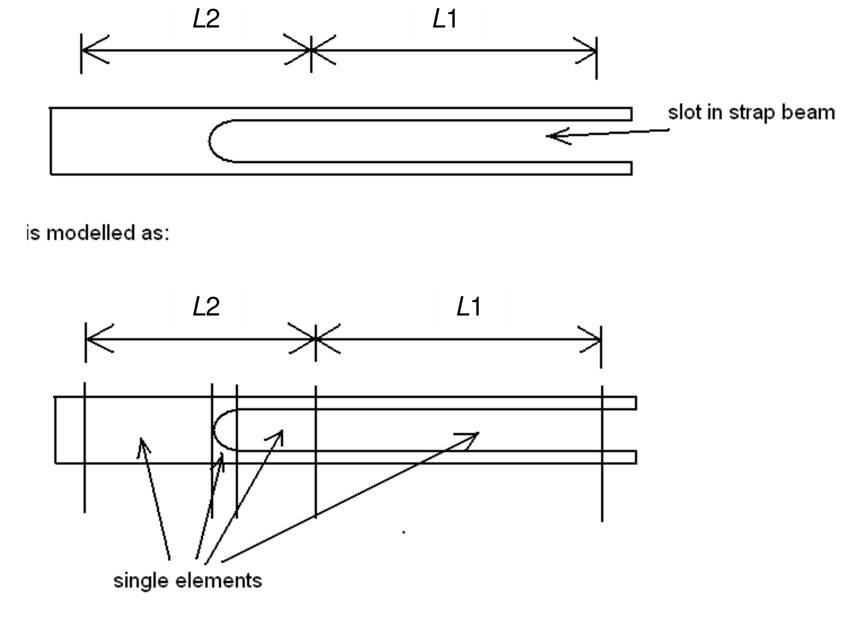


Figure 87: Modelling the strap beam (plan view)

Whenever the beam lengths $L1$ or $L2$ are subject to an increase, then so too are the lengths and positions of all the elements that lie within elem1 or elem2. The process for handling this is similar to that described for changing the height of the fulcrum and work elements. For example if elem2 has to have its length increased (Figure 88) to prevent a collision between the contact and work limbs then the length increase, *delta_l*, of elem2 is calculated by:

$$delta\_l = (\text{new\_contact\_thickness} / 2) + (\text{new\_work\_thickness} / 2) - L2$$

$$\text{new length of elem2, } L2' = L2 + delta\_l$$

$$delta\_l\_elem = delta\_l / no\_of\_beam\_elem2\_elements.$$

This element length increase of *delta_l_elem* is then assigned to each of the individual elements within elem2, and the positions of the elements with respect to each other (d_x). For element x:

$$l_x' = l_x + delta\_l\_elem$$

$$d_x' = d_x + (s\_elem_x - 1) * delta\_l\_elem$$

where s_elem_x is the element position number.

Elements may also have their lengths changed as a result of thickness increases to the work or fulcrum elements that contact the beam. For example if the increase in the work limb is such that the slot in the workpiece has to be extended then the neighbouring element to the slot will have to be shortened. At the same time the width of the beam has to be altered to accommodate the thickness change of the work limb, as illustrated in Figure 89. If a thickness increase of δt is applied to the work element that interfaces with the beam, then the beam elements need to be adapted until the slot in the beam, whose details are listed in the schema, is long enough and wide enough to accept the work element.

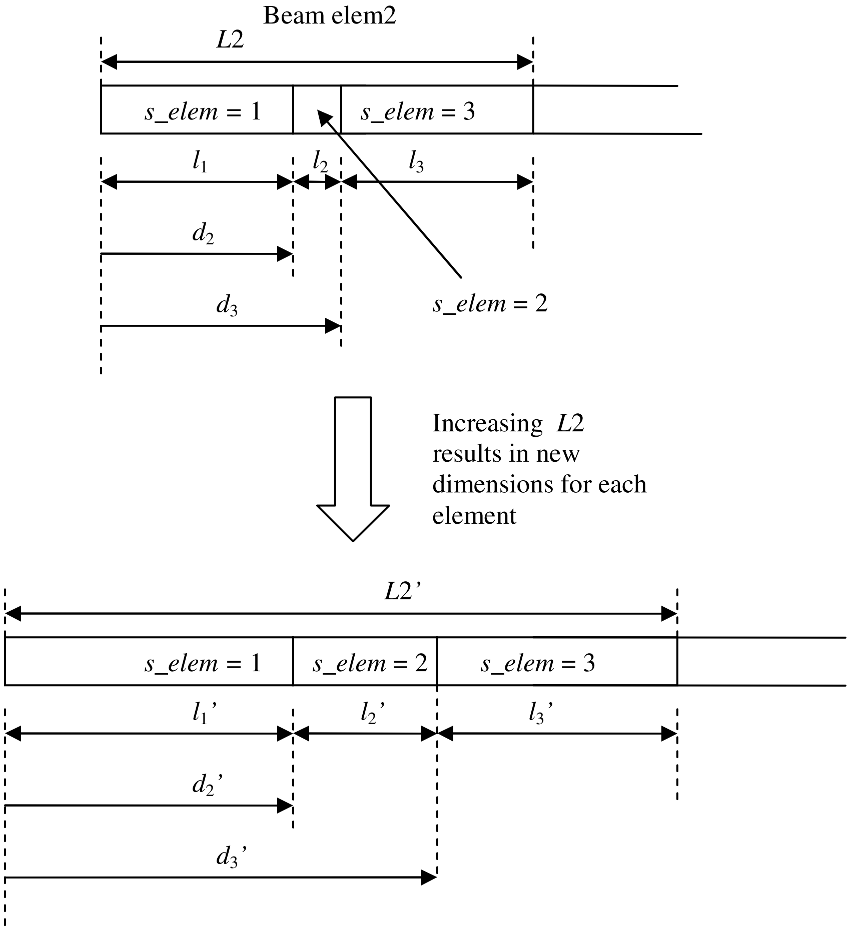


Figure 88: Modifying elements within elem2 (side projection view)

4.3.3.2.1.1.3 Modifying Element Connections

The connections between elements are also held in the schema. Details include the type (such as dowel pins, threaded bolt connections, and so on), number, and dimensions of connections, and the positions of connections. The case schema details which elements are connected to each other in terms of whom they mate to and whom they mate from. Elements mate-to other elements away from the workpiece, as illustrated in Figure 90 where element E2 mates to element E3 and element E3 mates from E2. The connection information held in the schema is for the mates-to connection only. To assist the retrieval of information for the mating-from connection, the schema contains the identity of the mates-from element and the required connection information can be retrieved from the schema entries for this mates-from element.

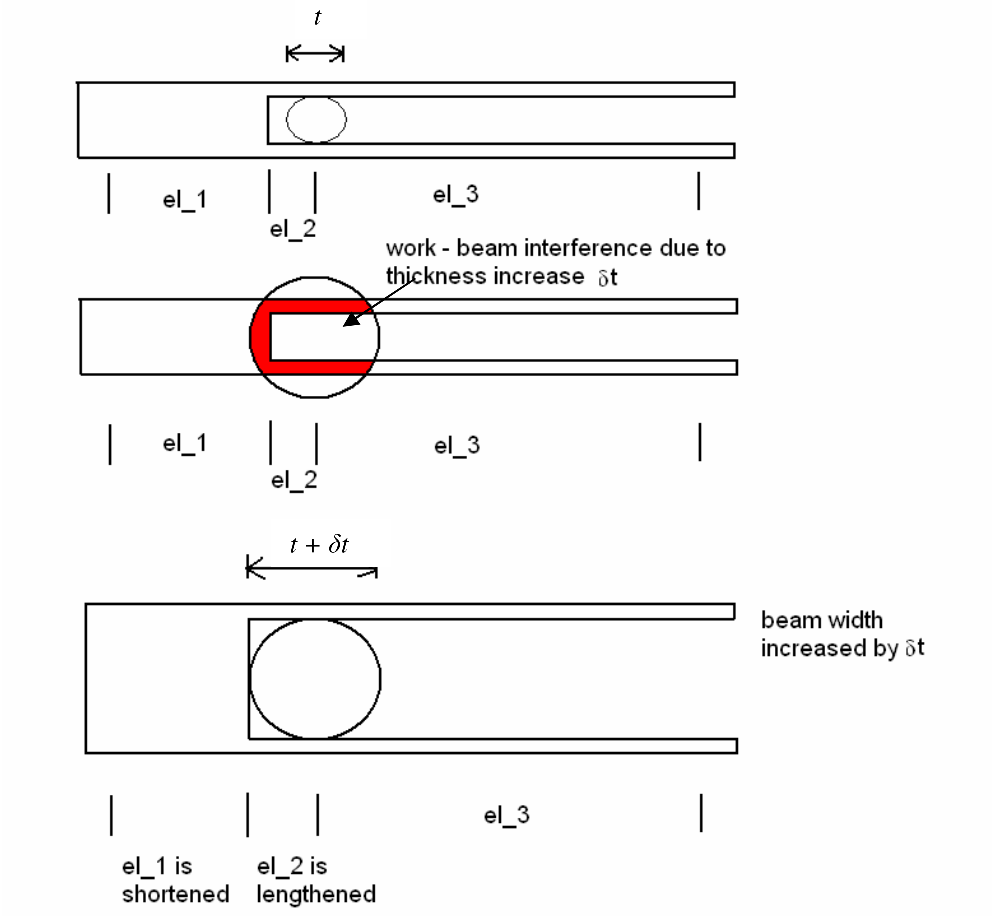


Figure 89: Modifying elements within the beam due to thickness increases of the work elements

When modifying the dimensions of elements of a DP, it is also necessary to alter the element connection dimensions. They are modified directly in proportion to the changes in the DP dimensions. The cross sectional area, the length, and the position of the connections can change. If for example a fulcrum element with a thickness *t* is subject to a thickness increase of *δt*, then the proportional increase in thickness of that element is *(t + δt)/t*. The cross sectional area of the connection in this element must correspondingly change by this same proportion. Thus if the diameter of the connections is *c*, then the modified diameter *c'* becomes:

$$c' = c * \left(\frac{t + \delta t}{t}\right)$$

Similarly the position of the connections must be changed. Normally the positions are specified as occurring on a diameter around the central axis of the element and the offset diameter *d* is modified to *d'* by:

$$d' = d * \left(\frac{t + \delta t}{t}\right)$$

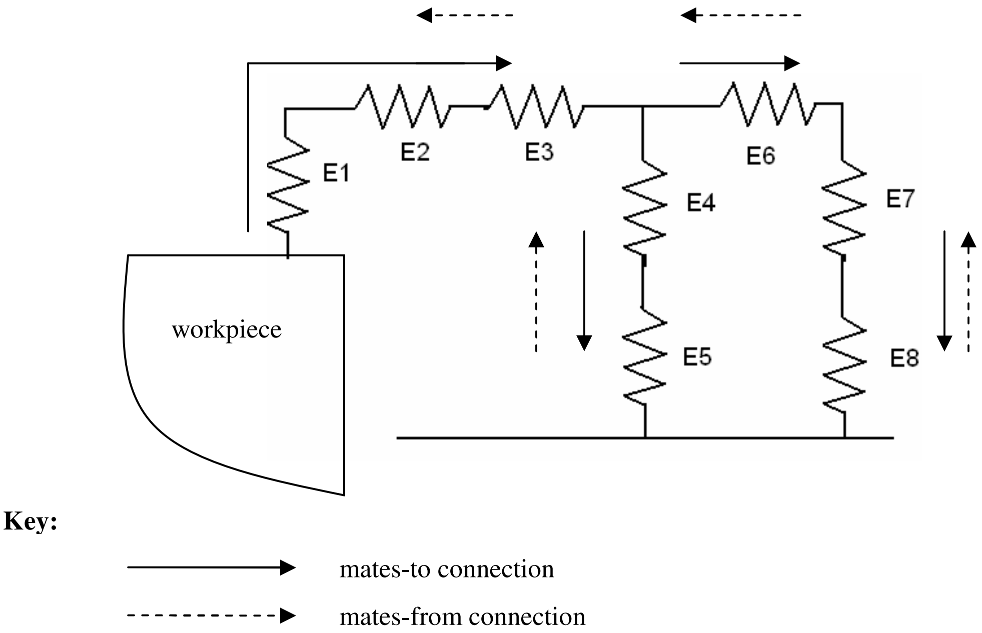


Figure 90: Mating conventions in CAFixD

Figure 91 illustrates both these changes. The change in length of any connections is similarly dependent on the change in length of the element.

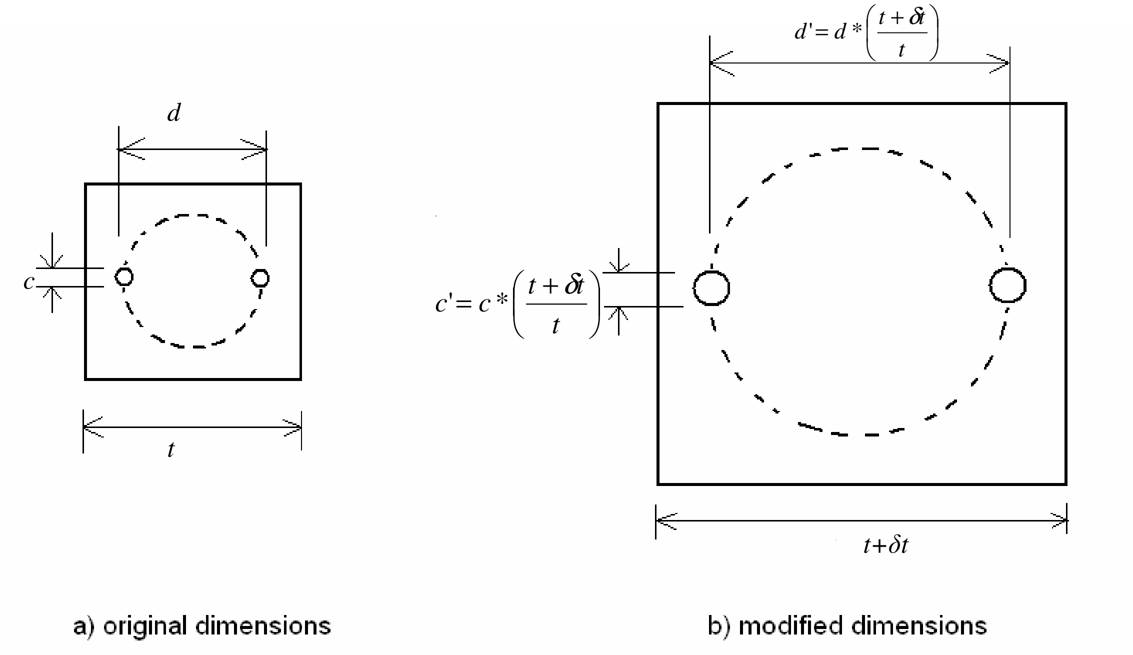


Figure 91: Modifying connection properties on a fulcrum element (cross sectional view)

4.3.3.2.1.2 Testing a Modified Design

Once a DP has been altered by a particular modification module, it has to be tested to ascertain how it would behave if used as the design solution. Testing is performed by the test module of the adaptation strategy. The test performed depends upon the FR the unit is being used to satisfy. If the FR is related to stiffness for example, then a displacement analysis is carried out on the unit. Continuing with the example of a third order clamping unit, the stiffness FR states that the unit should have a specific stiffness, such that when subjected to a force *P* during machining, the deflection of the unit *d* will not be greater than that allowed by the design tolerance. The purpose of the testing module is to calculate the displacement *d* (Figure 92).

The virtual force method (Hibbler, 1997) is used to carry out the displacement analysis on all locating and clamping units. The principle of virtual force states that the virtual work done by an external virtual force upon a real displacement system is equal to the virtual work done by internal virtual forces, which are in equilibrium with the external virtual force, upon the real deformation. Denoting the external virtual work by *W* and the internal virtual work by *VW*, the principle of external virtual force can be expressed by:

$$W = VW \tag{1}$$

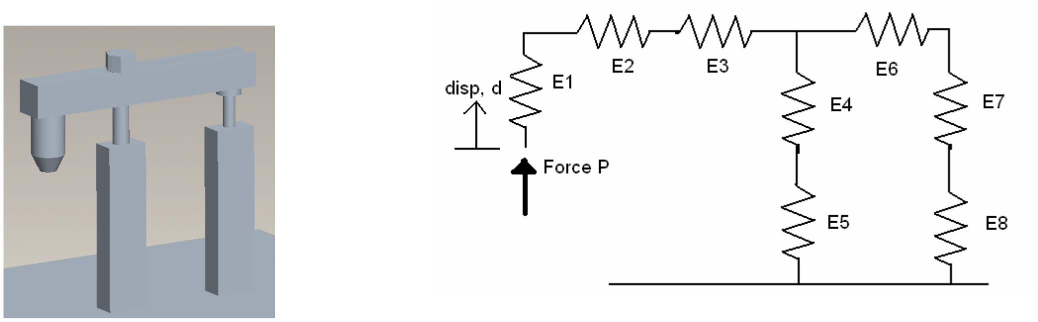


Figure 92: The displacment analysis for a clamping unit

VW represents the strain energy, which is the work done by internal forces. When applying the principle of virtual force to find a particular deflection at a point, a fictitious unit load is applied at the point of interest and in the direction of the desired deflection. This unit load is the external virtual force. The external virtual work done by this force *P'* is equal to the force magnitude multiplied by the displacement of the real system Δ. The internal virtual work is equal to the internal forces (*u*) caused by the external virtual force *P'* multiplied by the internal displacements of the real system *δ*. For simplicity the magnitude of the external virtual force *P* is set to 1, thus equation 1 becomes:

$$1 \cdot \Delta = \sum u \cdot dL \tag{2}$$

P' = 1 lb = external virtual unit load acting in direction of Δ;
u = internal virtual load acting on the element (lb);

Δ = external displacement caused by real loads (inches);

dL = internal displacement of the element in the direction of u, caused by the real loads (inches).

The right hand side of equation 2 represents the strain energy of the system. The equations for internal virtual work for a single element as a result of axial and shear force loads, as well as bending moments, are presented in Table 13, where:

E = Young's modulus of elasticity of the element material (lb/in);
A = cross sectional area of an element (in^2);
n = internal virtual axial load caused by the external virtual load (lb);
N = internal real axial load acting on an element caused by the real external load (lb);
V = real internal shear load caused by the real external load (lb);
v = internal virtual shear caused by the external virtual load (lb);
G = shear modulus of elasticity of the element material (lb/in);
M = real internal moment caused by the real external loads (lb.in);
m = virtual internal moment caused by the virtual external loads (lb.in);
I = moment of inertia (in^4);
L = length of element (in).
f_s = form factor (a dimensionless number that is unique for a specific cross sectional area shape).

Deformation caused by	***Strain energy***	***Internal virtual work***
Axial load, N	$\int_0^L \frac{N^2}{2EA}dx$	$\int_0^L \frac{nN}{2EA}dx$
Shear load, V	$\int_0^L \frac{f_s V^2}{2GA}dx$	$\int_o^L \frac{f_s vV}{GA}dx$
Bending moment, M	$\int_0^L \frac{M^2}{2EI}dx$	$\int_0^L \frac{mM}{EI}dx$

Table 13: Internal virtual work equations for shear, axial, and bending moment loads (Hibbeler, 1997)

The equations for internal virtual work can be incorporated into equation 2 to yield:

$$1 \cdot \Delta = \int_0^L \frac{nN}{AE} dx + \int_0^L \frac{mM}{EI} + \int_0^L \frac{f_s vV}{GA} \tag{3}$$

This equation allows the displacement of the real system Δ to be calculated. For a third order clamping unit the analysis makes the following assumptions:

1. the strap beam elements are subjected to bending moments and shear forces as a result of the external force *P*;
2. bending moments arising at joints between the work, fulcrum, beam, and contact limbs are neglected.

Thus the clamp is modelled as presented in Figure 93. The contact and fulcrum limbs are in compression with the work limb in tension. The displacement *d* is a function of the combined displacements d_{beam}, $d_{contact}$, d_{work}, *and* $d_{fulcrum}$, which are the displacements of the beam, contact, work, and fulcrum limbs respectively:

$$d = d_{beam} + d_{contact} + d_{work} + d_{fulcrum} \tag{4}$$

Thus the solution for *d* boils down to applying equation 3 to each of the elements in the contact, work, fulcrum, and beam elements to determine their individual displacements which are then summed using equation 4. The procedure is to:

- create the real and virtual force systems;
- calculate the forces F_w and F_f for the real system;
- apply the virtual unit load and determine the internal virtual forces f_w and f_f;
- apply equation 3 to determine the displacement of each element;
- apply equation 4 to determine the displacement *d*.

Figure 93 has already presented the real force systems, and the virtual force system for the beam is illustrated in Figure 94. The virtual unit load is placed at the workpiece/clamping unit interface (f_c = 1 lb). The stiffness of the unit must act against the workpiece pushing up against the unit as a result of the machining forces, thus the displacement d (Figure 92) points in the direction shown as this is the expected direction of movement.

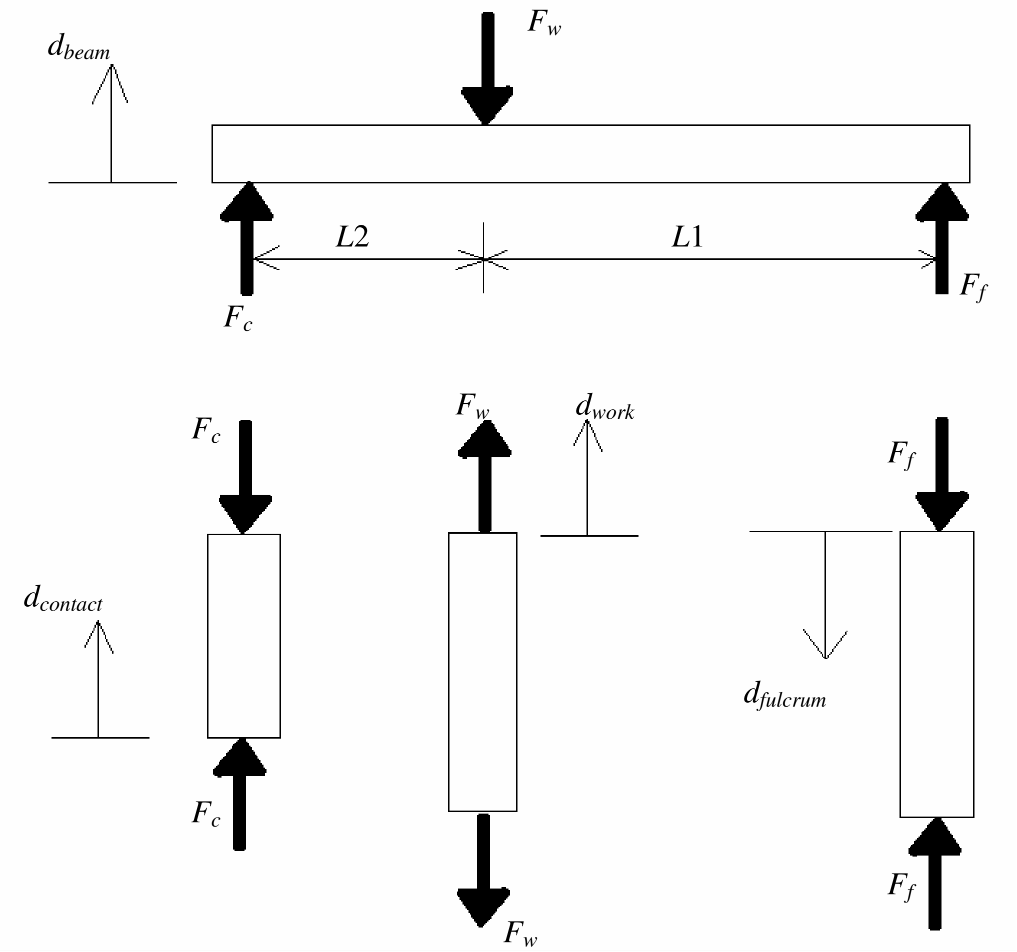


Figure 93: Boundary conditions for the unit stiffness analysis

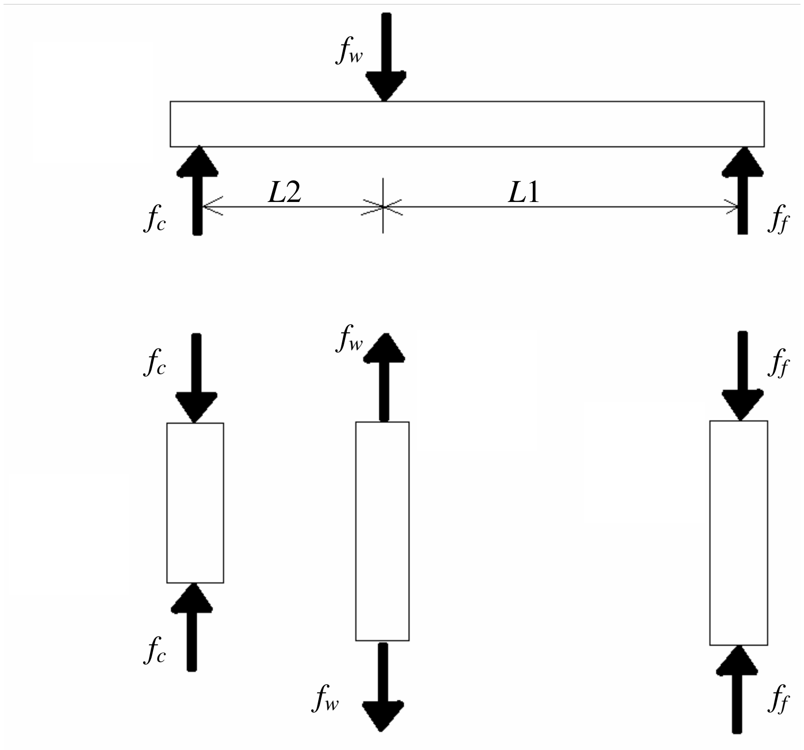


Figure 94: The virtual force system

The equations of equilibrium are applied to the strap beam to obtain solutions for the force. Initially this is done for the real force system.

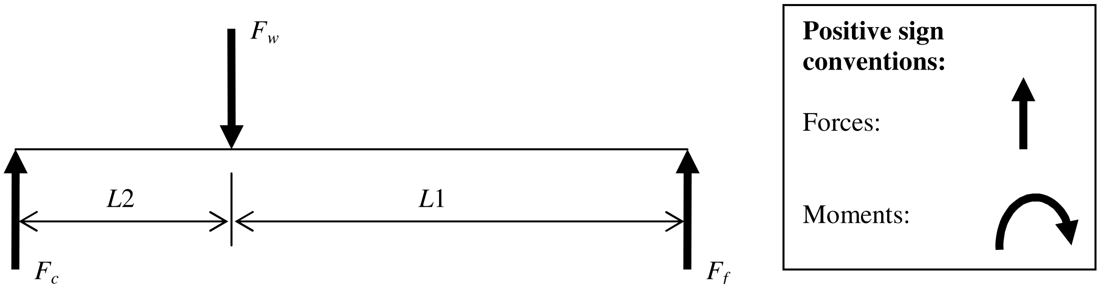


Figure 95: Obtaining the internal forces for the real system

Equilibrium conditions (positive sign conventions as denoted in Figure 95):

1. Σ (Moments about F_w) = 0

   $(F_c * L2) - (F_f * L1) = 0$

   $$F_f = F_c * L2 / L1 \qquad (5)$$

2. Σ (Forces acting in vertical direction) = 0

   $F_c + F_f - F_w = 0$

   $$F_w = F_c + F_f \qquad (6)$$

F_c is the known force (it is calculated when generating the second FR set, FR_2, earlier on in the design process) thus the forces F_f and F_w can be calculated from equations 5 and 6. The process is then repeated for the virtual force system:

Equilibrium conditions:

1. Σ (Moments about f_w) = 0

   $(f_c * L2) - (f_f * L1) = 0$

   $f_f = f_c * L2 / L1$

2. Σ (Forces acting in vertical direction) = 0

   $f_c + f_f - f_w = 0$

   $f_w = f_c + f_f$

The displacement for each element in the DP can now be calculated. To perform the integration required in equation 3, the beam must be split into segments across which there is continuity of loading. To calculate d_{beam}, the beam is split into two segments elem1 and elem2.

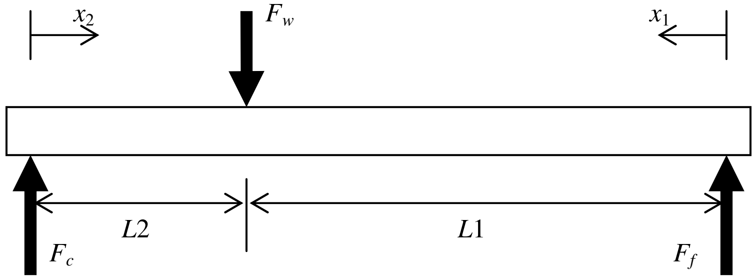
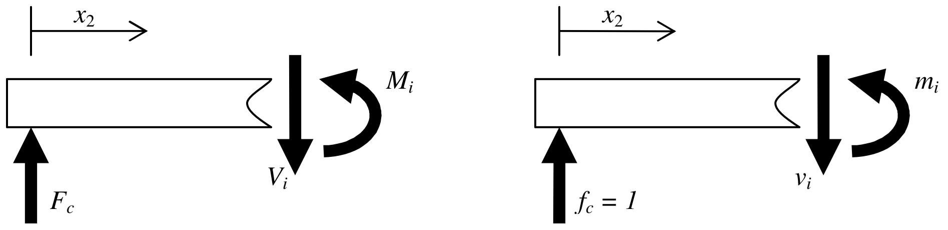


Figure 96: Splitting up the beam

Each of these segments can contain any number of elements. Recalling Figure 92 elem2 has two elements in it whilst elem1 has one. For each element within a segment, the internal forces and moments caused by the external forces need to be calculated. Again these are calculated using the equilibrium equations for both the real and virtual system of forces. In each case solutions are the internal real or virtual shear forces (*V* and *v* respectively) and the internal real or virtual moments (*M* and *m* respectively). Figure 97 presents the solutions for any element *i* in elem2, and Figure 98 contains the same for any element *j* within elem1.



Real force system:

Applying equilibrium yields:

$V_i = F_c$
$M_i = V_i * x_2$

Virtual force system:

Applying equilibrium yields:

$v_i = f_c = 1\ lb$
$m_i = v_i * x_2$

Figure 97: Equilibrium solutions for elem2

Real force system: **Virtual force system:**

Applying equilibrium yields:

$V_j = -F_f$

$M_j = -V_j * x_1$

Applying equilibrium yields:

$v_j = -f_f$

$m_j = -v_j * x_1$

Figure 98: Equilibrium solutions for elem1

Now equation 3 can be applied, but the beam is not subjected to an axial loading thus the displacement equation simplifies to:

$$1.d_{beam} = \underbrace{\sum_{i=1}^{n}\int_{start\_i}^{end\_i}\frac{m_i M_i}{E_i I_i}dx_2 + \sum_{j=1}^{p}\int_{start\_i}^{end\_i}\frac{m_j M_j}{E_j I_j}dx_1}_{\text{Bending component of displacement}} + \underbrace{\sum_{i=1}^{n}\frac{f_s v_i V_i L_i}{G_i A_i} + \sum_{j=1}^{p}\frac{f_s v_j V_j L_j}{G_j A_j}}_{\text{Shear component of displacement}}$$

where:

end_i and *end_j* are the end positions of the element *i* or *j* along axis x_2 or x_1 respectively;
start_i and *start_j* are the start positions of the element *i* or *j* along axis x_2 or x_1 respectively;
L_i and L_j are the lengths of the element *i* or *j* respectively;
n and *p* are the number of elements in elem1 and elem2 respectively.

Equation 3 can now be applied to the remaining limbs allowing their respective displacements to be determined. Thus for the fulcrum, work, and contact limbs containing *a, b,* and *c* elements respectively then:

$$1 * d_{contact} = \sum_{i=1}^{c} \frac{f_c F_c L_i}{A_i E_i}$$

$$1 * d_{work} = \sum_{i=1}^{b} \frac{f_w F_w L_i}{A_i E_i}$$

$$1 * d_{fulcrum} = \sum_{i=1}^{a} \frac{f_f F_f L_i}{A_i E_i}$$

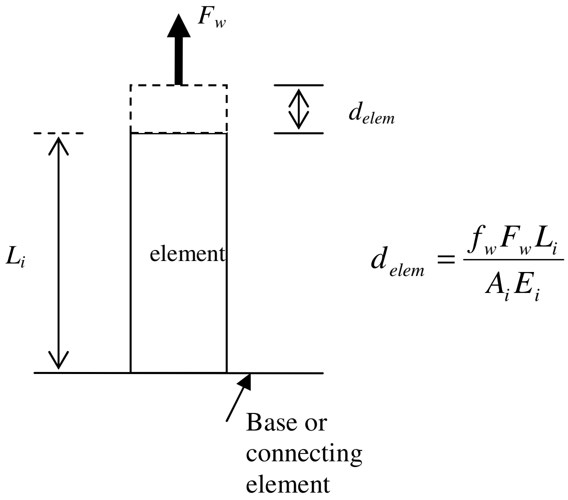


Figure 99: Calculating d_{work} for element i

4.3.3.2.1.3 Controlling an Adaptation Strategy

The modification module makes changes to a design which is subsequently tested by the testing module. The control module then evaluates the design using the testing results and decides what should happen next. Specifically, the control module for a stiffness adaptation strategy will make one of three decisions:

1. If the modified DP satisfies the functional requirement for which it is in intended, then the DP is passed to the DP/adaptation strategy evaluator (detailed in section 4.3.3.2.2).
2. If the modified DP does not satisfy the functional requirement but the control module still feels that a working solution can be achieved, then the DP is returned to the modification module with suggestions for an appropriate alteration.
3. If the modified DP does not satisfy the functional requirement and the control module feels that a working solution cannot be achieved with this adaptation strategy, then the adaptation strategy is abandoned and the design process moves on to consider the next possible adaptation strategy.

Two control modules will be discussed – the *dimension_control( )* and the *material_control( )* modules. The *dimension_control( )* module controls the execution of the *alter-thickness( )* and *alter_width( )* modification modules, while *material_control( )* drives the *alter_material( )* module.

Figure 100 presents the execution path of a *dimension_control( )* module. One of the first tasks the module performs is to compare the displacement of the DP (*calc_disp* is obtained from implementing a call to the testing module) to that required in the FR (*des_disp*). A satisfactory design is obtained when the difference between the calculated and design displacement is less than a pre-specified computational accuracy (*des_accuracy*). If the calculated displacement is greater than the design displacement then the unit needs to have its dimensions increased to afford an enlargement in unit stiffness. An initial basic dimension change (*dim_change*) is applied to the DP and tested, and the control module modifies the value of *dim_change* until *calc_disp* and *des_disp* are in agreement.

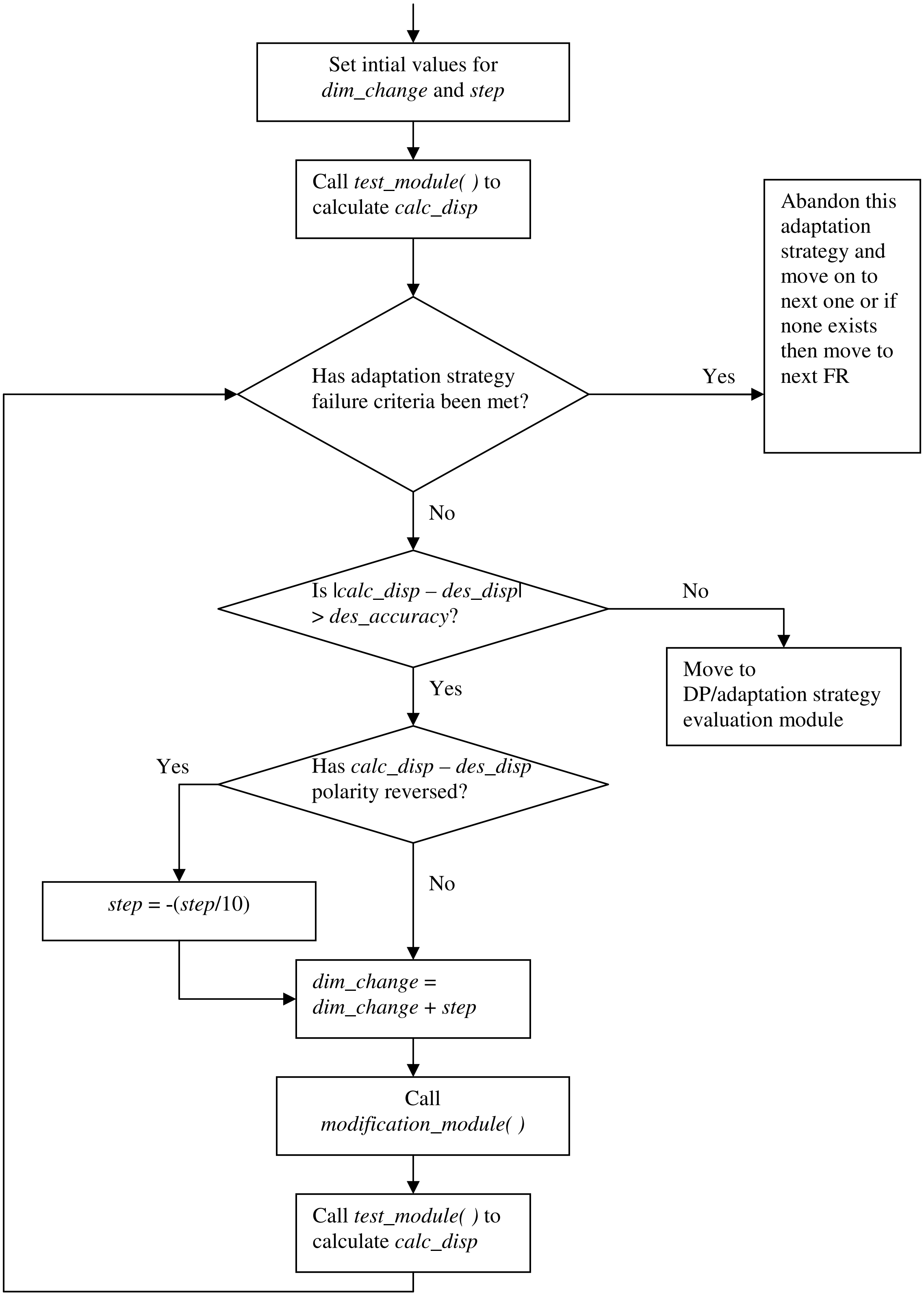


Figure 100: Flow diagram of *dimension_control( )* module

dim_change is altered by a value *step* each time the control loop executes. The *step* value is gradually refined each time there is a crossover in the polarity of (*calc_disp* – *des_disp*). Consider that the loop is in operation and a changeover has occurred on the 10th execution of the loop, as illustrated in Table 14. At the beginning of the ninth loop, the dimension change is 1.8 with a step of 0.1. The testing module has returned a value for *calc_disp* which is greater than *des_disp*. Thus the dimension has to be increased again to increase the stiffness so the new value for *dim_change* is:

$$dim\_change' = dim\_change + step = 1.8 + 0.1 = 1.9$$

At the end of ninth loop the dimension change is 1.9 inches, with a step increment of 0.1 inches. This dimension change is passed to the modification module, implemented, and subsequently tested. During loop ten, the control module evaluates the results of this testing and deduces that the modified unit is now stronger than necessary because *calc_disp* is less than *des_disp*. (*calc_disp* – *des_disp*) has gone from having a positive to a negative polarity and the solution for the dimension change lies somewhere between 1.8 and 1.9. The value of *step* is refined by dividing it by 10 and reversing its polarity. At the end of loop 10 *dim_change* has a value of 1.89 and the new value of *step* is -0.01 inches. This design is tested and the process repeated until a value of *dim_change* is ascertained that results in agreement in the values of *calc_disp* and *des_disp* within the desired computational accuracy. When this occurs, the control module sends the DP to the DP/adaptation strategy evaluation module for further analysis in terms of the DP's performance with respect to the design preferences.

Loop cycle no.	dim_change	step	Polarity of calc_disp – des_disp
8	1.8	0.1	+
9	1.9	0.1	-
10	1.89	-0.01	-
11	1.88	-0.01	-

Table 14: Refining the dimension change

The control module also monitors progress of the solution to determine if any of the criteria for abandoning an adaptation strategy have been met. These criteria define when an adaptation strategy is likely to fail. Two criteria are used, one of which is related to the polarity reversal of (*calc_disp – des_disp*). The second concerns the effect design modifications have on the performance level of the DP.

With regard to monitoring the polarity reversal of (*calc_disp – des_disp*), failure by this criterion can be identified reasonably early on in the control loop execution. If the loop continues to execute without a polarity reversal occurring, then the adaptation strategy is aborted. An example of where an adaptation strategy might fail is the *width_modification( )* module for a vertical clamp. Increasing the width dimensions of the elements can result in collision between the work, contact, and fulcrum elements (this issue was discussed in section 4.3.3.2.1.2) for which the solution is to increase the length of the strap beam until there are no collisions. However, although increasing the dimensions of the elements increases the unit stiffness, lengthening the beam decreases the stiffness of the strap, particularly with regard to the displacement induced by bending.

The net effect therefore will be a reduction in the effectiveness of the width alteration, although it may still be a positive effect. The control module however will determine that after a number of attempts at modification without a polarity reversal, the adaptation is not worth pursuing. If this effect however is more detrimental than the positive effect induced by the width increase, then the solution strategy is doomed to failure and if left to run, the loop would execute for infinity. To counteract this possibility, the control module applies the second criterion that checks to see if the strategy is resulting in an improved stiffness. If it finds however that increasing the width is consistently resulting in a decrease in stiffness of the unit, then the strategy is aborted as failed and the next strategy implemented and evaluated.

The *material_control( )* module (Figure 101) is much simpler. The modification module simply cycles through each of the materials that are held in the domain knowledge base, implementing each one. The testing module calculates the displacement of the DP and the control module determines if the behaviour of the DP is acceptable or not. If the FR is satisfied then the control module passes the DP onto the DP/adaptation strategy evaluation module for further consideration. If the FR is not satisfied then the next material is tried.

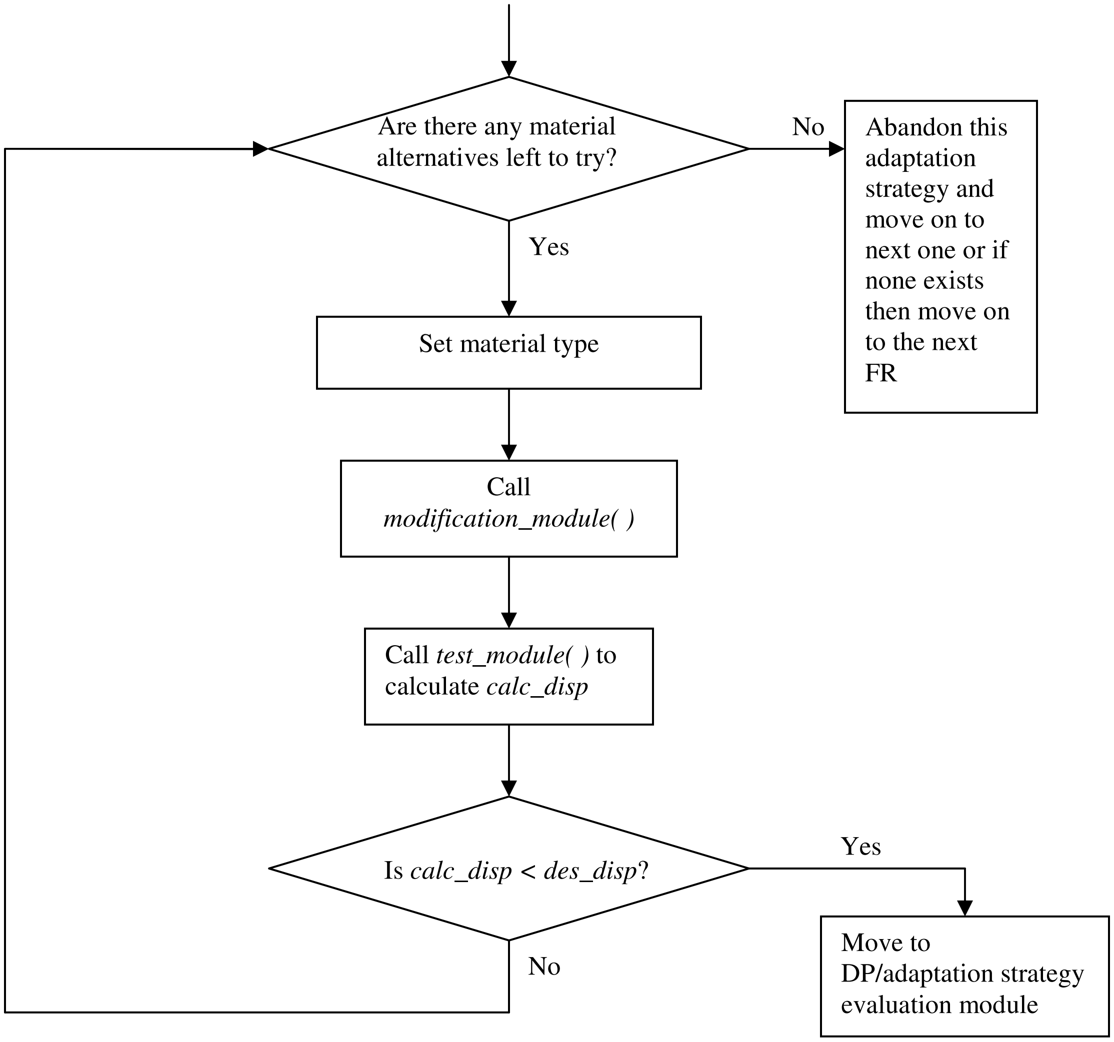


Figure 101: The *material_control( )* module

4.3.3.2.2 Evaluating Different DP/Adaptation Strategy Combinations

Once an adaptation strategy has been successfully implemented then the DP is further evaluated by considering how well it contributes to the overall fixture design's ability to satisfy the design preferences recorded by the user in the utility curves. These utility curves express preferences for the global constraint attribute values of the design, to each of which the DP may or may not make a contribution. A set of functions are invoked to determine the individual contributions that a DP will make.

These functions are essentially heuristic in nature. In particular, functions exist to determine the cost, weight, and loading, assembly, unloading, and disassembly times of the fixture units. For example the cost of a locating unit is dependent upon the unit material type, the volume of material used in the unit, the accuracy required of the unit, and the connections used within the unit:

Locating unit cost ($) = f(material type, volume, locating accuracy, connection type, number of connections)
*= volume * material cost per unit volume + cost of connection type * number of connections + cost of accuracy*

This function is applied to each element of the unit and the cost of each element summed to determine the cost for the complete unit. Costs of different materials and connections are widely accessible in available literature (Callister, 2000). For the purposes of the CAFixD method, accuracy costs are determined from assumed relationships such as that presented in Figure 102.

The function that calculates the assembly time of a particular unit is dependent upon the number and type of connections between elements. Similar to the cost function, assembly time is calculated for each individual element and then summed to obtain the time for the entire unit. Different types of connections include:

- Dowel pin connections;
- Threaded bolt connections;
- Snap fit connections;
- Alignment only connections;

- Rivet connections;
- Insert connections;
- Nut and bolt threaded connections.

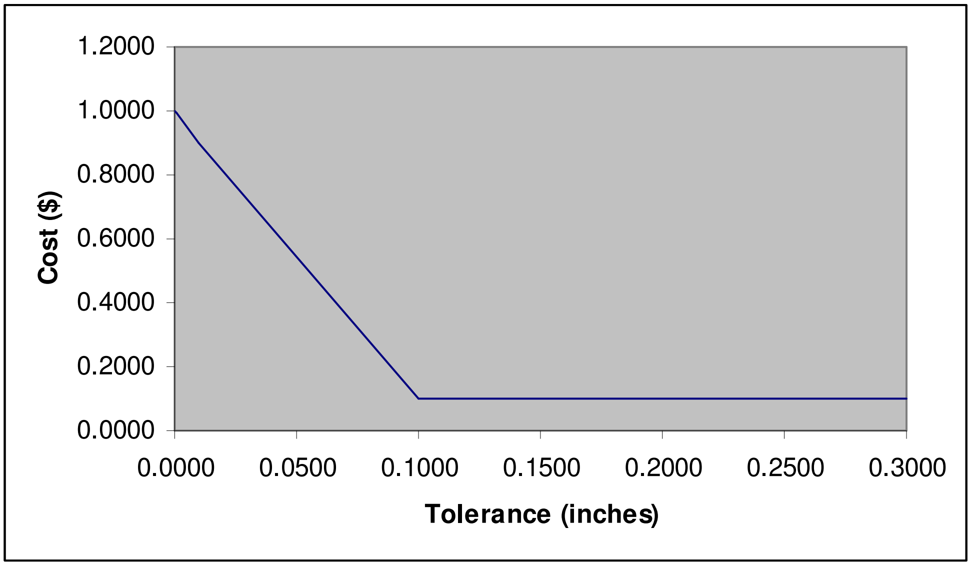


Figure 102: An assumed accuracy cost function

Whenever an element is physically assembled into a unit, there are a number of operations that need to be performed. These can include:

- retrieval operations in which an element and possibly tools for assembling the element need to physically retrieved;
- orientation operations in which elements and/or tools need to be correctly oriented;
- alignment operations in which elements and/or tools need to be correctly aligned;
- insertion operations in which elements and/or tools are inserted into other elements/tools;
- screw operations when two elements are joined by screwing them together or screwing a third element such as a nut to join them together;
- push operations in which elements are joined by some form of interference fit;

- rivet operations in which two elements are riveted together.

The CAFixD method has a database of standard times for executing any of the above operations. Each of the connection types will involve a different number of these operations, and the assembly time associated with a particular type of connection cost is dependent upon the type and number of these operations. For example a bolt connection will involve the following operations:

- 3 retrieval operations – the element, bolt, and wrench for tightening the bolt must all be retrieved;
- 3 orientation operations – the element, bolt, and wrench must all be orientated properly;
- 3 alignment operations – the element must be aligned to its mating element, the bolt must be aligned to the mating hole in the element, and the wrench must be aligned with the bolt;
- 2 insertion operations – the bolt must be inserted into the element mating hole and the wrench must mate with the bolt head;
- 1 screw operation – the bolt must be tightened.

Thus the assembly time for a screw connection, $t_{assembly}$ is:

$$t_{assembly} = 3 * t_{retrieval} + 3 * t_{orientation} + 3 * t_{alignment} + 2 * t_{insertion} + 1 * t_{screw}$$

where $t_{operation}$ represents the time recorded in the database for the particular operation named. Similar approaches are adopted for the remaining functions that determine loading, disassembly, and unloading times.

Once the performance values for each of the constraint attributes have been determined for a single DP, the DP and these performance values are added to the initial design set up at the start of the adaptability-based retrieval process (after the original DP used for the current FR in this design and its associated performance values have been removed).

These updated attribute performance values for the complete design can then be compared to the design preferences. The utility values for each of the attributes (U_{cost}, U_{weight}, $U_{assembly}$, etc.) can be obtained from the utility curves and combined to generate the overall utility *U(X)* for the complete fixture design containing this DP/adaptation strategy combination. *U(X)* is obtained using the following multiplicative:

$$U(X) = \frac{1}{K}\left[\left[\prod_{i=1}^{n}\left(Kk_iU_i\left(x_i\right)+1\right)\right]-1\right]$$

U(X) = overall utility of the complete set of performance objectives *X*;
x_i = performance level of each attribute *i*;
X = set of attributes (x_1, x_2,….,x_n);
k_i = assessed single attribute scaling constant,
$U_i(x_i)$ = assessed single attribute utility value
i = 1,2,….,*n* attributes;
K = overall scaling constant.
K is obtained by normalizing *U(X)* in the standard way:

$$1+K=\prod_{i=1}^{n}\left(1+Kk_i\right)$$

The *U(X)* values for all possible DP/adaptation strategy that can be used to satisfy a FR or group of FRs can be computed and the “adaptation mapping layout” representation of the CAFixD retrieval method can be updated as illustrated in Figure 103 by listing the *U(X)* values for each DP/adaptation strategy. The combination that returns the highest *U(X)* is chosen as the final DP solution. In the example presented in Figure 103 $\text{PV}_{2.7.1a}$ returns the highest *U(X)* value and would be chosen as the final solution.

This adaptation mapping layout can therefore act as a record of design rationale. It outlines the various possible courses of action, and the reasons for choosing one over another have been recorded in terms of the utility value *U(X)* associated with each major design decision.

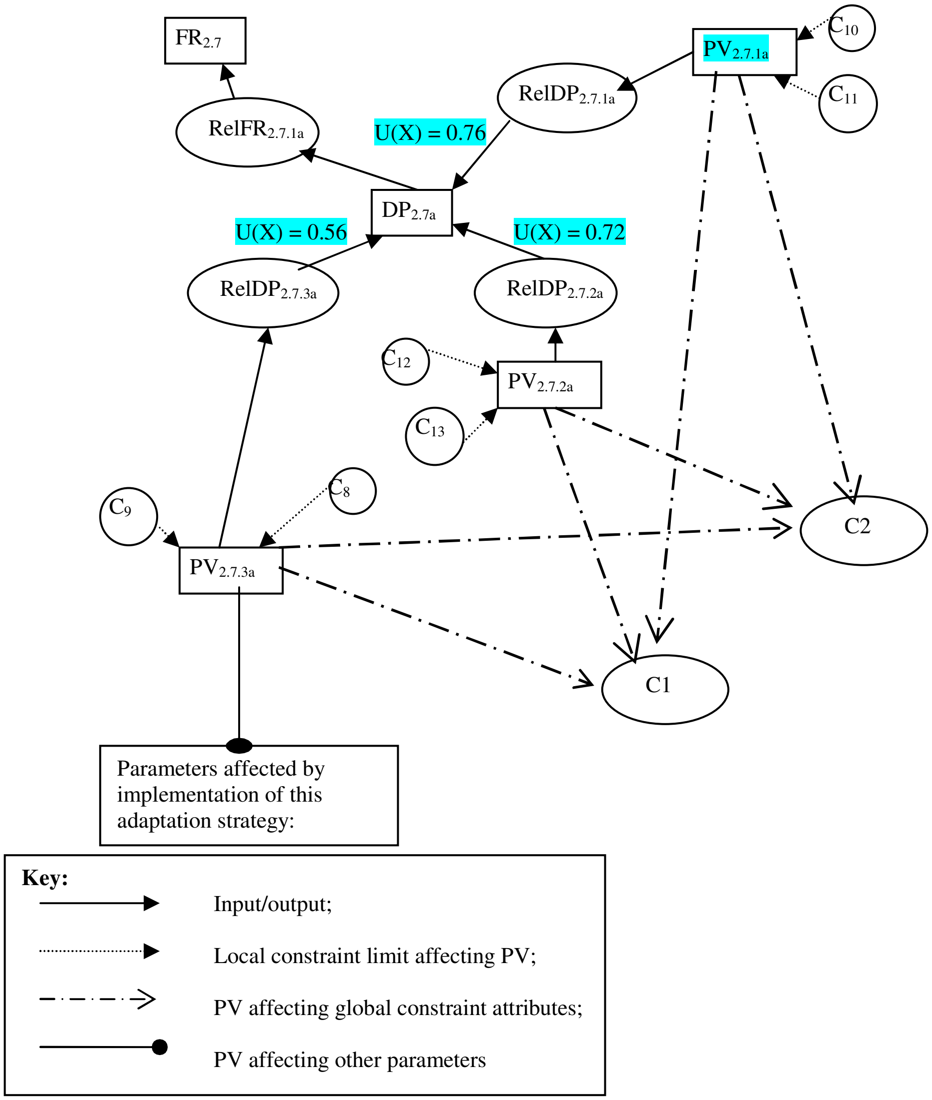


Figure 103: Updating the adaptation mapping layout to include U(X)

The CAFixD method requires that no more than six global constraint attributes be considered and the utility analysis can proceed without any special alterations to the standard execution of the technique. However in a more general design situation there may be a need to consider a higher number of attributes. The literature review noted that high numbers of attributes resulted in the utility always tending to 1. To counteract this effect, a simple grouping strategy is proposed for discussion. The procedure is:

1. define utility curves and scaling constants for each attribute as per the standard procedure outlined in section 4.3.2.1;
2. split the attributes randomly into j groups such that each group has an even number of attributes in it (where each group should have a maximum of six attributes);
3. For each group calculate the normalizing constant K using the scaling constants from that group only to obtain a number of K values $K_1, K_2, \ldots\ldots K_j$;
4. Calculate the utility for each group $U_1(x_1), U_2(x_2), \ldots\ldots\ldots\ldots U_j(x_j)$;
5. To each of these groups apply the same scaling constant value $k_{standard}$;
6. If more than six groups exist then repeat steps 2 to 5;
7. If less than six groups exist then calculate $K_{standard}$ using $k_{standard}$ and calculate $U(X)$.

Table 15 illustrates two designs that are almost identical with the exception of their performance with respect to attribute three (design one has a utility of 0.65 whereas design two has a utility of 0.55) return the same overall utility $U(X)$ for the design of 0.99994. If however the grouping approach is adopted as demonstrated in Table 16 and the attributes are split up into four groups of four, then the results become clearer,. Design one returns a higher $U(X)$ of 0.9727 whereas design two returns a value of 0.9719. This is the expected result since design one has the higher utility for attribute three. The obvious limitation to the technique is that it is invalid for situations where attributes cannot be gathered into groups that are the same size. Also, it should be noted that although the utility tends to one, it will rarely get there but the comparison between $U(X)$ values would have to be performed between numbers that are almost identical. The proposed method merely makes the comparison simpler by virtue of the fact that there is no need to go to significant numbers of decimal places when comparing different $U(X)$ values.

Design 1

Attribute *i*	k	$U_i(x_i)$
1	0.7	0.75
2	0.4	0.78
3	0.6	0.65
4	0.45	0.7
5	0.3	0.65
6	0.9	0.97
7	0.5	0.6
8	0.7	0.5
9	0.35	0.6
10	0.65	0.75
11	0.5	0.8
12	0.8	0.9
13	0.5	0.9
14	0.8	0.7
15	0.3	0.3
16	0.6	0.7

K = -1.
$U(X)$ = 0.99994

Design 2

Attribute *i*	k	$U_i(x_i)$
1	0.7	0.75
2	0.4	0.78
3	0.6	0.55
4	0.45	0.7
5	0.3	0.65
6	0.9	0.97
7	0.5	0.6
8	0.7	0.5
9	0.35	0.6
10	0.65	0.75
11	0.5	0.8
12	0.8	0.9
13	0.5	0.9
14	0.8	0.7
15	0.3	0.3
16	0.6	0.7

K = -1.
$U(X)$ = 0.99994

Table 15: Results using standard utility analysis for high numbers of attributes

Attribute *i*	k	$U_i(x_i)$	K_{G1}	$U_{G1}(x_{G1})$	$k_{standard}$
1	0.7	0.75	-0.94849	0.874777	0.5
2	0.4	0.78			
3	0.6	0.65			
4	0.45	0.7			
5	0.3	0.65	-0.98781	0.960548	0.5
6	0.9	0.97			
7	0.5	0.6			
8	0.7	0.5			
9	0.35	0.6	-0.97228	0.949591	0.5
10	0.65	0.75			
11	0.5	0.8			
12	0.8	0.9			
13	0.5	0.9	-0.96462	0.890139	0.5
14	0.8	0.7			
15	0.3	0.3			
16	0.6	0.7			

K = -0.91262
$U(X)$ = 0.9727

Table 16: Employing the grouping method for design 1

4.4 Review

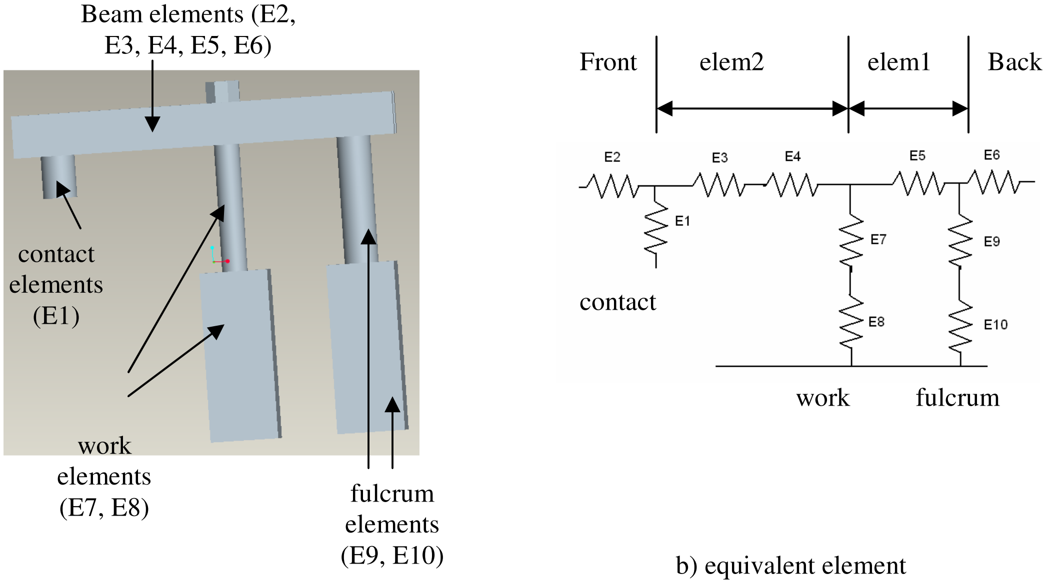
This chapter has sought to detail the CAFixD method and the manner in which it navigates towards a solution. Much of the focus within the CAFixD method concerns the indexing and retrieval of design cases. The use of axiomatic design principles assists the indexing of design cases by function and this is reflected in the hierarchies which exist in the second case library. The retrieval process is strongly linked to a deep understanding of the manner in which a physical structure behaves: i.e., how the physical characteristics of the structure allow it to perform its functions. Basing the retrieval mechanism upon structure behaviour adds a certain flexibility to the method in that there are various means by which a design can be repaired. If one strategy fails then another can be tried, and this ability to implement alternative methods of repairing cases can afford a greater probability of returning a satisfactory solution.

Chapter 5 – Worked Examples

Chapter 4 detailed the CAFixD method. This chapter presents two examples, the first of which illustrates how a design case is stored in case library 2. The second presents an example of the operation of the CAFixD method, in which a fixture design is generated for a given workpiece.

5.1 Indexing Example

Design case 2 consists of a series of types of fixture units, such as the clamping unit presented in Figure 104a. The unit is a third order vertical clamping unit, where the work force is applied by a threaded bolt upon the strap clamp. It provides a stiffness of 17765 lb/in of and a clamping force of 35lb. The unit itself is composed of 6 components but is described as being composed of 10 elements to aid any stiffness analysis it may be subject to. The strap beam is the component that has been split into 5 artificial elements, as illustrated in the element representation presented in Figure 104b. The completed schema for the unit is presented in Table 17 and the completed element schema for element 4 is presented in Table 18. Appendix B presents the full case schema and drawings for the clamping unit. It is worthwhile noting that the system implementation of the CAFixD methd only supports the units listed in the schema tables.



a) clamping unit

b) equivalent element representation

Figure 104: A vertical clamping unit

Clamping unit attribute	Value	Comment
Class type	VC0132	Class type within case library 2
Unit ID	VC0132C1	Identifying name for unit
Stiffness FR performance	17765 lb/in	Unit stiffness
Clamping force FR performance	35 lb	Unit clamping force
Acting height	3 inches	Contact point with workpiece is 3 inches from the base of the unit
Chip shedding ability	No	Does the unit have a chip shedding ability?
Unit cost	$ 1.825566	-
Unit weight	1.199557 lb	-
Loading time associated with unit	0.583333 mins	-
Unit assembly time	4.816667 mins	-
Unloading time associated with unit	0.45 mins	-
Force actuation	TO1A	Threaded bolt force actuation
Total no. of elements	10	Total number of elements within the unit
No. of fulcrum elements	2	Number of elements in the fulcrum limb
No. or work elements	2	Number of elements in the work limb
No.of length BeamE1 elements	1	Number of elements in beam_elem1
No.of length BeamE2 elements	2	Number of elements in beam_elem2
Length of L1	1.5 inches	
Length of L2	2 inches	
(Work) L2 beam element	4	Beam element to which work limb connects
(Fulcrum) L1 beam element	5	Beam element to which fulcrum limb connects
C beam element	2	Beam element to which contact limb connects
Work limb max thickness	0.8 inches	Maximum thickness in the work limb
Fulcrum limb maximum thickness	0.8 inches	Maximum thickness in the fulcrum limb
Contact limb max thickness	0.4 inches	Maximum thickness in the contact limb
Work element	7	Work element that contacts strap beam
Fulcrum element	9	Fulcrum element that contacts strap beam
Contact element	1	Contact element that contacts strap beam

Table 17: The completed schema for the clamping unit

Element attribute	Value	Comment
Element #	4	Element number
Limb Element No.	2	Position along limb
Structure type	Block	Cross section
Element type	beam_elem2	Limb element is situated in
Dist from end	1.5 inches	Distance element is from the end of beam_elem2
Length	0.5 inches	Element length
Start CS b or radius	0.5 inches	Element thickness at start of element
End CS b or radius	0.5 inches	Element thickness at end of element
Start CS h or radius	0.6 inches	Element width at start of element
End CS h or radius	0.6 inches	Element width at endof element
Material mod	StSteel304	Material type
Height adjust	No	Is the element subject to a height adjustment?
Slot consideration	Yes	Is there a slot in the element?
Slot width	0.3 inches	Width of slot
Available slot length	0.5 inches	Length of slot
Connection to next element	None	Not a real component so the connection type is none (connection details are not applicable to this element)
No. of connections	0	Not applicable to this element
Offset distance	0	Not applicable to this element
Mated from	3	Mates from element 3
Mated to	5	Mates to element 5
Connection diameter	0	Not applicable to this element

Table 18: Completed element schema for element 4

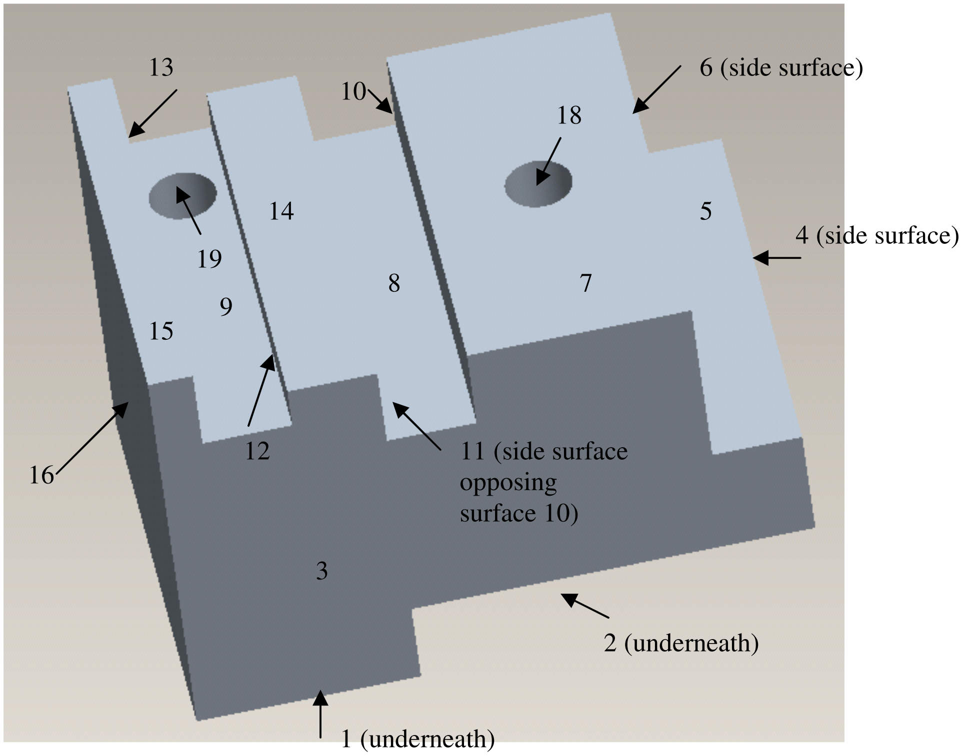
5.2 Operation Example

The operation of the CAFixD method will be demonstrated through the use of a worked example in which a fixture will be developed for the workpiece presented in Figure 105. It is a simple workpiece composed of planar surfaces and two holes. Features to be machined are surfaces 7, 8, and 9 in addition to holes 18 and 19. The CAD model contains all information related to workpiece's geometry, as well as information defining features (machined surfaces), their tolerances, and non-machined surfaces. Appendix C provides the complete geometric information for the workpiece. The machining table (Table 19) contains all the information required to machine the workpiece including for example the machining forces, the type of machine tool used, and the direction of tool movement.

5.2.1 Determining the Locating Model

The first stage in the solution process is to analyse the datum information to determine the locating directions. The datums specified in the tolerances are surfaces 2, 3, and 16. The DMSRG for the workpiece is presented in Figure 106. From the summary of the datum information detailed in Table 20, there are three candidate locating directions. These are checked to determine if they are all mutually perpendicular to each other and after confirmation of this the next step is to identify the primary, secondary, and tertiary locating directions. Also as all features use these surfaces as their datums, then there is no need for an extra setup. Thus only one fixture is sought for this workpiece.

The primary locating direction is normally governed by the type of machining operations to be performed and the machine type. To perform the end milling, drilling, and face machining of the workpiece features using a vertical mill the workpiece must be positioned such that the normal of the machined features 7, 8, 9, 18, and 19 are coincident with the spindle axis of the machine tool. Thus the primary locating directions must act in the opposite direction to these normals. The orientation of the normals of each of these features is held in the CAD workpiece model and are summarised in Table 21.



Machined features are 7, 8, 9, 18, and 19.

The tolerances for each feature are:

Feature 7:

∥	0.1	2

Feature 8:

∥	0.11	2

Feature 9:

∥	0.11	2

Feature 18:

⌖	0.1	2	3	16
⊥	0.06	2		

Feature 19:

⌖	0.1	2	3	16
⊥	0.06	2		

Figure 105: The workpiece and design tolerances

Machine type	**Tool accuracy**					
	Along x axis (inches)	Along y axis (inches)	Along z axis (inches)	Around x axis (rad)	Around y axis (rad)	Around z axis (rad)
Vertical mill	0.00002	0.00002	0.00002	8.75E-5	8.75E-5	8.75E-5

					Initial Direction of tool motion		
Feature ID	**Operation type**	**Toolpath**	**Tangential force (lb)**	**Thrust force (lb)**	**x**	**y**	**z**
7	FACE	SPIRAL	23	354	0	0	-1
8	ENDMILL	BACKFORTH	50	150	0	0	-1
9	ENDMILL	BACKFORTH	50	150	0	0	-1
18	DRILL	INOUT	50	200	0	-1	0
19	DRILL	INOUT	50	200	0	-1	0

Table 19: The machining information

Datum surface	Datum orientation	Features with this datum	Number of times datum referenced
2	0,1,0	7, 8, 9, 18, 19	5
3	0,0,1	18,19	2
16	1,0,0	18,19	2

Table 20: Tabular format of DMSRG

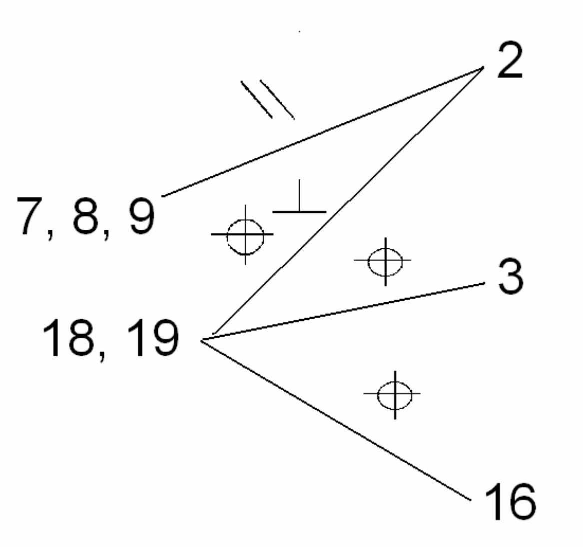


Figure 106: The DMSRG for the workpiece

Feature	Feature type	Orientation of normal
7	Plane	0,-1,0
8	Plane	0,-1,0
9	Plane	0,-1,0
18	Hole	0,-1,0
19	Hole	0,-1,0

Table 21: Orientation of normals for each machined feature

All features have a normal orientation of (0,-1,0) thus the primary locating direction should be the opposite of this orientation (0,1,0) and from Table 20 the only datum having this orientation is surface 2. Of the two remaining datum directions in Table 20, no decision is made concerning which should provide the direction of secondary and tertiary locating should act in. Thus Table 20 can be updated as highlighted in Table 22 by assigning known locating directions.

Datum surface	Datum orientation	Features with this datum	Number of times datum referenced	Locating direction
2	0,1,0	7, 8, 9, 18, 19	5	Primary
3	0,0,1	18,19	2	Secondary or tertiary
16	1,0,0	18,19	2	Secondary or tertiary

Table 22: Refining the selection of primary, secondary, and tertiary locating directions

The next step is to identify the locating faces and coordinates of locating points. The objective of this part of the design process is to maximise the area of location provided by the fixture. For each orientation, workpiece surfaces exhibiting this orientation are grouped together and evaluated for possible use as locating surfaces. Consider primary locating, where two workpiece surfaces (1 and 2) have the correct orientation. Both surfaces are plane surfaces, and thus for primary locating three locating points need to be used to constrain the required three degrees of freedom. Locating point $P1$ must constrain linear movement along the y axis, $P2$ constrain rotation around the x axis, and $P3$

constrain rotation around the *z* axis. A general rule adopted in the CAFixD method is that at least one locating point must always act on the datum surface, thus the decisions that have to be made are:

1. Should surface 1 also be used for locating?
2. If so, then how should the locating points be distributed between surfaces 1 and 2?

The first question is answered by considering where to place *P*3. *P*3 should constrain rotation around the z axis, and following the general rule of maximising location area, the objective is to maximise the distance between *P*1 and *P*3 along the *x* axis. The locator *P*3 can be placed at either position *P*3' or *P*3'' (Figure 107). Using *P*3'' provides a greater distance as length *l_P*3" is larger than *l_P*3', so surface 1 should be used as the surface on which *P*3 acts. The second question is therefore should *P*2 also act on surface 1?

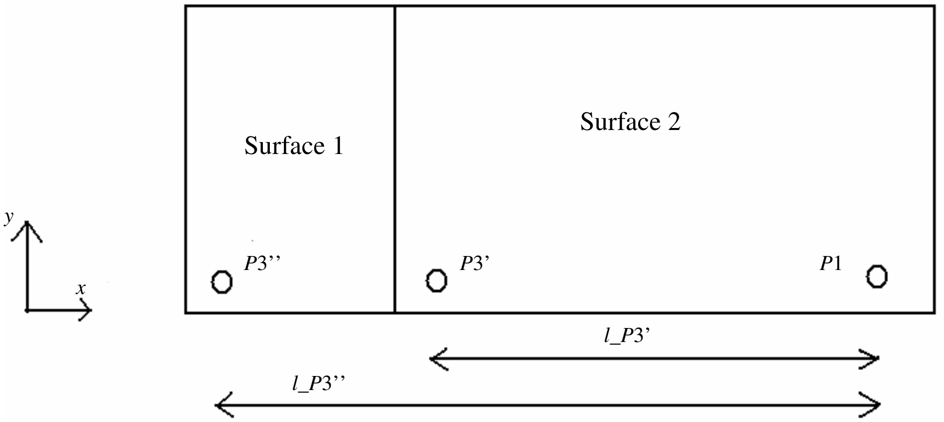


Figure 107: Evaluating the use of surface 1 for locating point P3

As surfaces 1 and 2 both have the same length in the z direction, there is no obvious advantage to using one surface over the other. The approach adopted is to vary the placement of *P*2 along the *x* axis and *P*3 along the *z* axis to obtain the maximum locating area, as illustrated in Figure 108. Table 23 presents the calculated results for triangular area and the measure of equilateralism as *P*2 is varied whilst positions *P*1 and *P*2 are held constant. The highlighted entry represents the most desirable choice for *P*2, so *P*2 is situated on surface 2.

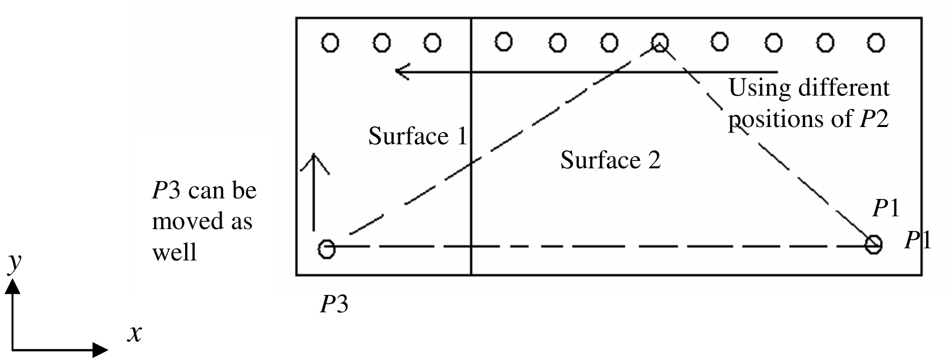


Figure 108: Maximising the locating area

*P*2 x	*P*2 z	Surface *P*2 exists on	Area	Measure of equilateralism
6.75	4.75	2	14.625	0.69457
6.306	4.75	2	14.625	0.718863
5.861	4.75	2	14.625	0.749036
5.417	4.75	2	14.625	0.785248
4.972	4.75	2	14.625	0.827534
4.528	4.75	2	14.625	0.845219
4.083	4.75	2	14.625	0.866349
3.639	4.75	2	14.625	0.893152
3.194	4.75	2	14.625	0.882449
2.75	4.75	2	14.625	0.857751
2.306	4.75	1	14.625	0.838787
1.861	4.75	1	14.625	0.810969
1.417	4.75	1	14.625	0.770956
0.972	4.75	1	14.625	0.73702
0.528	4.75	1	14.625	0.709077
0	4.75	1	14.625	0.683388

Table 23: Determining the optimum position for *P*2

A similar process is repeated to determine which direction should be used to provide secondary locating. Whichever orientation (and subsequent surfaces with this orientation) offers the greatest distance between locators (only two locators are used in secondary locating) is chosen as the secondary locating direction. Using this criterion surface 3 provides secondary locating and surface 16 tertiary. All surfaces used for locating are planar in nature, thus plane locating 3-2-1 variation 3 and its associated skeleton FR set can be retrieved from case library 1. Thus the setup and fixture planning stages are complete, resulting in the conceptual plan detailed in Figure 109 and Table 24. FRs 1.1.1 and 1.1.2 and their DPs can be updated with these details, as illustrated in Figure 110.

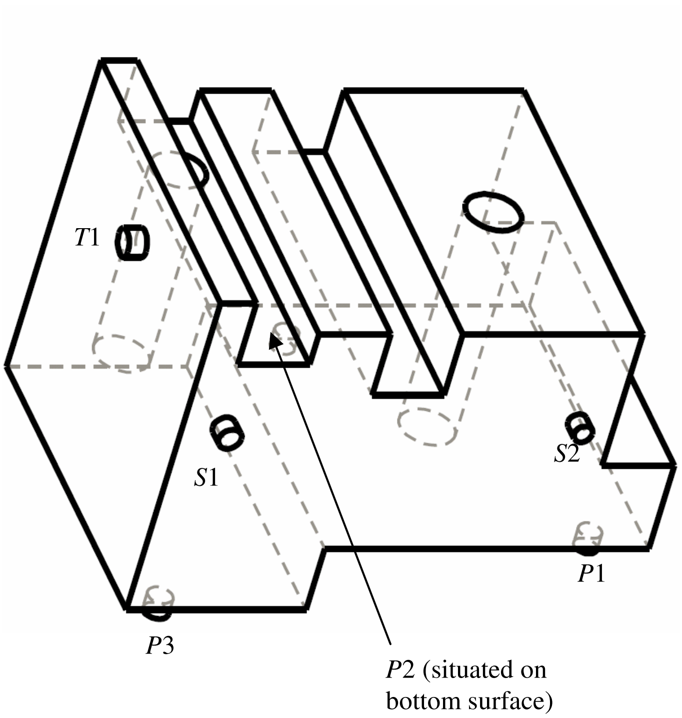


Figure 109: The locating point distribution of conceptual design

Relevant FRs	Locator	Surface	Coordinates
1.1.1.1 & 1.1.2.1	Primary (*P*1)	2	(6.75,1,0.25)
1.1.1.2 & 1.1.2.2	Tertiary (*T*1)	16	(0,2.5,2.5)
1.1.1.3 & 1.1.2.3	Secondary (*S*1)	3	(0.25,2.25,0)
1.1.1.4 & 1.1.2.4	Primary(*P*2)	2	(3.639,1,4.75)
1.1.1.5 & 1.1.2.5	Secondary (*S*2)	3	(5.75,2.25,0)
1.1.1.6 & 1.1.2.6	Primary (*P*3)	1	(0.25,0,0.25)

Table 24: The conceptual design details

FR_1 – Locate workpiece to required accuracy
  $FR_{1.1}$ – Locate the workpiece
    $FR_{1.1.1}$ – Control six degrees of freedom (6 FRs)
      $FR_{1.1.1.1}$ – Control DoF along the *y* axis
      $FR_{1.1.1.2}$ – Control DoF along the *x* axis
      $FR_{1.1.1.3}$ – Control DoF along the *z* axis
      $FR_{1.1.1.4}$ – Control DoF around the *x* axis
      $FR_{1.1.1.5}$ – Control DoF around the *y* axis
      $FR_{1.1.1.6}$ – Control DoF around the *z* axis

    $FR_{1.1.2}$ – Provide contact between locator and workpiece (6FRs)
      $FR_{1.1.2.1}$ – Contact workpiece with locator $P1$
      $FR_{1.1.2.2}$ – Contact workpiece with locator $T1$
      $FR_{1.1.2.3}$ – Contact workpiece with locator $S1$
      $FR_{1.1.2.4}$ – Contact workpiece with locator $P2$
      $FR_{1.1.2.5}$ – Contact workpiece with locator $S2$
      $FR_{1.1.2.6}$ – Contact workpiece with locator $P3$

DP_1 – Fixture locating arrangement
  $DP_{1.1}$ – 3-2-1 locating principle variation 3
    $DP_{1.1.1}$ – locator/workpiece interface surface (6DPs)
      $DP_{1.1.1.1}$ – Surface 2
      $DP_{1.1.1.2}$ – Surface 16
      $DP_{1.1.1.3}$ – Surface 3
      $DP_{1.1.1.4}$ – Surface 2
      $DP_{1.1.1.5}$ – Surface 3
      $DP_{1.1.1.6}$ – Surface 1

    $DP_{1.1.2}$ – workpiece/locator interface contact coordinates (6DPs)
      $DP_{1.1.1.1}$ – Coordinates (6.75,1, 0.25)
      $DP_{1.1.1.2}$ – Coordinates (0,2.5,2.5)
      $DP_{1.1.1.3}$ – Coordinates (0.25,2.25,0)
      $DP_{1.1.1.4}$ – Coordinates (3.639,1,4.75)
      $DP_{1.1.1.5}$ – Coordinates (5.75,2.25,0)
      $DP_{1.1.1.6}$ – Coordinates (0.25,0,0.25)

Figure 110: The updated skeleton FR set upon completion of setup and fixture planning

5.2.2 Completing the FR Skeleton

The solution process now proceeds to performing the sensitivity analysis, with the aim of determining which of the workpiece design tolerances should be used to guide the tolerance assignment stage. Each locator pair is examined and the effect of any rotation caused by that pair upon the position of the workpiece features calculated and compared to the design tolerance for that feature. This allows the calculation of the sensitivity of the feature to rotations caused by variations in the locating point pair.

Initially locating point pair $P1$ and $P2$ will be evaluated. Feature 7 (a rectangular planar surface) has a parallel tolerance of 0.1 inches. The rotation caused by the variation Tol_{P1} and Tol_{P2} will result in vertical shifts at either end of feature 7 causing the start and end coordinates of the feature to change from $S7Starty_{P1/P2}$ and $S7End_{P1/P2}$ to $S7Starty_{P1/P2}'$ and $S7Endy_{P1/P2}'$ respectively. A rotation of 2° is assumed for the rotation.

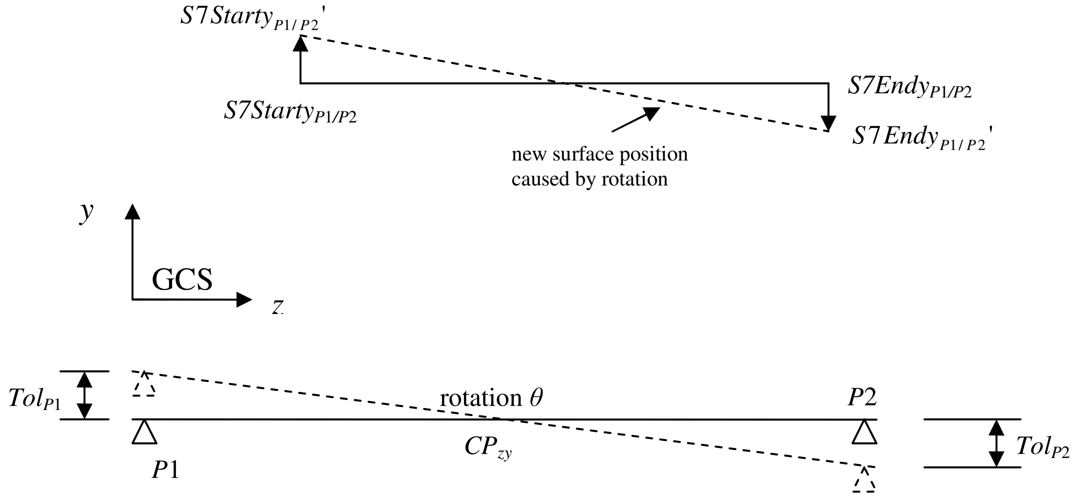


Figure 111: Analyzing the workpiece tolerances

The new positions can be calculated as follows:

$$S7Endy_{P1/P2}' = (S7Endz - CPx_{xy})\sin\theta + (S7Endy - CPy_{xy})\cos\theta$$
$$S7Starty_{P1/P2}' = (S7Startz - CPx_{xy})\sin\theta + (S7Starty - CPy_{xy})\cos\theta$$

where:

$S7Startz$ = original z coordinate of start of feature 7 = 0;

$S7Starty$ = original y coordinate of start of feature 7 = 4.5;

$S7Starty_{P1/P2}'$ = new y coordinate of start of feature 7 relative to center point CP_{zy};

CPz_{zy} = z coordinate of center point between locators P1 and P2 = (0.25 + 4.75)/2 = 2.5;

CPy_{zy} = y coordinate of center point between locators P1 and P2 = (1+1)/2 = 1;

θ = assumed angle of rotation = 2°;

$S7Endz$ = original z coordinate of end of feature 7 = 5;

$S7Endy$ = original y coordinate of end of feature 7 = 4.5;

$S7Endy_{P1/P2}'$ = new y coordinate of start of feature 7 relative to center point CP_{zy}.

The resultant shift in the y direction ($S7\Delta y_{P1/P2}$) is calculated as follows (the answer is squared and then rooted to give only the magnitude of the shift):

$$S7\Delta y_{P1/P2} = \sqrt{\left(S7Endy_{P1/P2}' - S7Starty_{P1/P2}'\right)^2}$$

The sensitivity of this surface tolerance is then determined by:

$$Sensitivity = S7\Delta y_{P1/P2}/\text{design tolerance}$$

Table 25 presents the results of the sensitivity of feature 7 to variation in locating point pair $P1/P2$. This entry is compared to other entries for the Δy shift caused by locating pair $P1$ and $P2$ in the sensitivity table. As this is the first feature tested the sensitivity table is empty and this would be the first entry, as indicated in Table 26.

Feature	$S7Starty_{P1/P2}'$	$S7Endy_{P1/P2}'$	$S7\Delta y_{P1/P2}$	**Design tolerance**	**Sensitivity**
7	3.910314566	4.084812	0.174497484	0.1	1.7449

Table 25: The sensitivity of feature 7 to variations in locating pair *P*1 and *P*2

	Locating pair *P*1/*P*2			**Locating pair *P*1/*P*3**			**Locating pair *S*1/*S*2**		
	Feature	Tolerance	Sensitivity	Feature	Tolerance	Sensitivity	Feature	Tolerance	Sensitivity
Max Δx/tol shift	0	0	0						
Max Δy/tol shift	7	*TPAR*	1.7449				0	0	0
Max Δz/tol shift				0	0	0			

Table 26: Updating the sensitivity table

The process is then repeated for the remaining tolerance descriptions, resulting in the final sensitivity analysis presented in Table 27. The table contains the feature identification, the tolerance for that feature, and the calculated sensitivity for the shift in a particular axis direction for each locating point pair. One note of interest is that when performing the analysis for the *P*1/*P*3 locating point pair, the *x* coordinate of locating point *P*2 should be used rather than *P*3. This accounts for the worst case scenario where constraining the rotational degree of freedom around the *x* axis is actually performed by locating point *P*2, as illustrated in Figure 112.

	Locating pair *P*1/*P*2			**Locating pair *P*1/*P*3**			**Locating pair *S*1/*S*2**		
	Feature	Tolerance	Sensitivity	Feature	Tolerance	Sensitivity	Feature	Tolerance	Sensitivity
Max Δx/tol shift	0	0	0	18	*TPER*	2.0358	18	*TPOS*	0.88314
Max Δy/tol shift	7	*TPAR*	1.7449	19	*TPOS*	1.4821	0	0	0
Max Δz/tol shift	18	*TPER*	2.0358	0	0	0	19	*TPOS*	0.71321

Table 27: The final sensitivity analysis table

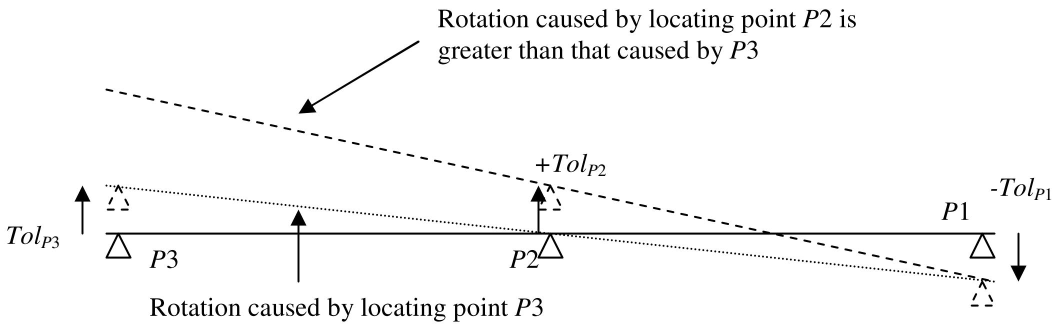


Figure 112: Using the *x* coordinate of locating point *P*2 instead of *P*3 during the sensitivity analysis

Once the sensitivity analysis has been completed, then the allowable tolerance for each locating position can be calculated. This is done for each locating pair and consists of eight steps.

1. For each locator pair, identify the most sensitive tolerance.
2. Determine the type of tolerance, its value, and the sensitivity.
3. Recalculate the shift caused in the relevant direction by the locator pair.
4. Determine the final tolerance allowed for that feature in the current direction.
5. Estimate the allowed angle of rotation using the sensitivity value.
6. Calculate the shift caused by this estimated angle.
7. Refine the estimated value of the allowed angle of rotation.
8. Calculate the allowed tolerances for the locator pair.

Consider the $P1/P2$ locating point pair. From the sensitivity analysis results the critical tolerance is the perpendicular tolerance of hole 18, for which the sensitivity is 2.0358, and the design tolerance is 0.06 inches. The shift in the z direction caused by the assumed rotation of 2° is:

$$\Delta z_{P1/P2\_Feature18} = Sensitivity * \text{design tolerance} = 2.0358 * 0.06 = 0.12214 \text{ inches}$$

The perpendicular tolerance on hole 18 dictates that the hole axis must be perpendicular to surface 2 within a range of 0.06 inches, as illustrated in Figure 113. The allowed tolerance zone for a perpendicular tolerance in a particular direction is assumed to be equal to the length of a square that can fit within the circle created by the *TPER* tolerance (Figure 114).

$$\begin{aligned}\text{Allowed tolerance} &= (\text{Design tolerance}) * \sin 45^{\circ} \\ &= 0.06 * \sin 45^{\circ} = 0.04243 \text{ inches}\end{aligned}$$

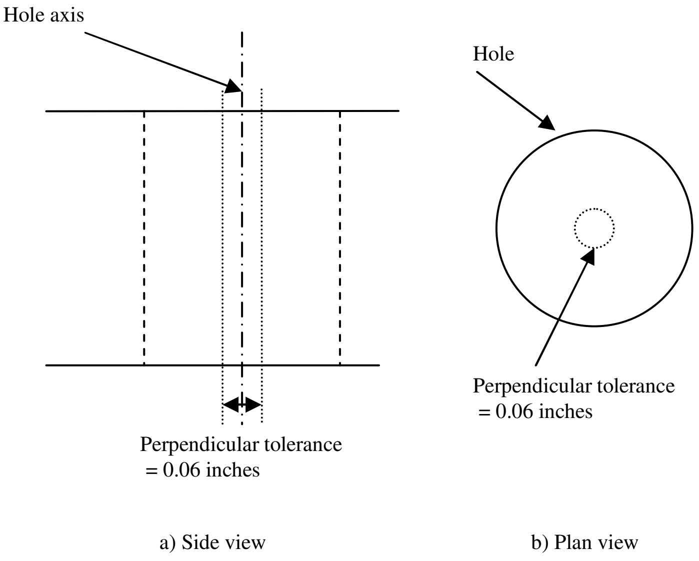


Figure 113: The perpendicular tolerance on hole 18

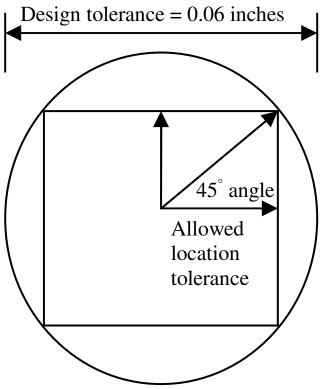


Figure 114: The allowed design tolerance on hole 18

Determining the allowed angle of rotation caused by locating tolerances, θ_{tol}, is a two stage process. Initially, an estimate of this angle, $\theta_{estimate}$ is obtained using the sensitivity value from the sensitivity table:

$$
\begin{aligned}
\theta_{estimate} &= (\text{allowed tolerance / shift in z direction caused by } 2^{\circ}) * 2^{\circ} \\
&= (0.042426 / 0.12214) * 2 \\
&= 0.69467^{\circ}
\end{aligned}
$$

This is only an estimate of the allowed angle of rotation. To check its accuracy, the angle has to be fed back into the equations used to determine the shift in position of a surface caused by a rotation during the sensitivity analysis:

$$S18Startz_{P1/P2}' = (S18Start18z - CPz_{zy})\cos\theta - (S18Starty - CPy_{zy})\sin\theta$$

$$S18Endz_{P1/P2}' = (S18End18z - CPz_{zy})\cos\theta - (S18Endy - CPy_{zy})\sin\theta$$

where:

$S18Startz$ = original z coordinate of start of hole 18 = 2.5;

$S18Starty$ = original y coordinate of start of hole 18 = 4.5;

$S18Startz_{P1/P2}'$ = new z coordinate of start of hole 18 relative to center point CP;

CPz_{zy} = z coordinate of center point between locators P1 and P2 = (0.25 + 4.75)/2 = 2.5;

CPy_{zy} = y coordinate of center point between locators P1 and P2 = (1+1)/2 = 1;

$\theta = \theta_{estimate} = 0.052108^{0}$;

$S18Endz$ = original z coordinate of end of hole 18 = 2.5;

$S18Endy$ = original y coordinate of end of hole 18 = 1;

$S18Endz_{P1/P2}'$ = new z coordinate of end of hole 18 relative to center point CP.

The shift of interest is the resultant shift in the z ($S18\Delta z_{P1/P2}$) direction is therefore:

$$S18\Delta z_{P1/P2} = \sqrt{(S18Startz_{P1/P2}' - S18Endz_{P1/P2}')^2}$$

Putting in the numbers gives $S18\Delta z_{P1/P2}$ = 0.042434 inches.

This value needs to be compared to the allowed design tolerance determined earlier on (0.042426 inches), thus the similarity measure is obtained by:

$$\begin{aligned} \textit{Similarity} &= S18\Delta z_{P1/P2} \text{ / Allowed design tolerance} \\ &= 0.042434 / 0.042426 \\ &= 1.000189. \end{aligned}$$

Thus, $\theta_{estimate}$ is a little large (*Similarity* should equal 1.0000) and needs to be reduced. This is done by subtracting a standard increment from $\theta_{estimate}$ until the similarity condition is satisfied. When $\theta_{estimate} = 0.69454674^{\circ}$, the similarity condition is satisfied (note this is less than the original estimate of 0.69467°). The allowed angle of rotation θ_{tol} caused by the location tolerance is:

$$\theta_{tol} = 0.69454674^{\circ} - \theta_{m/c\_rot}$$

where θ_{m/c_rot} is the accuracy of the machine tool around a particular axis and for the $P1/P2$ locators the axis of relevance is the x axis. Recalling the machining data detailed in Table 19, θ_{tol} becomes 0.68954674°.

The next stage is to use θ_{tol} to determine the allowed tolerances at the locating positions $P1$ and $P2$ (Tol_{P1} and Tol_{P2}).

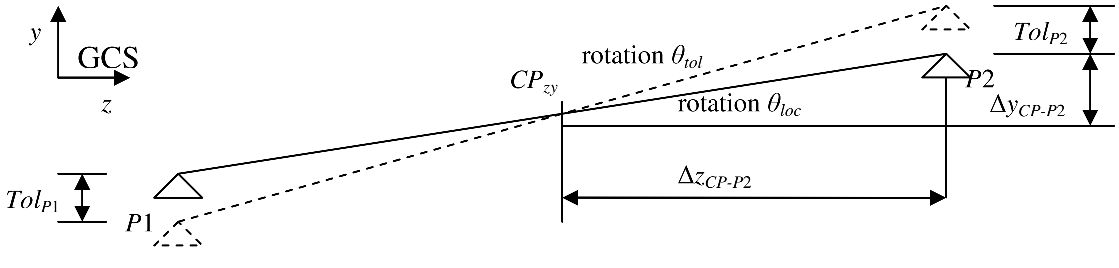


Figure 115: Determining Tol_{P1} and Tol_{P2}

θ_{tol} = angle of rotation caused by location tolerance = 0.68954674°

θ_{loc} = angle of rotation caused by different y coordinates of locating points = 0°

θ = overall angle of rotation = $\theta_{loc} + \theta_{tol} = 0.68954674^\circ$

$Tol_{P2} = Tol_{P1}$ = allowed tolerance for each locator

$\Delta z_{CP\text{-}P2}$ = z coordinate $P2$ – z coordinate CP

$= 4.75 - 2.5$

$= 2.25$

$\Delta y_{CP\text{-}P2}$ = y coordinate $P2$ – y coordinate CP

$= 1 - 1$

$= 0$

$tan\ \theta = (\Delta y_{CP\text{-}P2} + Tol_{P2}) / \Delta z_{CP\text{-}P2}$ where

$Tol_{P2} = (tan\ \theta * \Delta z_{CP\text{-}P2}) - \Delta y_{CP\text{-}P2}$

$= tan\ (0.68954674^\circ) * 2.25 - 0$

$= 0.02708$ inches

The allowed tolerance on locating points $P1$ and $P2$ is therefore 0.02708 inches and the tolerance assignment table reads:

Locating point	***P*1**	***P*2**	***P*3**	***S*1**	***S*2**	***T*1**
Tolerance, Δ	0.02708	0.02708				

Table 28: Updating the tolerance table (units are inches)

The process then repeats for each of the remaining locator pairs. Two points of interest arise, the first when determining the tolerance allowance for the locating pair $P1/P3$. As with the sensitivity analysis the coordinates of $P2$ are substituted in for $P3$ to account for the worst case scenario (Figure 112). This results in a revised set of locator allowance values for $P1$ and $P2$ ($\Delta = 0.018724$ inches) and as this tolerance is less than that already calculated for $P1$ and $P2$, then the new value is adopted at locating points $P1$ and $P2$.

The second issue relates to the derivation of Δ for locating points $S1$, $S2$, and $T1$. The most sensitive tolerance is the true position tolerance on Hole 18. The shift in the x direction is the sum of three shifts each of which is caused by different locating point effects:

$$S18\Delta x_{allowed} = S18\Delta x_{P1/P2} + S18\Delta x_{S1/S2} + S18\Delta x_{T1}$$

where

$S18\Delta x_{allowed}$ = the x shift allowed by the design tolerance of feature 18;

$S18\Delta x_{P1/P2}$ = the x shift caused by the $P1/P3$ locator interaction;

$S18\Delta x_{S1/S2}$ = the x shift caused by the $S1/S2$ locator interaction;

$S18\Delta x_{T1}$ = the x shift caused by the $T1$ locator.

$S18\Delta x_{P1/P2}$ can be calculated as the tolerance of each locating position has already been calculated. $S18\Delta x_{S1/S2}$ and $S18\Delta x_{T1}$ are unknown and the assumption is made that $S18\Delta x_{S1/S2} = S18\Delta x_{T1}$, thus the above equation simplifies to:

$$(S18\Delta x_{allowed} - S18\Delta x_{P1/P3}) / 2 = S18\Delta x_{S1/S2}$$

Once $S18\Delta x_{S1/S2}$ has been calculated from the above equation, the tolerance at each locating point can be calculated in a similar vein to that described for determining Δ for $P1$ and $P2$. Thus at the end of the tolerance analysis the allowed Δ values for each locating position are as listed in Table 29. This is the first approximation of the Δ values, and should be passed to Hu's system (2001) for verification and refinement through equal reduction of each Δ until all design tolerances are specified. For the purposes of this worked example of the CAFixD method, it shall be assumed that the values presented in Table 29 are satisfactory and allow the design tolerances to be achieved.

Locating point	***P*1**	***T*1**	***S*1**	***P*2**	***S*2**	***P*3**
Tolerance, Δ	0.018724	0.006247	0.006625	0.018724	0.006625	0.018724

Table 29: The allowed tolerance, Δ, of each locating point (inches)

Δ must then be divided and allocated to each of the contributing factors using the standard heuristics discussed in section 4.2.3.1.2. Thus for example consider locating point P1:

$$\Delta_{P1} = \Delta_{loc} + \Delta_{surf} + \Delta_{m/c} + \Delta_{m/c\_rot} + \Delta_{disp} + \Delta_{clamp} + \Delta_{wp}$$

where

Δ_{P1} = total allowed tolerance at locating point P1 = 0.018724 inches;

$\Delta_{m/c}$ = linear tolerance of the machine tool in the direction of location = 0.00002 inches;

Δ_{m/c_rot} = rotational tolerance of the machine tool (0.005°) and has been accounted for already during the determination of θ_{tol};

Δ_{surf} = tolerance of the locating surface at the locating point = 0.002 inches (assumed value);

Δ_{loc} = tolerance of a locator at a locating point;

Δ_{disp} = tolerance allocated to displacement of locating unit during machining;

Δ_{clamp} = tolerance allocated to displacement of locating unit due to clamping;

Δ_{wp} = tolerance allocated to displacement/deformation of workpiece due to clamping and machining forces = 0 (assumed value).

The following heuristics are invoked to determine Δ_{loc}, Δ_{disp}, Δ_{clamp} (Boyes, 1999):

$$\Delta_{loc} = 0.6 * (\Delta - \Delta_{surf} - \Delta_{m/c} - \Delta_{wp})$$

$$\Delta_{disp} = 0.3 * (\Delta - \Delta_{surf} - \Delta_{m/c} - \Delta_{wp})$$

$$\Delta_{clamp} = 0.1 * (\Delta - \Delta_{surf} - \Delta_{m/c} - \Delta_{wp})$$

Repeating the process for all six points yields the tolerance assignment presented in Table 30.

Tolerance assignment	***P*1**	***T*1**	***S*1**	***P*2**	***S*2**	***P*3**
Tolerance (Δ)	0.018724	0.006247	0.006625	0.018724	0.006625	0.018724
Δ_{loc} (inches)	0.010022	0.002536	0.002763	0.010022	0.002763	0.010022
Δ_{surf} (inches)	0.002	0.002	0.002	0.002	0.002	0.002
$\Delta_{m/c}$ (inches)	0.00002	0.00002	0.00002	0.00002	0.00002	0.00002
Δ_{disp} (inches)	0.005011	0.001268	0.001382	0.005011	0.001382	0.005011
Δ_{clamp} (inches)	0.00167	0.000423	0.000461	0.00167	0.000461	0.00167
Δ_{wp} (inches)	0	0	0	0	0	0
Δ_{m/c_rot} (degrees)	0.005	0.005	0.005	0.005	0.005	0.005

Table 30: The tolerance assignments for each locating point

The forces are then analysed to calculate the required stiffness of each locator and clamp. Each clamping unit is assumed to have the experience the same machining force as the locating unit against which it acts. The maximum forces acting in each locating direction are presented in Figure 116 and each locating unit must be able to withstand the machining and clamping forces such that their deflection is less than the combined values of Δ_{disp} and Δ_{clamp}. A standard clamping force of 50lbs is assigned to each clamping unit. Table 31 presents a summary of the machining and clamping forces each locating point must support. The stiffness for each locating unit is calculated through:

$$\text{Stiffness} = \text{force} / \text{allowed displacement}$$

where for locating units the force is equal to the sum of the machining and clamping forces and for clamping units the force is the machining force only. Table 32 presents the stiffness requirement for each locating and clamping point. The outstanding issues regarding the clamping points at this stage are the determination of the clamping directions and positions. The clamping directions are simply the reverse of the locating orientations. The clamping positions should be such that the clamping axis is parallel to and passes through the locating axis. This condition can be satisfied for all clamping/locating pairs with the exception of that for locating position *P*2. The desired clamping axis is presented in Figure 117 and requires that surface 7 be used for clamping. Unfortunately this is not feasible because surface 7 is machined in this setup, thus an alternative surface has to be found. Of the remaining candidates only surfaces 5, 14, and 15 are possible since the remainder are due to be machined. The criterion for selecting the clamping position is to choose the surface that results in the clamping axis with the smallest offset from the ideal axis, which for this workpiece is surface 14. The clamping details are presented in Table 33.

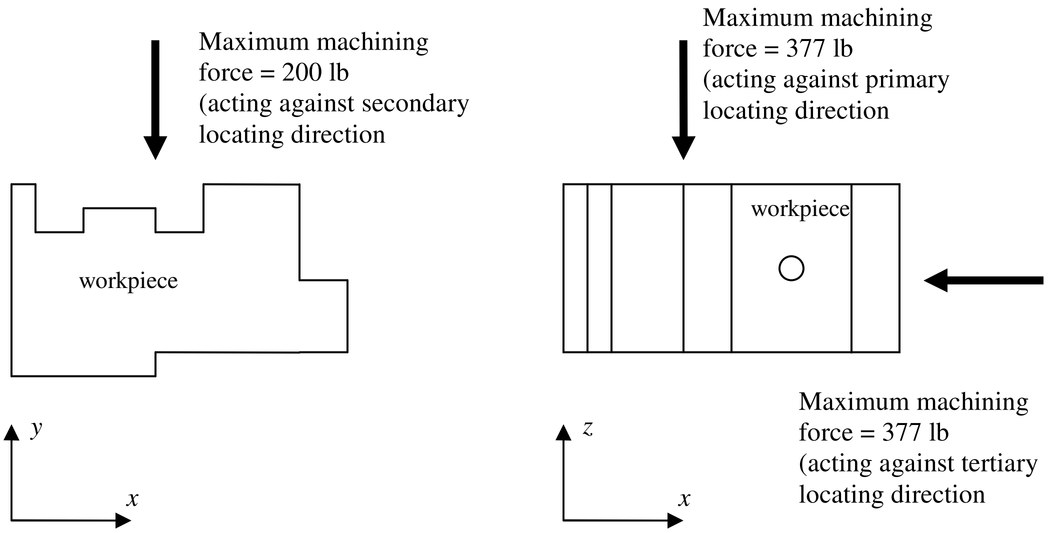


Figure 116: Maximum machining forces acting against each locating direction

Force type	***P*1**	***T*1**	***S*1**	***P*2**	***S*2**	***P*3**
Machining force (lb)	200	377	377	200	377	200
Clamping force (lb)	50	50	50	50	50	50

Table 31: Summary of machining and clamping forces acting against each locator

Stiffness assignment	Experienced force (lb)	Allowed displacement (inches)	Stiffness (lb/in)
Locating point *P*1	250	0.006681	37416.89
Locating point *T*1	427	0.001691	252542.66
Locating point *S*1	427	0.001842	231809.99
Clamping point against *P*1	200	0.006681	29933.51
Clamping point against *T*1	377	0.001691	222970.92
Clamping point against *S*1	377	0.001842	204665.96
Locating point *P*2	250	0.006681	37416.89
Locating point *S*2	427	0.001842	231809.99
Clamping point against *P*2	200	0.006681	29933.51
Clamping point against *S*2	377	0.001842	204665.96
Locating point *P*3	250	0.006681	37416.89
Clamping point against *P*3	200	0.006681	29933.51

Table 32: The required stiffness at each locating and clamping point

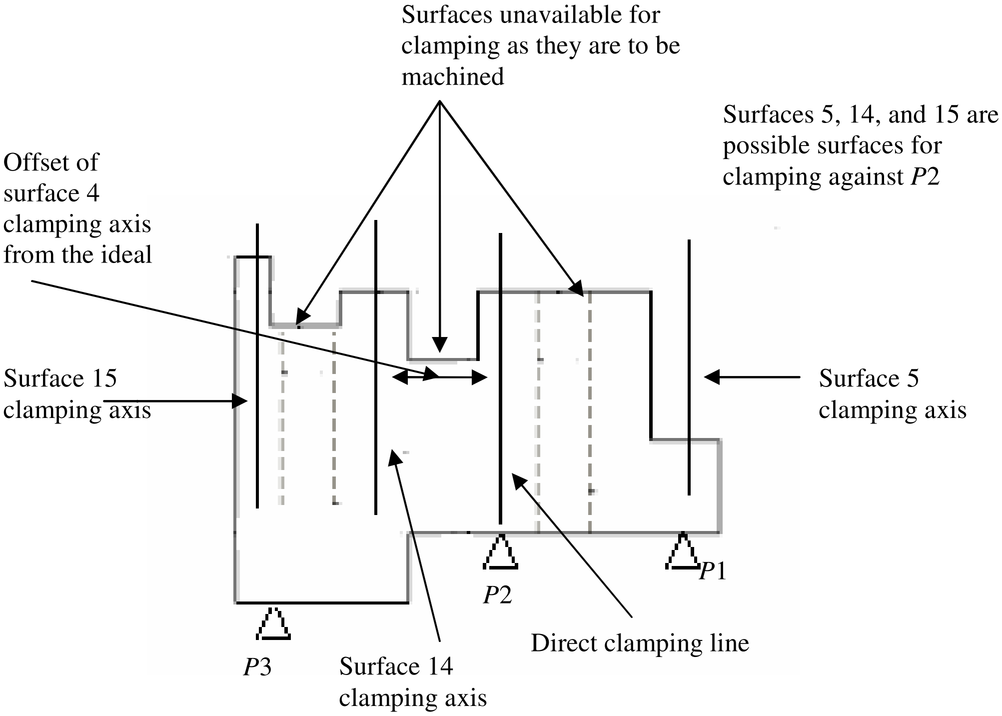


Figure 117: Obtaining a clamping position to act against locating point *P*2

Locator clamp acts against	Clamping surface	Clamping orientation	Clamping position
*P*1	5	(0,-1,0)	(6.75,2.35,0.25)
*T*1	6	(-1,0,0)	(6,2.5,2.5)
*S*1	17	(0,0,-1)	(0.25,2.25,5)
*P*2	14	(0,-1,0)	(2,4.5,4.75)
*S*2	17	(0,0,-1)	(5.75,2.25,5)
*P*3	15	(0,-1,0)	(0.25,5,0.25)

Table 33: Clamping orientations and positions

At this stage the FR and DP skeletons can be filled in with details of the clamping and location accuracy requirements. The complete FR and DP lists for this example are presented in Appendix D, but can be summarised as follows:

- $FR_{1.1}$ was filled in earlier during the identification of a suitable conceptual model;
- $FR_{1.2}$ has three subgroups of FRs:
    - $FR_{1.2.1}$ lists the required accuracy, Δ_{loc}, of each of the six locating units. The DPs for these FRs are unknown at this stage. The solutions will be the locating units generated during the retrieval stage of the design process.
    - $FR_{1.2.2}$ lists the machine misalignments, both linear $\Delta_{m/c}$ and rotational Δ_{m/c_rot}, that need to be accounted for. The DPs are simply the magnitude of these alignments that were accounted for during the tolerance assignment stage.
    - $FR_{1.2.3}$ lists the locating surface errors, Δ_{surf}, that need to be accounted for. The DPs are simply the magnitude of these errors that were accounted for during the tolerance assignment stage.
- $FR_{2.1}$ has three subgroups of FRs detailing the stability and stiffness requirements:
    - $FR_{2.1.1}$ lists the clamping forces that each of the six clamping units needs to provide (these are summarised in Table 31). The DPs are unknown at this stage but will be the individual clamping units generated during the retrieval stage of the design process.

- $FR_{2.1.2}$ lists the stiffness required at each locating and clamping point (these are presented in Table 32). The DPs are unknown at this stage but will be the individual clamping units generated during the retrieval stage of the design process.
- $FR_{2.1.3}$ lists the need for each clamp to contact the workpiece. The relevant DPs are the clamping coordinates detailed in Table 33.
- $FR_{2.1.4}$ lists the clamping directions required at each clamping position. The DPs are the workpiece surfaces upon which the clamps act (as detailed in Table 33).

5.2.3 Retrieving Suitable Units from Case Library 2

Before the individual locating and clamping units can be generated, the design preferences need to be defined. A detailed description of the process by which these are generated and some examples are described in section 4.3.2.1 but to recap there are four basic stages to defining design preferences:

- define the global constraint attributes that solutions are to be evaluated against;
- specify the acceptable range of performance that is sought of a design for each of those attributes;
- generate the utility curve for each constraint attribute that specifies the utility of different values of performance within the accepted range;
- determine the scaling constant for each constraint attribute, which is a measure of the importance of one attribute relative to the others.

For this example, five constraint attributes are considered. These are fixture cost, weight, loading time, assembly time, and unloading time. The utility curves for each constraint attribute are presented in the following figures. The original curves obtained from the user are presented together with the cubic approximations used by the CAFixD method in its utility calculations. As the figures indicate there is a close match between this cubic approximation and the curves entered by the user. Table 34 details the scaling constant (k_i) for each individual attribute and the overall scaling constant, K.

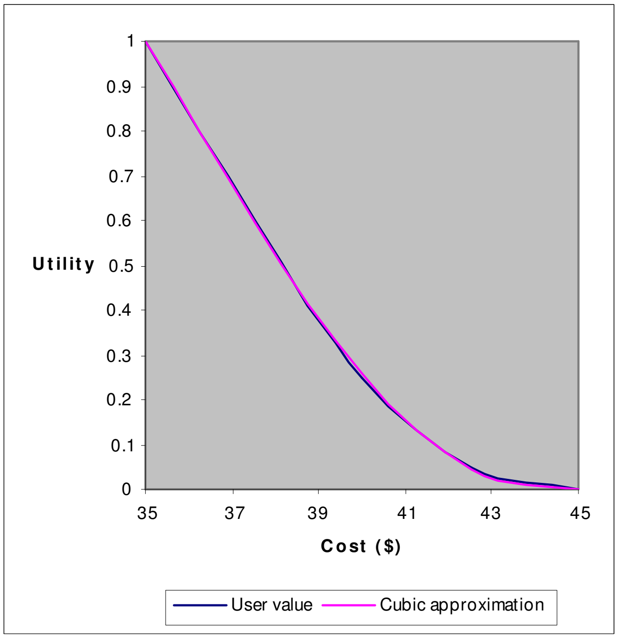


Figure 118: Utility curve for fixture cost

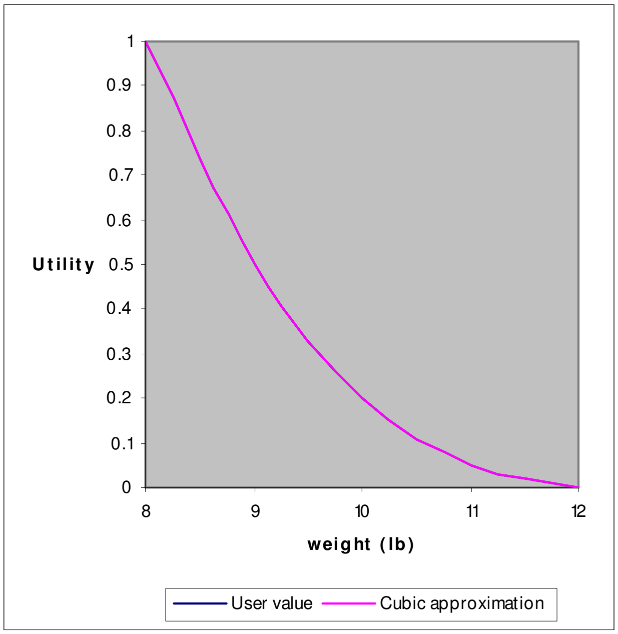


Figure 119: Utility curve for weight

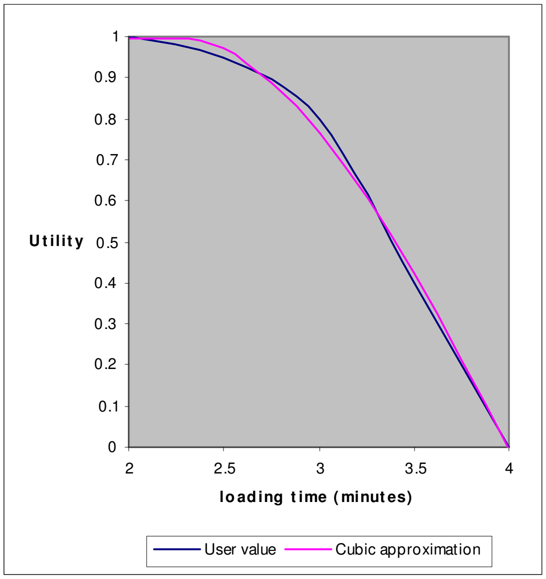


Figure 120: Utility curve for loading time

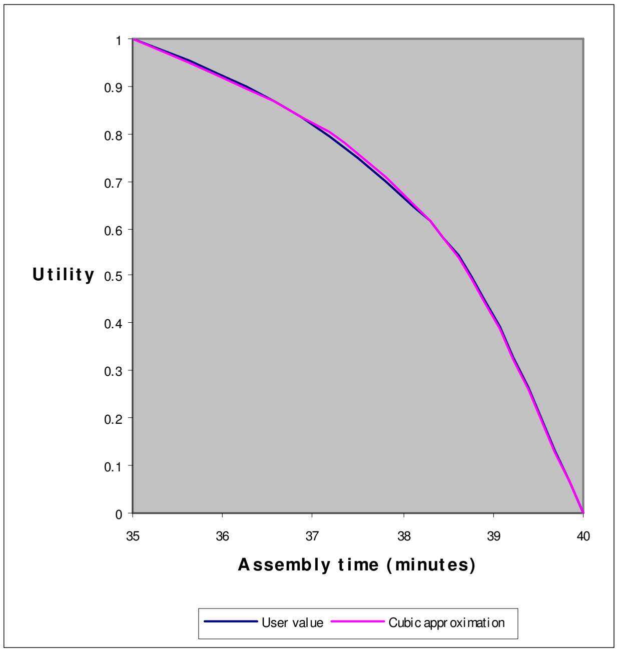


Figure 121: Utility curve for assembly time

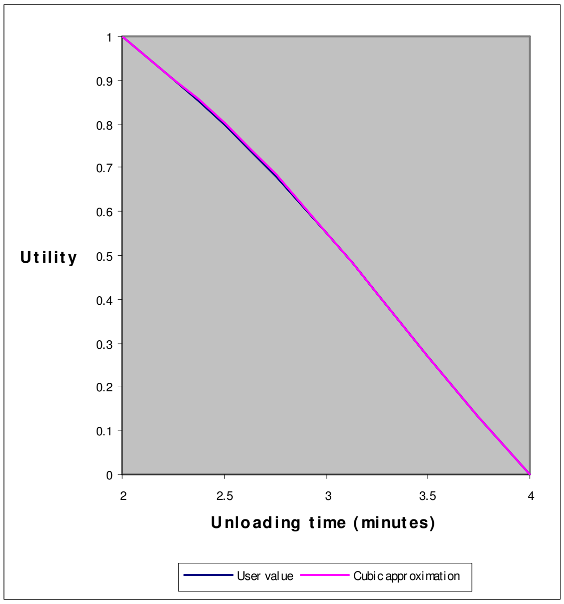


Figure 122: Utility curve for unloading time

Constraint attribute	Scaling constant value
Cost	0.67
Weight	0.35
Loading time	0.23
Assembly time	0.54
Unloading time	0.29
Overall	-0.9262283

Table 34: Individual scaling constants k_i and overall scaling constant K

The first step of the retrieval process is to determine which cases in case library 2 are suitable for use within the retrieved conceptual model. For simple plane 3-2-1 locating (variation 3) where no chip shedding requirements have been specified, and there are no complex issues related to the workpiece geometry there are few restrictions on which cases can be used other than ensuring that both the basic function type (locating or stiffness) and direction of action (vertical or horizontal) are satisfied.

Table 35 presents a sample of the results from the functional similarity-based retrieval stage. For each locating and clamping point, possible DPs are listed which can qualitatively (but not quantitatively) satisfy the appropriate FRs associated with each point. That is they are capable of providing a certain stiffness capability in the correct direction, but may not in their current form be able to offer the correct magnitude of stiffness. The adaptability-based retrieval stage of the design process will determine how and if they can be modified and will pick the design solution for each FR or group of FRs that is most in keeping with the design preferences.

Locating/clamping point	Possible DP	Possible DP
*P*1	VL011C1	VL012C1
*T*1	HL013C1	HL013C2
*S*1	HL013C1	HL013C2
*P*2	VL011C1	VL012C1
*S*2	HL013C1	HL013C2
*P*3	VL011C1	VL012C1
Clamp against *P*1	VC0132C1	VC022C1
Clamp against *T*1	HC021C1	HC022C1
Clamp against *S*1	HC021C1	HC022C1
Clamp against *P*2	VC0132C1	VC022C1
Clamp against *S*2	HC021C1	HC022C1
Clamp against *P*3	VC0132C1	VC022C1

Table 35: Output of results from functional similarity-based retrieval

The first stage of this part of the process is to generate a qualitatively complete design and compute its associated performance values for each of the global constraint attributes. This design is used as an initial reference point for comparing designs. The highlighted designs in the second column of Table 35 are randomly chosen as this initial design. The case library holds each of these units performance with regard to the global constraint attributes, and these are displayed in Appendix E. Summing these numbers provides the attribute performance values for this initial, which are listed in Table 36.

Attribute	Performance level
Cost ($)	38.64
Weight (lb)	9.219
Loading time (mins)	3.0999
Assembly time (mins)	37.56
Unloading time (mins)	2.55

Table 36: Attribute performance values for initial design

The retrieval process continues by picking each candidate DP in turn and repairing it to satisfy the FR or group of FRs for which it is being considered. Each method of repair for a particular DP is instigated and evaluated by comparing the ability of the repaired design to meet the design preferences. Consider as an example the DP VC0132C1 whose details were presented in section 4.4.1. This is a vertical clamp considered as a candidate for clamping against locating point P1. It has two FRs associated with it – stiffness and clamping force. Its current performance values are:

- stiffness of 17765 lb/in, and;
- clamping force of 35 lb.

The requirements for the current fixture problem are:

- stiffness of 29933 lb/in;
- clamping force of 50 lb.

Thus the design requires adaptation. To modify the stiffness of the clamp there are three possible adaptation strategies:

- modify the thickness of the clamp elements using the *strap_thickness_adapt( )* strategy;
- modify the width of the clamp components using the *strap_width_adapt( )* strategy;

- modify the clamp material using the *strap_material_adapt( )* strategy.

Testing of the modification module is performed by the *strap_clamp_third_order_disp_func( )* test module. The first two adaptation strategies share a common control module, *dimension_control( ),* whilst the material modifications are supervised by the *material_control( )* module.

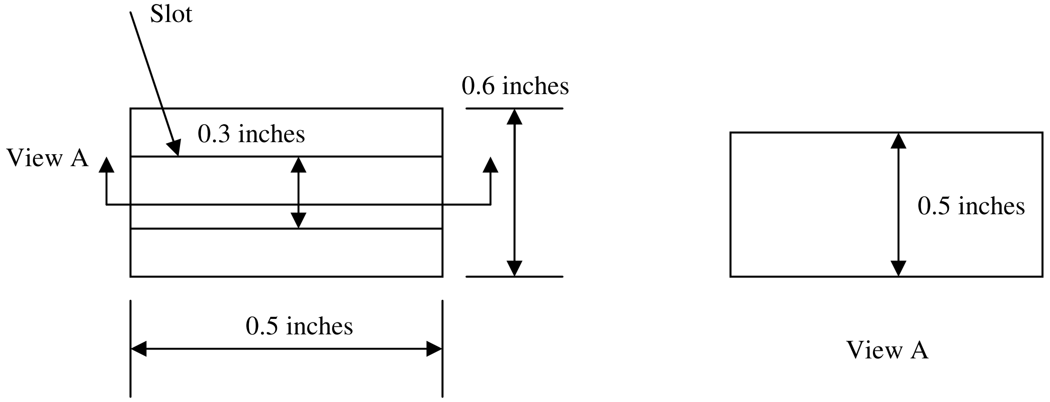
To modify the clamping force there is only the *strap_torque( )* adaptation strategy in which the *torque_calc_third_order( )* directly calculates the torque required to produce the desired clamping force on the workpiece.

The first adaptation method to be invoked alters the thickness of the clamp elements using the *alter_ thickness( )* modification module. The control module makes an initial guess at the required thickness change (0.1 inches) which is then implemented by the modification module. Consider for example element 4 of the clamp, presented in Figure 123a. Element 4 contains a slot into which a mating element (a cylindrical element) from the work limb of the clamp fits. When altering the thickness of element 4 from 0.5 to 0.6 inches, the same change will also apply to the connecting cylindrical element from the work limb. Thus the slot width on element 4 must be increased to be able to accept this mating element. The width of element 4 must also be increased to account for the increase in slot width. This results in the modified dimensions of element 4 presented in Figure 123b. All of the elements within the clamp undergo similar forms of modification and when this is complete the testing module is called to determine the likely behaviour of the clamp when subjected to the machining forces.

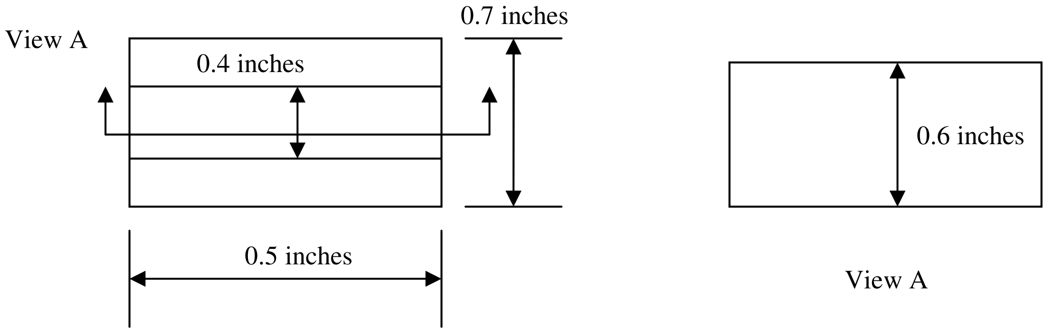
The required stiffness of the clamp is based upon the machining forces and the allowed displacement, and the test module calculates the likely displacement of the clamp rather than the stiffness itself. Initially the forces on the work and fulcrum limbs are calculated by applying the equilibrium conditions on the beam for both the real and virtual force systems. Figure 124 presents the calculated real and virtual forces. These forces are then used to calculate the internal forces acting on each element (see Figure 125). The displacement of a single element can then be calculated using the virtual work method, thus for element 4 which is subject to bending and shear dispalcements:

$$d_4 = \int_{s}^{x_2} \frac{m_4 M_4}{E_4 I_4} dx_2 + \frac{f_s v_4 V_4 L_4}{G_4 A_4}$$

This is repeated for all elements and their respective displacements summed to determine the displacement of the clamp at the workpiece interface.

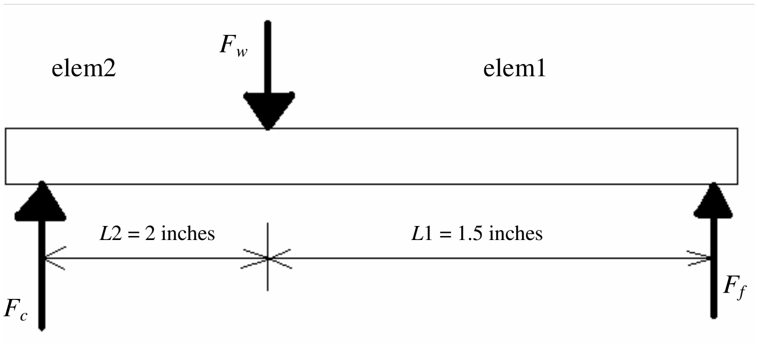


a) before modification



a) after modification

Figure 123: Element 4 a) before and b) after modification



$F_f = F_c * L2 / L1 = 266.67$ lb $\qquad F_w = F_c + F_f = 466.67$ lb

$f_f = f_c * L2 / L1 = 1.33$ lb $\qquad f_w = f_c + f_f = 2.33$ lb

Figure 124: Calculating F_f and F_w

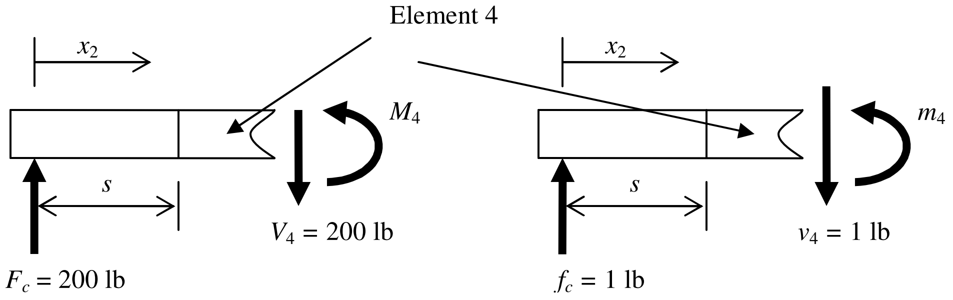

Real force system: **Virtual force system:**

Figure 125: Free body diagram for element 4

The control module then evaluates the modified design and determines a future course of action. The key factor used during the control process is the polarity change of *calc_disp* – *des_disp* (this is the calculated displacement – the design displacement). The dimension change sent to the modification module is modified by a step value: i.e., *dim_change* = *dim_change* + *step*. Whenever a polarity change occurs, the step used in the dimension change is decreased by dividing it by 10 and reversing its polarity.

Table 37 presents the manner in which the control module converges on a solution by controlling the value of the step change. After each polarity reversal (represented by the highlighted rows) the step change is altered. Eventually, the clamp is successfully repaired when a dimension change of +0.09678089 inches is applied to the thickness of the clamping elements. In practice this level of accuracy of a dimension change is not practical, but is adopted here to illustrate how a solution is reached.

Dimension change	Applied *step* value	Calculated displacement	Design displacement	*calc_disp – des_disp*	Success
0	-	0.011258	0.006681	0.004576	No
0.1	0.1	0.006578	0.006681	-0.0001	No
0.09	-0.01	0.006907	0.006681	0.000226	No
0.091	0.001	0.006873	0.006681	0.000192	No
0.092	0.001	0.00684	0.006681	0.000158	No
0.093	0.001	0.006806	0.006681	0.000125	No
0.094	0.001	0.006773	0.006681	9.13E-05	No
0.095	0.001	0.00674	0.006681	5.83E-05	No
0.096	0.001	0.006707	0.006681	2.55E-05	No
0.097	0.001	0.006674	0.006681	-7.1E-06	No
0.0969	-0.0001	0.006678	0.006681	-3.9E-06	No
0.0968	-0.0001	0.006681	0.006681	-6.2E-07	No
0.0967	-0.0001	0.006684	0.006681	2.63E-06	No
0.09671	0.00001	0.006684	0.006681	2.31E-06	No
0.09672	0.00001	0.006683	0.006681	1.98E-06	No
0.09673	0.00001	0.006683	0.006681	1.66E-06	No
0.09674	0.00001	0.006683	0.006681	1.33E-06	No
0.09675	0.00001	0.006682	0.006681	1E-06	No
0.09676	0.00001	0.006682	0.006681	6.79E-07	No
0.09677	0.00001	0.006682	0.006681	3.53E-07	No
0.09678	0.00001	0.006682	0.006681	2.81E-08	No
0.09679	0.00001	0.006681	0.006681	-3E-07	No
0.096789	-0.000001	0.006681	0.006681	-2.6E-07	No
0.096788	-0.000001	0.006681	0.006681	-2.3E-07	No
0.096787	-0.000001	0.006681	0.006681	-2E-07	No
0.096786	-0.000001	0.006681	0.006681	-1.7E-07	No
0.096785	-0.000001	0.006681	0.006681	-1.3E-07	No
0.096784	-0.000001	0.006681	0.006681	-1E-07	No
0.096783	-0.000001	0.006681	0.006681	-6.9E-08	No
0.096782	-0.000001	0.006681	0.006681	-3.7E-08	No
0.096781	-0.000001	0.006681	0.006681	-4.4E-09	No
0.09678	-0.000001	0.006682	0.006681	2.81E-08	No
0.0967801	0.0000001	0.006681	0.006681	2.49E-08	No
0.0967802	0.0000001	0.006681	0.006681	2.16E-08	No
0.0967803	0.0000001	0.006681	0.006681	1.84E-08	No
0.0967804	0.0000001	0.006681	0.006681	1.51E-08	No
0.0967805	0.0000001	0.006681	0.006681	1.19E-08	No
0.0967806	0.0000001	0.006681	0.006681	8.61E-09	No
0.0967807	0.0000001	0.006681	0.006681	5.35E-09	No
0.0967808	0.0000001	0.006681	0.006681	2.1E-09	No
0.0967809	0.0000001	0.006681	0.006681	-1.2E-09	No
0.09678089	-0.00000001	0.006681	0.006681	-8.3E-10	Yes

Table 37: Modification results for *strap_thickness_adapt( )* strategy (inches)

Once a successful solution has been achieved, the constraint attribute performance values can be determined for the modified unit, as illustrated in Table 38.

Attribute	Original clamp performance levels	Modified clamp performance levels
Cost ($)	1.83	2.18
Weight (lb)	1.1996	1.5624
Loading time (mins)	0.583	0.583
Assembly time (mins)	4.82	4.82
Unloading time (mins)	0.45	0.45

Table 38: The updated constraint attributes for the clamp

These can then be incorporated into the performance values for the overall fixture design and the utility of the new design (which has the repaired clamping unit in it) calculated. The utility for each individual performance constraint is presented in Table 39, and the overall utility can be determined using the multiplicative as described in section 4.3.3.2.2 to yield an overall utility of 0.765965.

Attribute	Original fixture performance levels	Updated fixture performance levels	Individual attribute utility
Cost	$ 38.64	$ 39.03	0.377664
Weight	9.219 lb	9.608299 lb	0.296877
Loading time	3.0999 mins	3.0999 mins	0.706441
Assembly time	37.56 mins	37.56 mins	0.750127
Unloading time	2.55 mins	2.55 mins	0.777805

Table 39: The updated attribute performance values for the modified fixture

The process is then repeated for the second adaptation strategy in which the width of the clamp elements is subject to modification. However, as the calculated displacement results detailed in Table 40 show, this adaptation strategy failed. Up until a dimension change of 0.7 inches there was a steady decrease in the displacement suffered by the clamp due to machining forces. However when the dimension change was 0.8 inches, the displacement increased. The cause of this is the fact that for a dimension change of 0.8 inches, the length of the beam has to increase between the work and fulcrum limbs to prevent them from colliding with one another. Extending the beam increases the bending displacement of the beam. In this case the detrimental effect of increasing the beam length $L1$ has been greater than the beneficial effect of increasing the width of the element. After three consecutive increases have been recorded in the calculated displacement, the control module aborts the adaptation strategy as a successful solution is deemed unlikely.

Dimension change	Calculated displacement	Design displacement	*Calc_disp – des_disp*	Improvement on last change	Success	*L*1
0	0.011258	0.006681	0.004576	-	No	1.5
0.1	0.010547	0.006681	0.003866	Yes	No	1.5
0.2	0.010146	0.006681	0.003464	Yes	No	1.5
0.3	0.009885	0.006681	0.003203	Yes	No	1.5
0.4	0.009701	0.006681	0.003019	Yes	No	1.5
0.5	0.009563	0.006681	0.002881	Yes	No	1.5
0.6	0.009456	0.006681	0.002774	Yes	No	1.5
0.7	0.00937	0.006681	0.002688	Yes	No	1.5
0.8	0.009769	0.006681	0.003088	No	No	1.6
0.9	0.010182	0.006681	0.003501	No	No	1.7
1	0.010602	0.006681	0.00392	No	No	1.8

Table 40: Testing results for the *alter_width( )* modification module (inches)

The third adaptation strategy involves altering the material from which the unit is constructed using the *material_modification( )* module. The control module is aware of four candidate materials and instructs the modification module to implement them one at a time. Each material is tested and the results are presented in Table 41. Only one material change resulted in a successful clamping unit. The updated constraint attributes performances for the clamping unit are provided in Table 42 and those values for the updated fixture design as a whole are outlined in Table 43. The utility associated with this adaptation strategy is 0.634513.

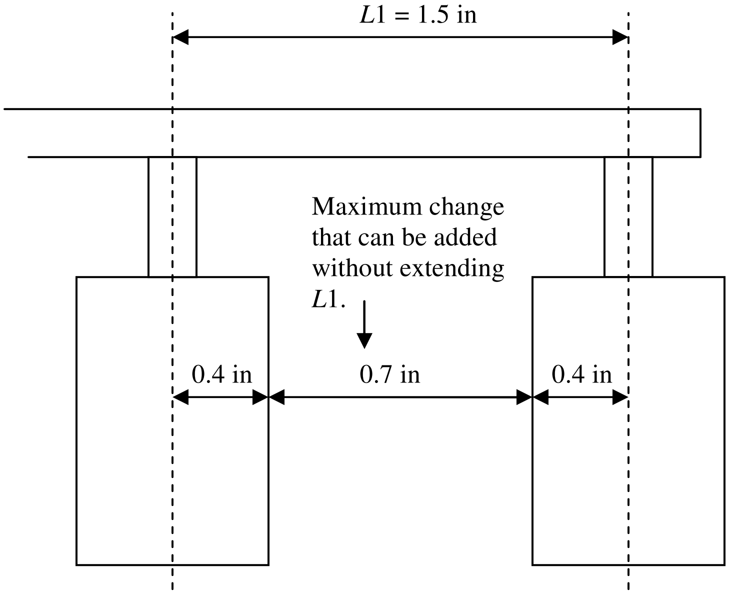


Figure 126: Limitations on modifying the work and fulcrum limbs

Material	Calculated displacement (inches)	Design displacement (inches)	Success
Stainless Steel 1304	0.011258	0.006681	No
Steel A36	0.010507	0.006681	No
Tungsten	0.005431	0.006681	Yes
Steel 1020	0.010507	0.006681	No

Table 41: Displacment results for different materials

Attribute	Original clamp performance levels	Modified clamp performance levels
Cost ($)	1.83	102.34
Weight (lb)	1.1996	2.893
Loading time (mins)	0.583	0.583
Assembly time (mins)	4.82	4.82
Unloading time (mins)	0.45	0.45

Table 42: The updated constraint attributes for the clamp

Attribute	Original fixture performance levels	Updated fixture performance levels	Individual attribute utility
Cost	$ 38.64	$ 139.19	0
Weight	9.22 lb	10.939 lb	0.055786
Loading time	3.099 mins	3.099 mins	0.706441
Assembly time	37.56 mins	37.56 mins	0.750127
Unloading time	2.55 mins	2.55 mins	0.777805

Table 43: The updated attribute performance values for the modified fixture

The results for each adaptation strategy are compared in Table 44. Only strategies 1 (thickness alteration) and 3 (material alteration) resulted in successful design solutions. Altering the width of the clamping unit failed to return a working design. Of the two successful strategies, the thickness alteration returns the design with the highest utility and this would be chosen as the final means for attaining the required stiffness. Appendix F presents the updated drawings for the clamping unit.

Adaptation strategy	Utility
Alter unit thickness	0.765965
Alter unit width	0
Alter unit material	0.634513

Table 44: Comparison of the utility of each adaptation strategy

Figure 127 illustrates the adaptation mapping layout for the stiffness FR/DP combination for the clamping unit. In the adaptation mapping layout:

- $FR_{2.1.1.1}$ is the stiffness required of the clamp (29933 lb/in);
- $DP_{2.1.1.1a}$ is the candidate clamping unit VC0132C1;
- $PV_{2.1.1.1a.1}$ is the thickness dimension change implemented using the *alter_thickness( )* modification module;

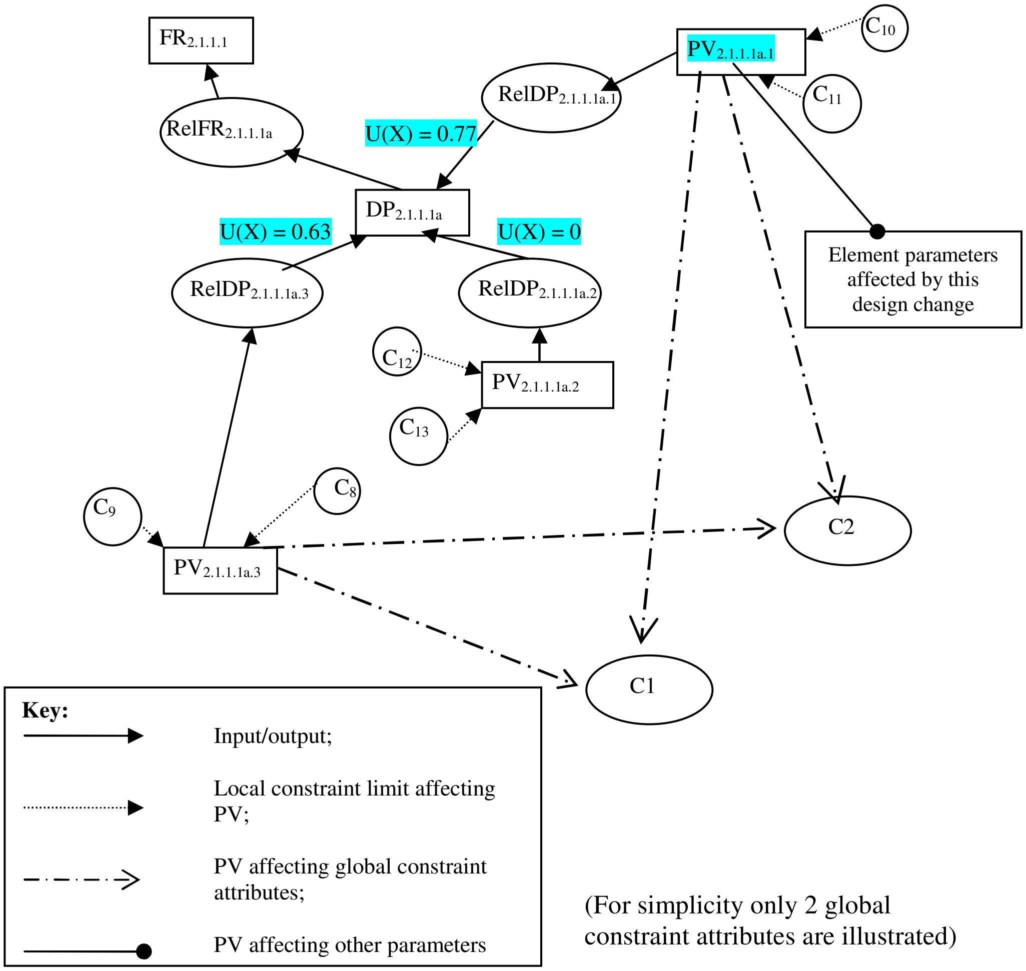
- $PV_{2.1.1.1a.2}$ is the width dimension change implemented using the *alter_width( )* modification module;
- $PV_{2.1.1.1a.3}$ is the material change implemented using the *alter_material( )* modification module;
- $RelFR_{2.1.1.1a}$ is the relationship between the FR and DP (this is the qualitative relationship established during the functionality-based retrieval stage when clamping units that could provide a vertical stiffness were sought);
- $RelDP_{2.1.1.1a.1}$ is the relationship that determines how the thickness design change affects the FR performance of the DP (this includes the control (*dimension_control( )* and *strap_clamp_third_order_disp_func( )* control and testing modules of the thickness adaptation strategy);
- $RelDP_{2.1.1.1a.2}$ is the relationship that determines how the width design change affects the FR performance of the DP (this includes the control (*dimension_control( )* and *strap_clamp_third_order_disp_func( )* control and testing modules of the thickness adaptation strategy);
- $RelDP_{2.1.1.1a.3}$ is the relationship that determines how the material design change affects the FR performance of a DP (this includes the *material_control( )* and *strap_clamp_third_order_disp_func( )* control and test modules of the material adaptation strategy).

The remaining FR for this unit is the clamping force FR. Currently the clamp provides a force of 35 lb, but the requirement is for 50 lb so the control module calls on the *torque_ calc_third_order( )* function to calculate the torque required at the bolt on the work limb. This modification results in no change to the attribute performances.

Thus for this DP the returned strategies are:

- Stiffness adaptation strategy: *strap_thickness_adapt( )*;
- Clamping force adaptation strategy: *strap_torque_ third_order( );*
- The returned utility for this DP/adaptation strategy combination is 0.7687858.

Appendix F presents the drawings for the updated clamp. The process is repeated for the remaining DPs returned by the functional similarity-based retrieval stage, and the DP/adaptation strategy with the highest utility value is chosen as the final solution for this particular group of FRs.



(For simplicity only 2 global constraint attributes are illustrated)

Figure 127: The adaptation mapping layout for this FR/DP combination

5.3 Review

This chapter has presented two examples. One illustrated the manner in which case knowledge is held in case library 2 and the second how a fixture unit is retrieved from the second case library during adaptability-based retrieval. This second example also illustrated how the CAFixD method supports the setup planning, fixture planning, unit design, and verification phases of fixture design.

Adaptation strategies play a crucial role in the adaptability-based retrieval stage. Evaluation of strategies is based heavily upon the wishes of the designer, who specifies design preferences in the form of utility curves. This adds a dynamic element to the design process in which the method has the ability to respond directly to design preferences. Thus given the same technical problem in terms of workpiece geometry, the method can respond in different ways to different users through the adoption of different adaptation strategies. In this way the method seeks to support the design process rather than control it by allowing the preferences of the user to guide decision making throughout the design tasks. Thus the modus operandi of the method is to support the designer using an understanding of the design preferences, rather than trying to impose a will of its own on the user. The designer remains the active party during design, and the method is a tool that reacts to the designer's wishes.

Chapter 6 – System Development and Implementation

A computer tool, called CAFixD, has been developed to demonstrate the methodology detailed in chapter 4. This chapter focuses on issues associated with creating this software implementation. An overview of the system is presented in section 6.1, followed by a discussion of the internal information flows, knowledge bases, and data formats used for communication with other CAD tools, as well as the system interface design.

6.1 System Overview

CAFixD has been developed using the Visual C++ language in conjunction with Tidestone Formula 1 Workbook Designer. Workbook Designer is a spreadsheet design tool and this spreadsheet capability is used to simplify information passing within CAFixD. It also acts as a convenient means of displaying system outputs and information to the user. Code written in the Visual C++ language controls the execution of CAFixD.

Overall, CAFixD has been developed as a stand-alone program that communicates with various other CAD tools and the user to gather information as and when it is required. The purpose of CAFixD is to process this information and use it to generate a fixture design, and then pass on the details of this fixture design to a CAD package that will create the design drawings. Figure 128 illustrates the overall relationship with other systems. CAFixD communicates with both CAD and Computer-aided Process Planning (CAPP) systems. CAPP systems generate the machining information for a workpiece. This information includes the machine tool type, details of the machining processes the workpiece will undergo, the cutting toolpath, and so on. One-way communication exists between the CAPP system and CAFixD, whilst two-way communication exists between CAFixD and the CAD system. CAFixD receives from the CAPP system information relating to machining processes the workpiece will undergo, such as machining forces and machine tool tolerances. CAFixD also receives workpiece information from the CAD system that details workpiece surfaces, features (these are the surfaces to be machined), dimensions, and tolerances. Together, these two sources of information are used to generate a conceptual fixture design and to define the list of FRs for which a design solution is sought.

To aid the detail design stage, CAFixD receives existing fixture designs from case library 2, which is contained within CAFixD. However a link exists between each case in the case library and the drawings of the case which are held in the CAD system. The CAFixD case library holds only the completed case and element schemas for a particular case, but does not contain the actual unit drawings. These are held within the CAD system, and a link exists between the CAFixD and CAD representations of units that identifies which CAD drawings and CAFixD cases are related to each other.

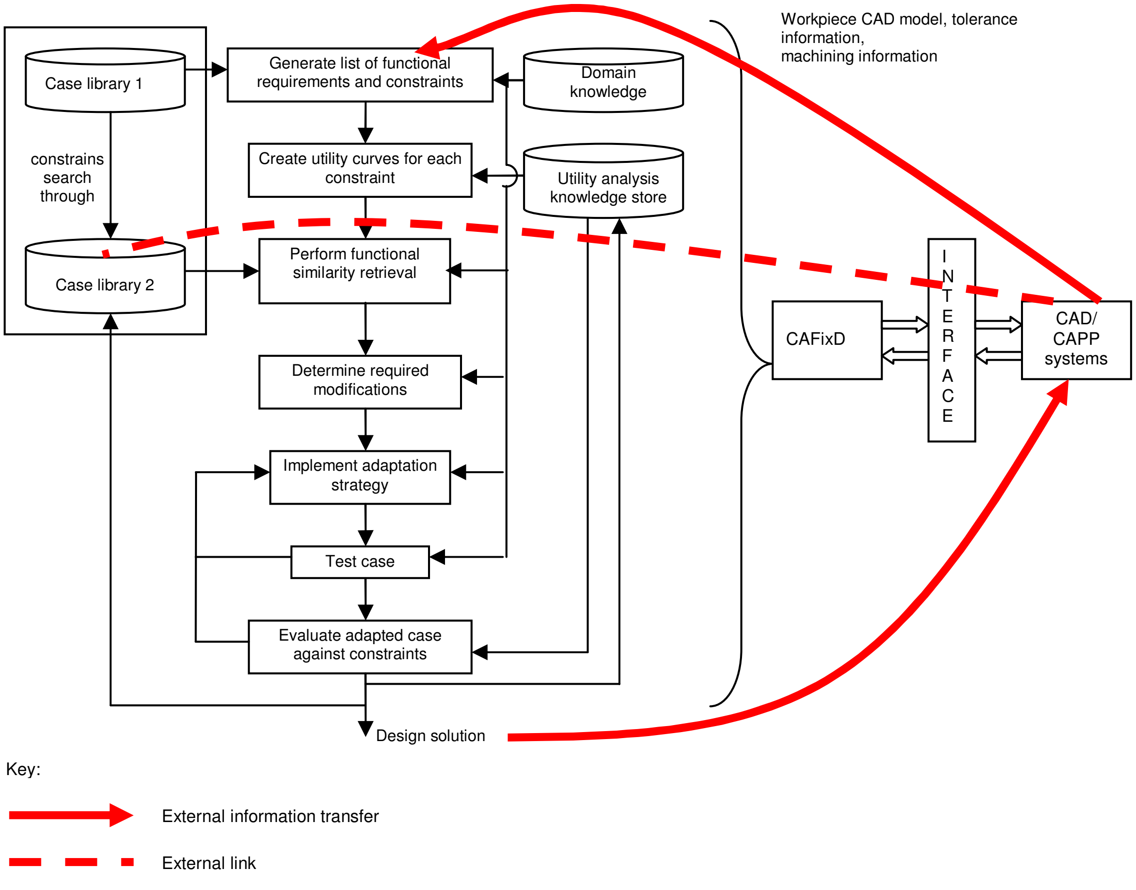


Figure 128: CAFixD system overview

To the CAD system, CAFixD sends a list of design modifications that are required to fix a design, which are subsequently implemented by the CAD system. This is the sole external output of CAFixD, but there are also two internal outputs:

1. the completed case and element schema for the new design solution is added to the case library;
2. the utility curves generated through the design process may also be stored in the utility analysis knowledge base (the decision to store these curves is left to the discretion of the user).

6.2 System Databases

A series of knowledge sources are used to support the operations performed by CAFixD. These sources are all contained within the CAFixD system. There are three sources, each of which may contain either declarative or procedural knowledge, or a combination of both. The three knowledge bases are the case base, the domain knowledge base, and the utility analysis knowledge base. Figure 129 illustrates a partial breakdown of the knowledge source hierarchy.

The case base contains the two case libraries, both of which are discussed in some detail in section 4.1. The utility analysis base contains execution knowledge in addition to previous design preferences held in the form of utility curves and scaling constants. These previous design preferences may be recalled and used again by the designer. It is also possible to edit existing curves and scaling constants before reuse. This feature is intended to simplify using the utility analysis approach. The process of generating utility curves can be a laborious process and is the main reason that the approach is not widely adopted in the engineering design community. CAFixD however allows the user to recall old curve sets and modify them. A simple modification may be to stretch the curve by extending the acceptable performance range, as illustrated in Figure 130. Alternatively, the shape of the curve can be altered using the standard lottery question process. This however is time consuming, so the ideal approach is to have a selection of previous curves that exhibit a wide variation in curve shape. The designer can then pick the desired shape and then simply modify the acceptable performance range.

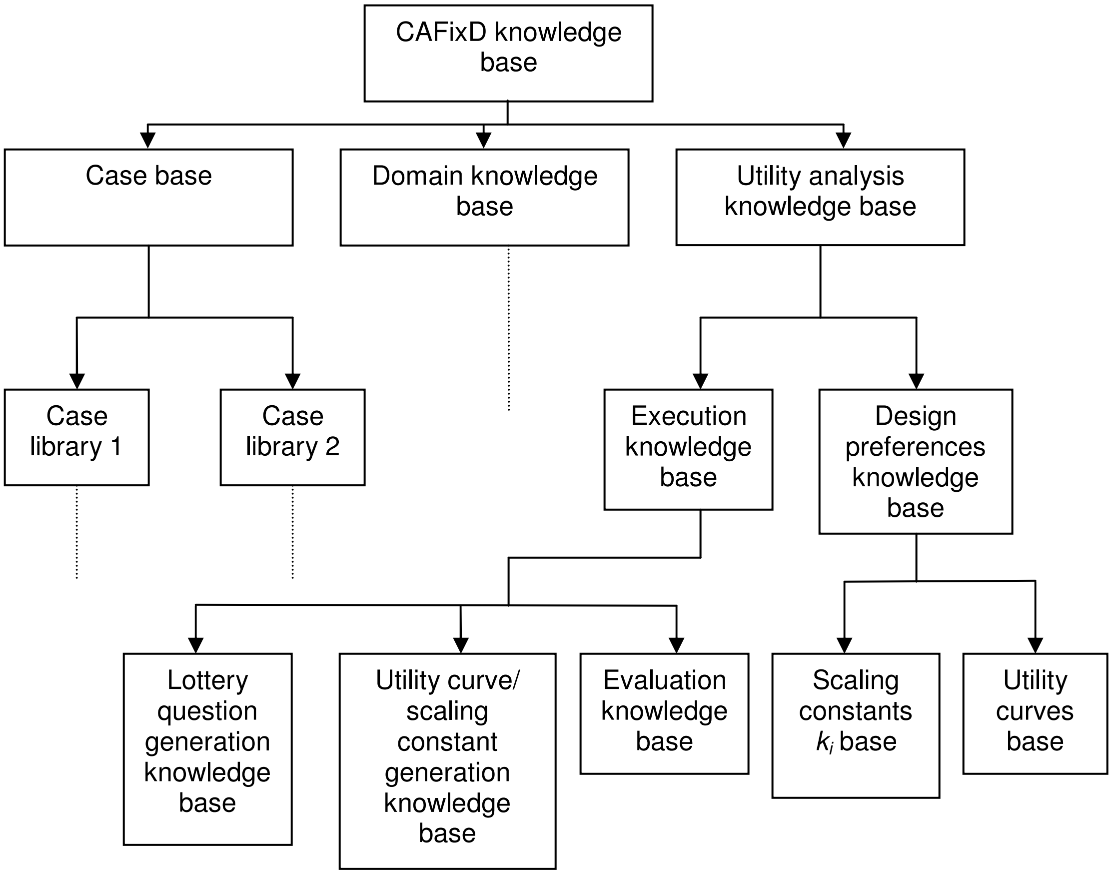


Figure 129: Databases that support CAFixD operation

The execution knowledge base contains knowledge of how to control the lottery question process and the utility curve generation store contains knowledge for generating the equivalent function of the curve. In CAFixD all curves are approximated to cubics. The evaluation knowledge base contains knowledge on how to determine the overall utility of a fixture design and how to evaluate different DP/adaptation strategy combinations.

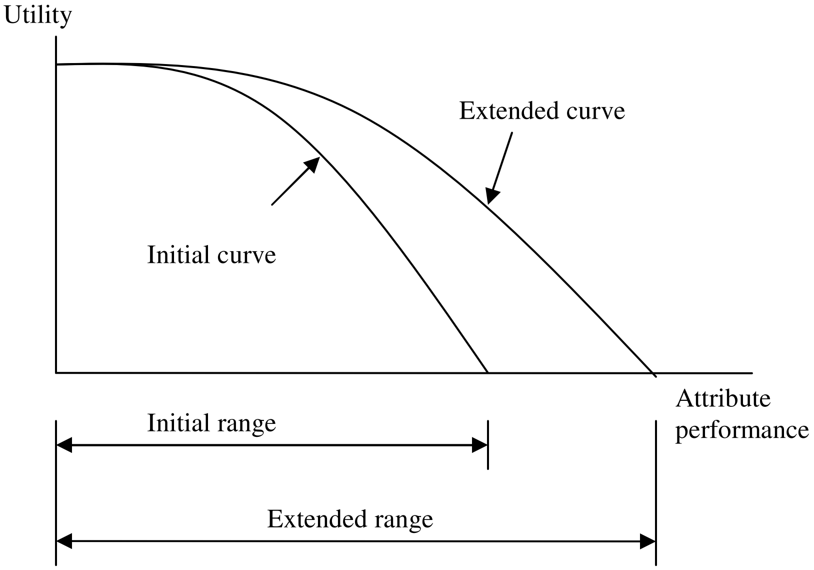


Figure 130: Modifying a utility curve

The remaining base contains the domain knowledge that supports both the FR generation and retrieval stages. Its contents, detailed in Figure 131, assist both the conceptual and detail design phases. The indexing knowledge base assists both the selection of a suitable locating principle design from case library 1 and subsequent refinement of the FR skeleton associated with the locating principle. Initially the DSMRG knowledge base is used to generate the DMSRG for the workpiece. This DMSRG (introduced in section 2.1.1) is a set of graphs that illustrate the relationship between the datum and machining surfaces in a particular setup. The DMSRG is subsequently analysed using knowledge from the locating knowledge store to determine the locating surfaces, subsequent conceptual model, locating point distributions, and position coordinates.

The tolerance analysis knowledge base supports refinement of the FR/DP skeleton by using the:

- tolerance type and sensitivity analysis knowledge bases to perform the sensitivity analysis;

- tolerance type and tolerance analysis knowledge bases to perform the tolerance analysis;
- tolerance assignment knowledge bases to support the tolerance assignment stage of the design process.

Applying knowledge from these sources results in the completion of the first group of FRs, which state the locating requirements for a workpiece. The force analysis knowledge base is used to refine the second group of FRs related to fixture stability. This knowledge helps determine the clamping orientations, surfaces, and coordinates. In addition it is also used to calculate the required stiffness at each locating and clamping point, and the required clamping forces.

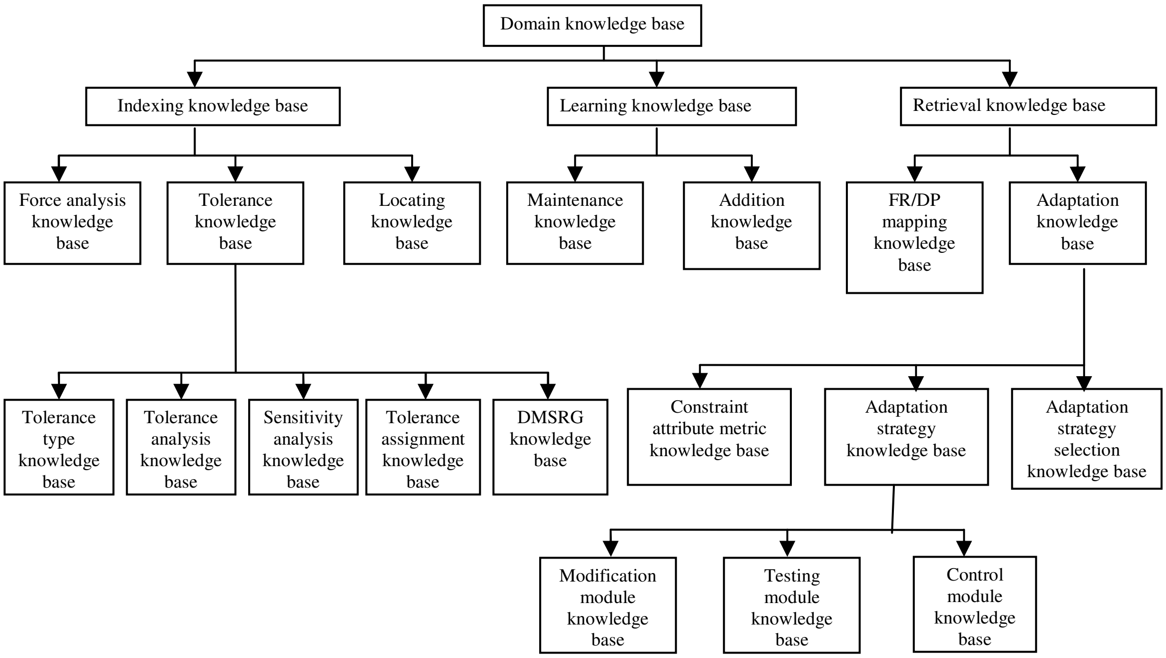


Figure 131: The domain knowledge database

The learning knowledge base assists the learning process with CAFixD. The addition knowledge base is used to control the process of storing new cases in the case library (in terms of where they should be put). The maintenance knowledge base is used to govern the maintenance of case library 2 by evaluating the usefulness of cases and determining those which are to be removed.

The retrieval knowledge base contains knowledge relating to both the functional similarity-based and adaptability-based retrieval processes. The former is a rule base used to determine which DPs in case library 2 can qualitatively satisfy each FR, and which FRs have common solutions. The adaptation knowledge base contains the adaptation strategies and the rules for selecting particular strategies. The adaptation strategy knowledge source contains the modification, testing, and control modules used in different adaptation strategies. The constraint attribute metric knowledge base contains the heuristic knowledge used to calculate a unit's performance values for each global constraint attribute.

6.3 Information Flows

The operation of CAFixD can be decomposed into four main processes. Initially the fixture conceptual design and the design FRs are generated. Following this the design preferences are recorded, which includes defining the global constraint attributes that apply for a given design situation and utility curves for each of those attributes. In the third process, the two stage case retrieval procedure is executed. Finally, the design modification file is created and maintenance of the case base is performed. Presented in the following four sections are the information flows for each process, which highlight where the knowledge required for the completion of each process is obtained.

6.3.1 Process 1 – Conceptual Design Generation

CAFixD requires input from external sources when developing the conceptual design using the process depicted in Figure 132. In this design stage, CAFixD is defining the fixture design problem statement, hence the need for considerable external input.

Information is sought from the CAD system regarding the workpiece information, from the CAPP system regarding machining process data, and from the user regarding specific requirements (i.e., which ergonomic FRs are required – as has been stated previously, these requirements cannot be generated automatically and need to be specifically requested by the designer). The output from this stage is the completed FR list detailing all locating, stability, and ergonomic requirements.

6.3.2 Process 2 – Generating Utility Curves and Scaling Constants

The generation of utility curves and scaling constants (Figure 133) is conducted interactively with the user. Lottery questions are generated for each FR and constraint, and the user response to each question is monitored and used to guide the lottery question generation process. The utility curves are then generated and stored in the system for use during case retrieval. The process is repeated to determine the scaling constants for each global constraint attribute. This is a fairly time consuming process, thus there is also the option for the user to simply choose a set of previously stored curves and either use them directly or modify them as desired.

6.3.3 Process 3 – Retrieval

From the retrieval stage onward the system requires no further user input and draws from its own knowledge sources to complete the design process, as illustrated in Figure 134. The functional mapping knowledge is used to identify cases within case library 2 that are able to satisfy either single FRs or groups of FRs. An initial reference design is then generated from these candidate cases and the global constraint attribute performance values for that design calculated using knowledge from the constraint metric base.

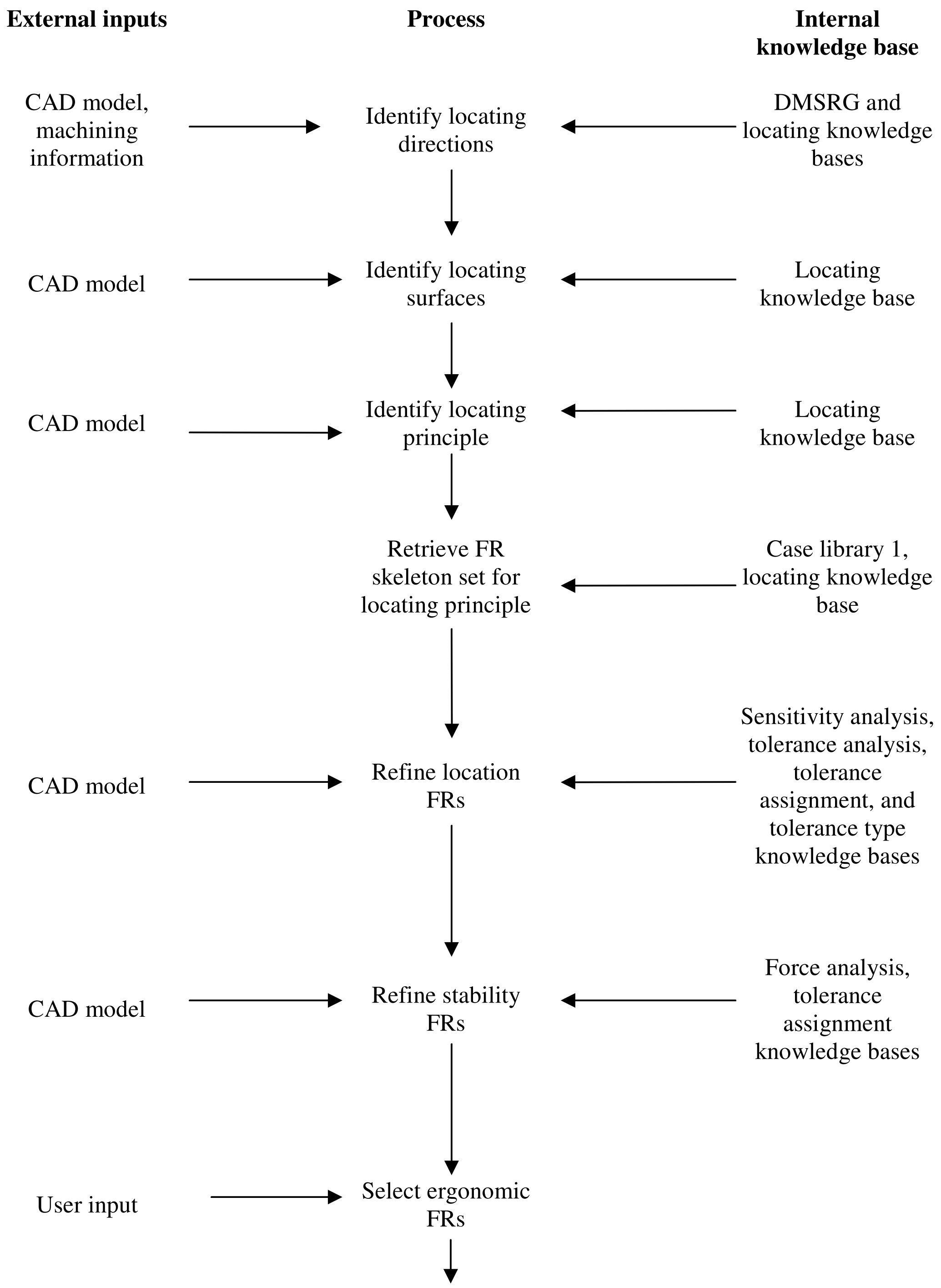


Figure 132: Generating a conceptual design

Adaptability guided retrieval is the most intensive operation CAFixD performs, where the system attempts to see into the future by determining both what modifications are required and also their likely impact. The adaptation strategy selection knowledge identifies the relevant strategies that can be used to fix designs, and the implementation of these strategies is controlled by their control modules. Modifications are implemented using knowledge from the modification modules base and subsequently tested. The constraint metric knowledge is used to calculate the attribute performance values of the repaired design and the evaluation module from the utility analysis knowledge base evaluates and ranks the DP/adaptation strategy combinations based upon the updated constraint attributes for the new fixture design. The highest ranked DP/adaptation strategy combinations for each FR or group of FRs are then chosen as the final design solutions.

6.3.4 Process 4 – Design Modification and Case-base Maintenance

The final operations that CAFixD performs are to generate the modification file that is passed onto the CAD system, and to maintain the case library. The fixture design "assembled" during the adaptability-based retrieval stage is proposed as the final design: i.e., this complete fixture design consists of the top ranked (as determined by the utility analysis evaluation module) individual design cases retrieved from case library 2. The modifications for that design are formulated and the modification file generated using the modification knowledge from the adaptation knowledge base.

The system then adds the individual units from the design to the appropriate sections of case library 2. The library is then subjected to maintenance, which is the removal of knowledge that fails to meet the usefulness criteria. This criteria is based upon how often knowledge is successfully used, and that which is rarely recalled is deleted from the case library, subject to the restrictions described in section 4.2.5 that are designed to ensure a good spread of case knowledge exists throughout the library.

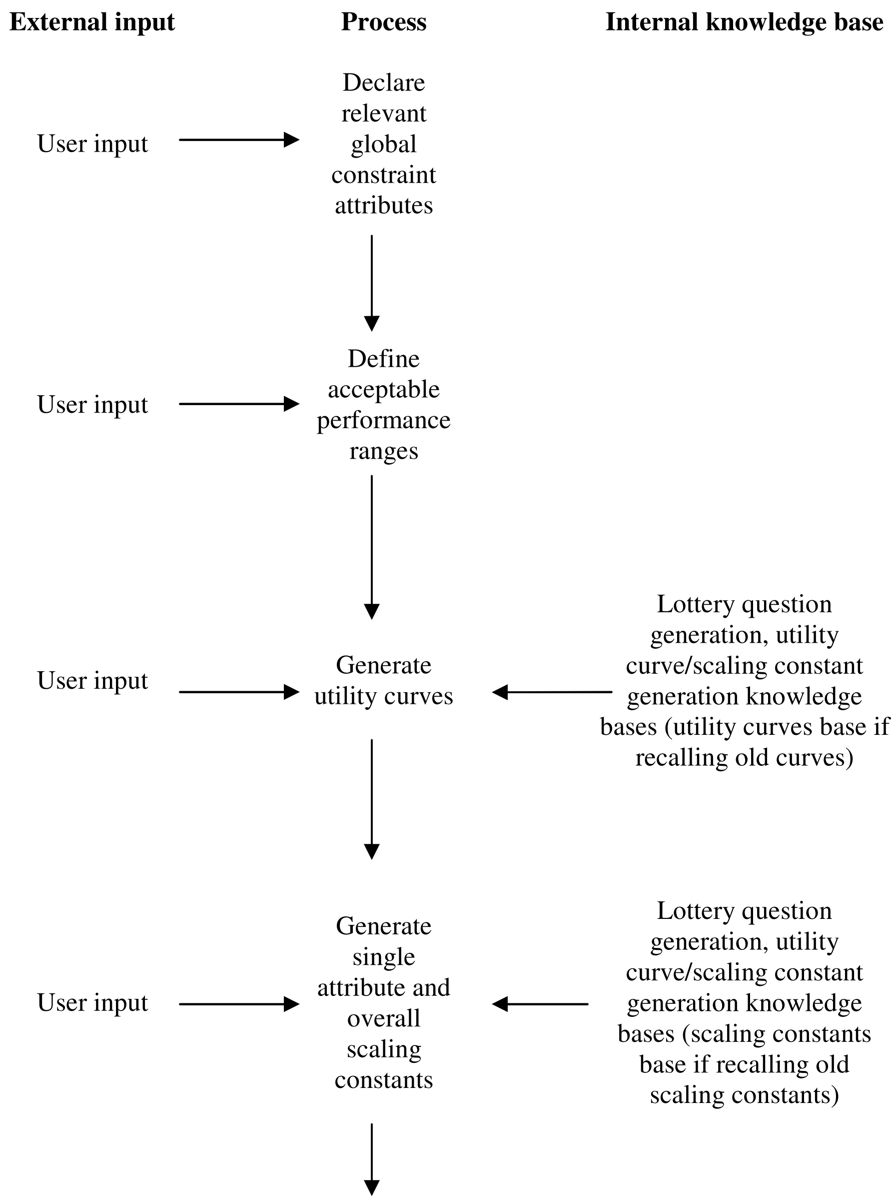


Figure 133: Generating utility curves and scaling constants

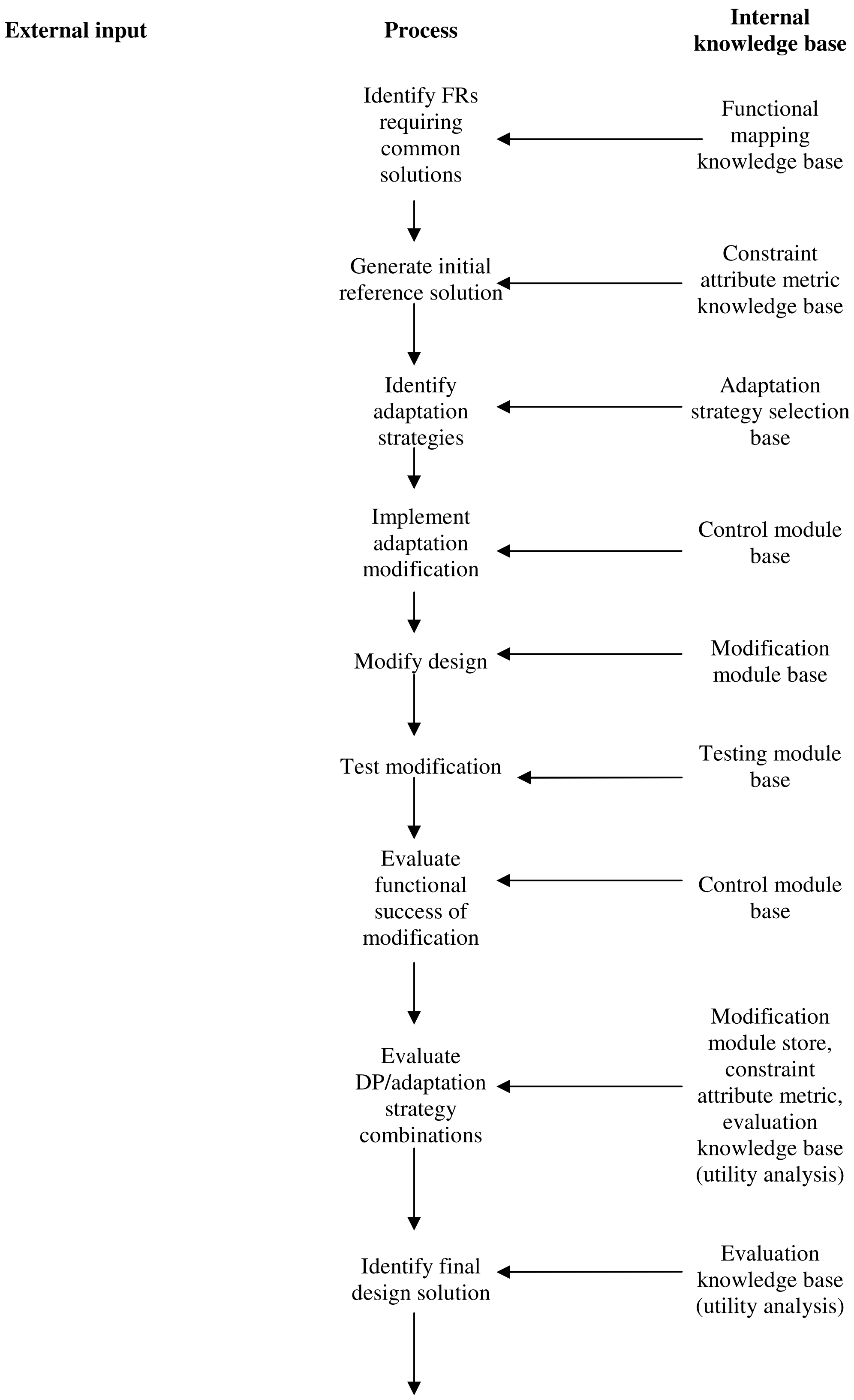


Figure 134: Retrieval based upon functional similarity

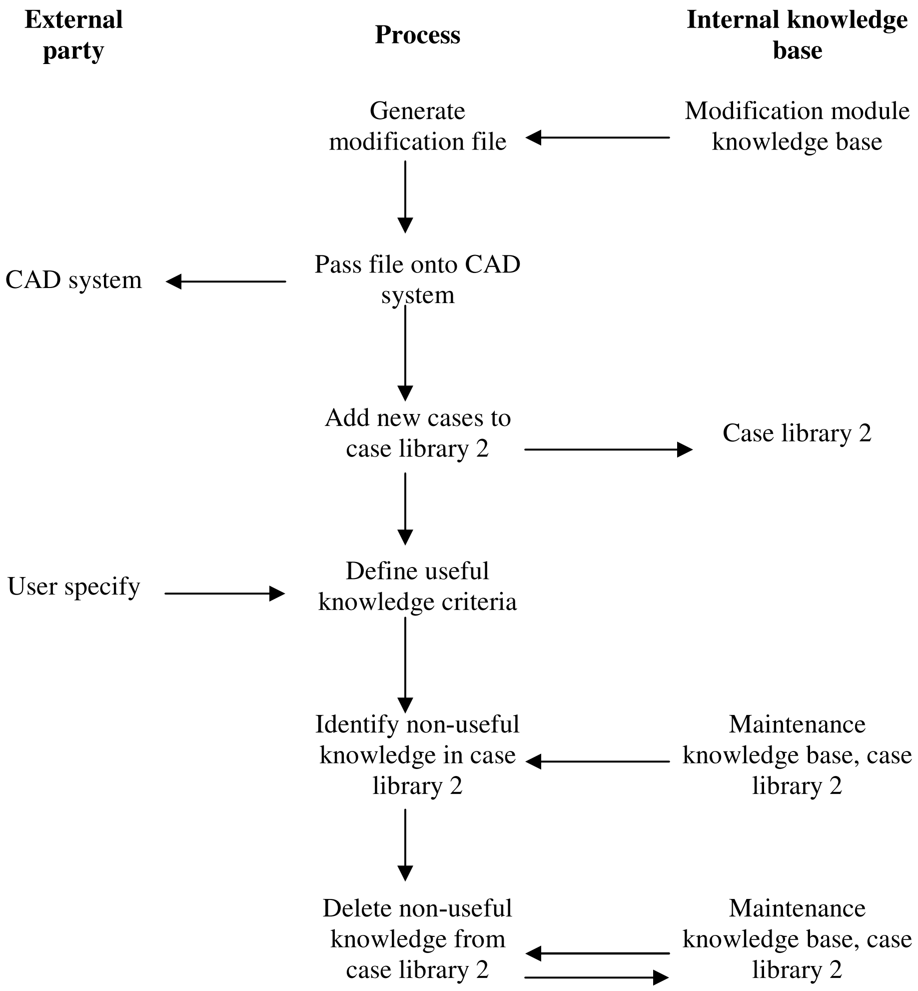


Figure 135: Modification and case-base maintenance

6.4 Data Formats and Communication

Section 5.3 highlighted that CAFixD communicates with other CAD/CAM systems. For successful communication to be possible, specific formats for the transfer of information between systems need to be defined. This section outlines the formats in which information is passed, as well as defining the nature of that information.

6.4.1 Data Format for Workpiece Information Transfer from CAD System

To assist in the generation of the conceptual fixture design (i.e., determination of the locating principle and locating/clamping points), CAFixD requires a significant amount of knowledge regarding the geometry of the workpiece. Specifically, CAFixD needs a list of the surfaces that comprise a workpiece and subsequent details of those surfaces. Currently CAFixD supports plane and hole surface types. Typical information required about a surface:

- the surface type;
- the surface identification tag;
- the surface material;
- the surface status (is it a surface that is to be machined, or has been machined, or has not been and is not due to be machined);
- the number of tolerances existing for a surface;
- the tolerance details (tolerance type, value, and datums);
- position of the local coordinate system of the surface relative to the workpiece coordinate system;
- orientation of the surface normal with respect to the workpiece coordinate system;
- the dimensions of the surface.

The geometric information required for each surface type varies. For a rectangular plane (RPLANE) the position and orientation of the surface's local coordinate system (LCS) relative to the workpiece global coordinate system (WCS) are required. The positive z axis of the LCS points directly into the surface. Looking into the surface, the LCS is located at the bottom left hand corner. The length value acts in the LCS x direction, and the height value in the LCS y direction, as depicted in Figure 136.

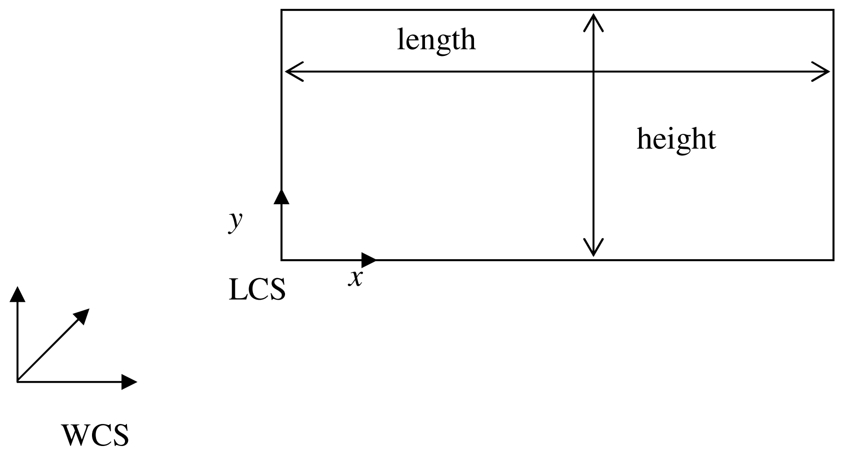


Figure 136: The geometric data of a rectangular plane

For a hole (HOLE) the position and orientation of the surface's local coordinate system (LCS) relative to the global coordinate system (GCS) are required. The LCS is located at one end of the central axis of the hole, with the positive *z* axis of the LCS pointing directly into the hole. The diameter and depth of the hole also have to be defined.

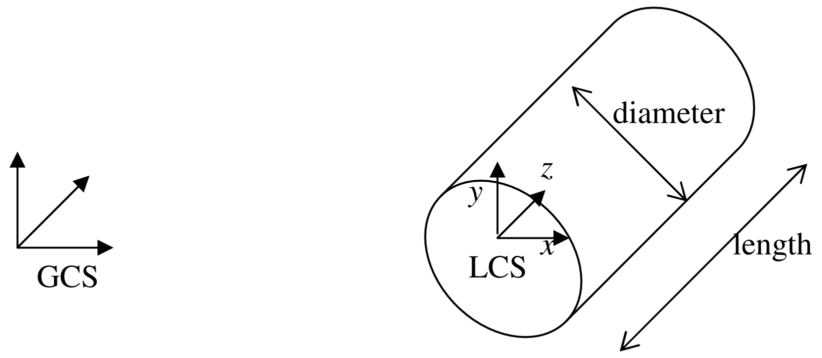


Figure 137: The geometric data of a hole

The data needs to supplied in an Excel worksheet and the data file for the workpiece from the example presented in section 4.4 can be viewed in Appendix G.

6.4.2 Data Format for Machining Information Transfer from CAPP System

To determine the both the fixture stability and locating tolerance requirements, CAFixD requires information regarding the machining processes the workpiece will undergo, as well as the accuracy of the machine tool itself. The specific machining information required is:

- machine type (e.g., vertical machine tool);
- accuracy along the *x, y,* and *z* axes;
- accuracy around the *x, y,* and *z* axes;
- machined surface;
- machining operation type;
- tangential and thrust machining forces ;
- toolpath type;
- initial direction of cutting tool.

As with the workpiece information, this data needs to be supplied in the form of an Excel worksheet, and the machining data for the example presented in section 4.4 can be viewed in Appendix H.

6.4.3 Data Format for Fixture Design Information Transfer with CAD System

The information required for each design case is held in the form of a case schema with an attached element schema which contains details of the individual elements that comprise a unit. These are held within case library 2 (again in an Excel spreadsheet) and are a direct replication of the schemas detailed for units in section 4.2.4. A sample schema for the clamping unit used for the example in section 4.4 is presented in Appendix B.

6.4.4 Data Format for Modification File Passed to CAD System

The output from CAFixD is a modification file (in Excel format) listing the necessary changes that need to be made to fix a current design. To perform the modifications the CAD system itself needs to have both an interface file to interpret the CAFixD modification file and a parametric modelling capability to subsequently perform the modifications on a design case. The CAFixD modification file details changes to:

- the dimensions of an element (length, height, and width);
- the material type of an element;
- the position of an element within a particular limb;
- the connections between elements (including length, diameter, and position of connectors).

A sample output file is presented in Table 45 for element 10 of the repaired clamping unit created during the example in section 4.4. The full modification file is presented in Appendix I. Element 10 has its length increased from 2 inches to 2.175 inches. All mating holes are subject to an increase of 0.0875 inches and the mating to connector has an increase in length of 0.0875 inches. The thickness (*start_b* and *end_b* dimensions) is increased to 0.8968 inches, as is the width (*start_h* and *end_h* dimensions). The “mate to” connector holes have their diameters increased as a result of the element cross section dimension changes to 0.112 inches, on an increased diameter offset of 0.673 inches. The “mate from” hole diameter is increased to 0.4968 inches to accommodate the dimension increase in the connecting fulcrum element, but remains centred within element 10.

Element number:	10
Set length to:	2.175
Modify connector hole depth by:	0.0875
Connector hole depth measured from:	'Mating to' surface:
Modify connector length by:	0.0875
Modify connector hole depth by:	0.0875
Connector hole depth measured from:	'Mating from' surface:
Set start_b dimension to:	0.8968
Dimension measured:	Across local central axis
Set 'mate to' connector diameter to:	0.1121
Set 'mate to' connector hole diameter to:	0.1121
Set connector offset (mate to) diameter to:	0.6726
Set 'mate from' connector hole diameter to:	0.4968
Set connector offset (mate from) diameter to:	0
Set end_b dimension to:	0.8968
Dimension measured:	Across local central axis
Set start_h dimension to:	0.8968
Dimension measured:	Across local central axis
Set end_h dimension to:	0.8968
Dimension measured:	Across local central axis

Table 45: The modification list for element 10

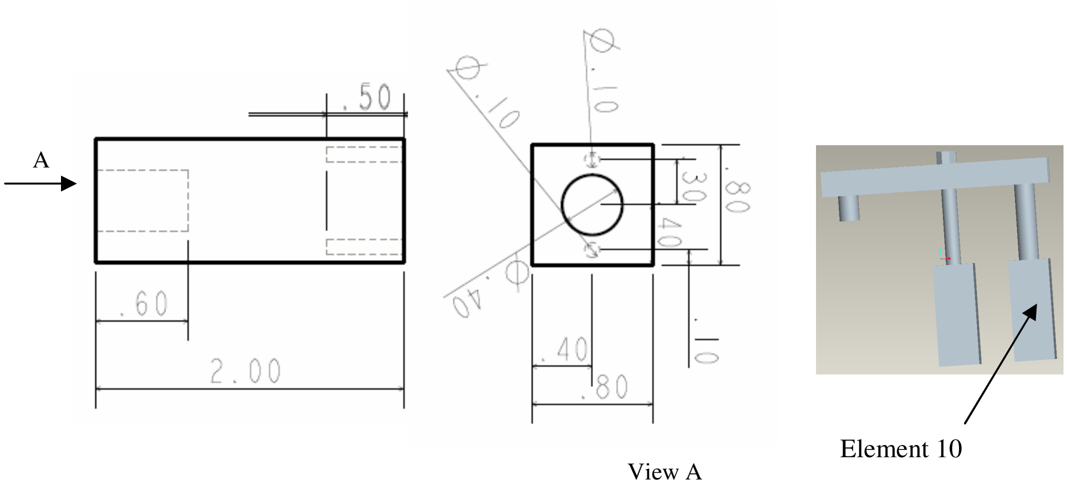


Figure 138: Element 10 before modifications

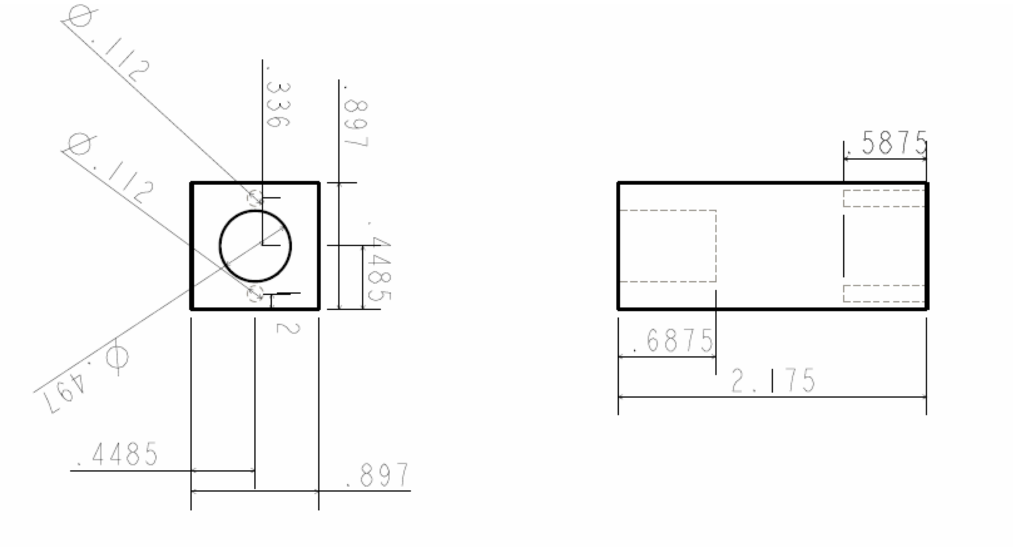


Figure 139: Element 10 after modifications

6.5 System Interface

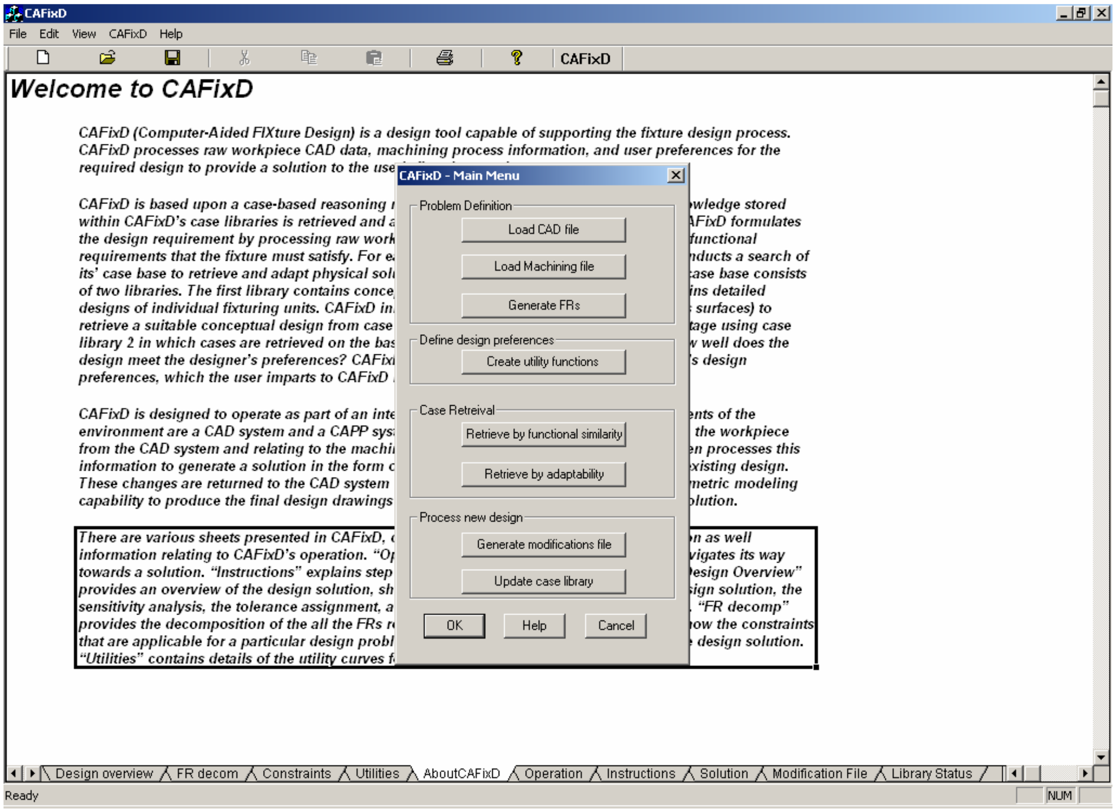
CAFixD is a menu driven system that attempts to guide the user sequentially through the fixture design process. The system accepts user input and then performs setup planning, fixture planning, unit design, and verification. Information is gathered from the user and other systems through dialogs, processed internally by CAFixD, and then relevant outputs are displayed to the user. CAFixD was created using both Visual C++ and Tidestone Formula One Version 6. The Tidestone software is a workbook design package that generates spreadsheet applications. This greatly facilitates the transfer of information to and from Excel worksheets, and is also a useful means of displaying CAFixD outputs to the user during execution. Furthermore, most users will already be familiar with the layout of a spreadsheet package and should therefore be comfortable with the layout of the CAFixD program and be able to navigate through it with some facility.

The main CAFixD screen is presented in Figure 140. The menu is divided into four main sections that represent the main stages of the design process. Initially, the design problem must be specified and expressed as a list of functional requirements that the design must satisfy. The designer inputs the workpiece and machining data to allow CAFixD to process this information, and also specifies which ergonomic FRs and constraints apply. The second stage involves the design preferences in the form of utility curves and scaling constants. Case retrieval is then performed on the basis of functional similarity and then adaptability, before the new design is subsequently processed (generation of the modifications file and maintenance of the case base).

As illustrated in Figure 140, there are ten sheets used to display information to the user. The first sheet (Design overview) is used to display an overview of the design and the design process to the user. Particular information displayed includes:

- the basic locating principle, the locating points, surfaces, and coordinates;
- the sensitivity analysis table;
- the tolerance assignment table;
- the machining forces acting on each locating point;
- all units retrieved during the functional similarity-based retrieval stage;
- the utility analysis results for each FR;
- any features that were not machined in the current setup.

The “FR decomposition” sheet lists the completed FR/DP skeleton for a problem, such as that presented in Appendix D. The “Constraints” sheet lists the global constraint attributes applicable to the design problem and their respective values. The “Utilities” sheet contains the details of the utility curves and scaling constants for each of the constraint attributes. The “About CAFixD”, “Instructions”, and “Operation” sheets are information sheets providing various operational details and help with regard to using CAFixD. The “Solution” sheet contains the completed schemas of the final design solutions for each FR or group of FRs. The “Modification file” sheet contains the modification lists for each element within each design solution. The final sheet presents a review of the case library status, an example of which is presented in Figure 141. Shortfalls in the case library 2 knowledge base are highlighted in red, and shortfalls occur when the net number of case example for a case type is less than the minimum acceptable number specified by the user.



Welcome to CAFixD

CAFixD (Computer-Aided FIXture Design) is a design tool capable of supporting the fixture design process.
CAFixD processes raw workpiece CAD data, machining process information, and user preferences for the
required design to provide a solution to the use

CAFixD is based upon a case-based reasoning wledge stored
within CAFixD's case libraries is retrieved and a AFixD formulates
the design requirement by processing raw work functional
requirements that the fixture must satisfy. For e nducts a search of
its' case base to retrieve and adapt physical sol ase base consists
of two libraries. The first library contains conce ins detailed
designs of individual fixturing units. CAFixD in surfaces) to
retrieve a suitable conceptual design from case tage using case
library 2 in which cases are retrieved on the bas w well does the
design meet the designer's preferences? CAFix 's design
preferences, which the user imparts to CAFixD

CAFixD is designed to operate as part of an inte nts of the
environment are a CAD system and a CAPP sys the workpiece
from the CAD system and relating to the machi en processes this
information to generate a solution in the form xisting design.
These changes are returned to the CAD system metric modeling
capability to produce the final design drawings olution.

There are various sheets presented in CAFixD, n as well
information relating to CAFixD's operation. "O vigates its way
towards a solution. "Instructions" explains step esign Overview"
provides an overview of the design solution, sh ign solution, the
sensitivity analysis, the tolerance assignment, a . "FR decomp"
provides the decomposition of the all the FRs r ow the constraints
that are applicable for a particular design probl design solution.
"Utilities" contains details of the utility curves f

Figure 140: The main CAFixD Screen

Case Type	Total number	Cases involved in too few retrievals	Net number
VL011	2	0	2
VL012	1	0	1
VL013	3	0	3
VL021	1	0	1
VL022	2	0	2
VL023	0	0	0
VL024	0	0	0
HL011	1	0	1
HL012	1	1	0
HL013	1	0	1
HL021	1	0	1
HL022	1	0	1
HL023	2	0	2
HL024	0	0	0
COML011	0	0	0
COML012	0	0	0
COML013	0	0	0
COML021	0	0	0
COML022	0	0	0
COML023	0	0	0
COML024	0	0	0
HC011	2	2	0
HC012	0	0	0

Figure 141: The status of case library 2

7. Conclusion

Thus far the objectives of the CAFixD methodology, the method itself, and a worked example of its operation have been presented. This chapter presents a review of how effective the CAFixD method is with regard to the objectives outlined in Chapter 3. Initially in section 7.1 the contributions of the CAFixD method are presented, followed by an evaluation of its effectiveness, culminating in a number of recommendations that if implemented would improve the effectiveness of the method.

7.1 Contributions

Overall the CAFixD approach involves decomposing a design problem into a number of sub-problems and obtaining solutions for each of those sub-problems, such that a satisfactory design solution is attained that meets the overall design requirement. The design requirement is rigorously defined by analysing the workpiece geometry, design tolerances, and machining forces. Initially the workpiece design datums are used to select a suitable conceptual locating model and its skeleton FR set from case library 1. By performing a sensitivity and tolerance analysis, the allowed tolerance allocated to each locating point within the conceptual model can be determined. These analyses allow the skeleton FR set to be completed and the design process progresses to obtaining individual units that satisfy the FRs generated for each locating and clamping position.

The complete fixture design is gradually developed one unit at a time in a basic hill climb approach. Identified candidate design cases (DPs) for particular FRs are retrieved from case library 2 and adaptation strategies are identified that can adapt the design so that it satisfies the new FR. Successful DP/adaptation strategy combinations are then evalauated with regard to how well they satisfy the preferences of the designer. These preferences relate to the global constraint attribute performance levels for the complete fixture design. Those combinations that best match the design preferences are chosen as the final solutions, and this process is repeated for each FR. Decision making within this stage of the design process is guided by preferences of the designer. The method reacts to the wishes of the designer and does not seek to impose its own desires upon the design solution. It provides a means for making decisions but the actual decisions made will be dependent upon the designer's preferences. In this way the method seeks to support designers, not replace them.

The contributions of the CAFixD method are argued from two positions. One is from a theoretical standpoint in terms of contributions towards design theory. The second is from a more application based viewpoint of developing an intelligent tool to assist fixture design.

From a theoretical standpoint, the contributions towards the process of design are mostly related to CBR and are argued to be:

- The integration of three design theories into a single functioning design method. The CAFixD method is modelled on a case-based reasoning form, but traditional CBR techniques have been replaced with alternative design theories. In particular axiomatic design is used as the chief means by which cases are indexed, and utility analysis is used to control the decision making process during retrieval.
- Axiomatic design decomposition is used to overcome the indexing problem inherent with any CBR approach. The surface attributes of a design problem are considered customer attributes (in axiomatic design parlance) and are analyzed to determine the specific functions that the design solution must satisfy.
- The use of utility analysis allows designers to express their preferences with greater clarity than possible with standard linear weighting techniques often associated with CBR techniques.
- Retrieval is split into two stages to overcome the computational issue often associated with adaptability-based retrieval. Initially functional mapping vets candidates in the case library to identify feasible candidate solutions. Adaptability-based retrieval then assumes control of generating design solutions by identifying possible means of repairing designs, instigating each repair strategy in turn, and evaluating each repair

against the wishes of the designer. Emphasis during retrieval is based upon satisfying the designer’s preferences, and extends beyond just finding something that functionally satisfies the design problem.

- The “adaptation mapping layout” is proposed as a representation to show both the relationships between FRs, DPs, and PVs, and the effects of implementing any particular adaptation strategy (in terms of calculated utility and the effects upon other parts of a DP caused by the implementation of a particular adaptation strategy).

Within the CAFD field, the contributions of the CAFixD method are argued to be:

- The development of a method that can assist all four stages of fixture design. Specifically:
    - The CAFixD method can identify multiple setups during setup planning.
    - During fixture planning the CAFixD method can identify feasible locating principles for workpieces, identify surfaces to be used for location and clamping, as well as the coordinates of the contact points, and provide an initial estimation of the locating tolerances.
    - During unit design the CAFixD method can generate individual clamping and locating units based upon an understanding of the allowed deflections of these units. This is achieved through an analysis of the machining and clamping forces together with the workpiece tolerance requirements.
    - During verification, the CAFixD method can confirm if a generated design is capable of satisfying the FRs associated with it by using a solid understanding of how a particular unit behaves. For example the stiffness analysis uses knowledge of how each fixture unit responds to experienced forces when evaluating if the unit is stiff enough and will allow the design tolerances to be achieved.
- The generation and use of a comprehensive formulation of the fixturing requirement to drive the design process. This understanding includes:

  - workpiece geometry;
  - workpiece design tolerances;
  - workpiece stability;
  - fixture unit stiffness;
  - fixture cost;
  - fixture usability;
  - fixture component collision;
  - fixture weight;
  - workpiece loading and unloading times;
  - fixture unit assembly times;
- The development of a method for determining the physical structure individual fixture units should assume. This generation of physical units is based not just upon satisfying workpiece geometry, but also upon the behaviour required of them: e.g., their displacement when subjected to machining forces.

7.2 Evaluation

Evaluation of the CAFixD method reveals not only its strengths as detailed in the previous section but also some aspects to which greater attention could be paid. The first such area relates to optimizing the utility, to which there are two limitations with the CAFixD method. Currently each adaptation strategy is evaluated in isolation, but an alternative approach might be to consider merging strategies together when searching for a solution. Consider the example of modifying a vertical unit to satisfy a stiffness requirement. The objective is to find the cheapest solution. A candidate case has the dimensions presented in Figure 142 and is made of material A, which has a modulus of elasticity of 28E6 lb/in. The unit stiffness is 2.53E6 lb/in.

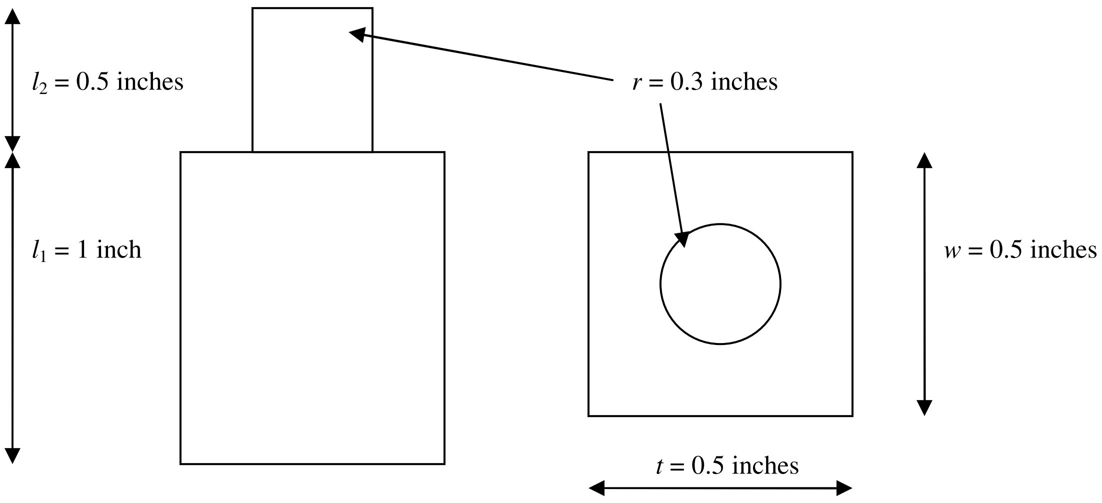


Figure 142: A vertical locating unit

Suppose that the desired stiffness is 6.1E6 lb/in. There are two possible adaptation strategies. One is to alter the cross sectional dimensions of the unit, and the other is to alter the material type. The available materials are A and B and their properties are listed in Table 46. Of the two strategies, only the dimension modification approach will work if each strategy is implemented in isolation, as illustrated in Table 47. If however the strategies are combined by altering both using material B and altering the dimensions, then a unit of satisfactory stiffness can be achieved at a cost below that obtained implementing the dimension adaptation strategy in its own (see Table 47). Thus combining strategies has resulted in the generation of a cheaper solution.

Material	Modulus of elasticity (lb/in)	Cost (\$/in^3)
A	28000000	3
B	20000000	1

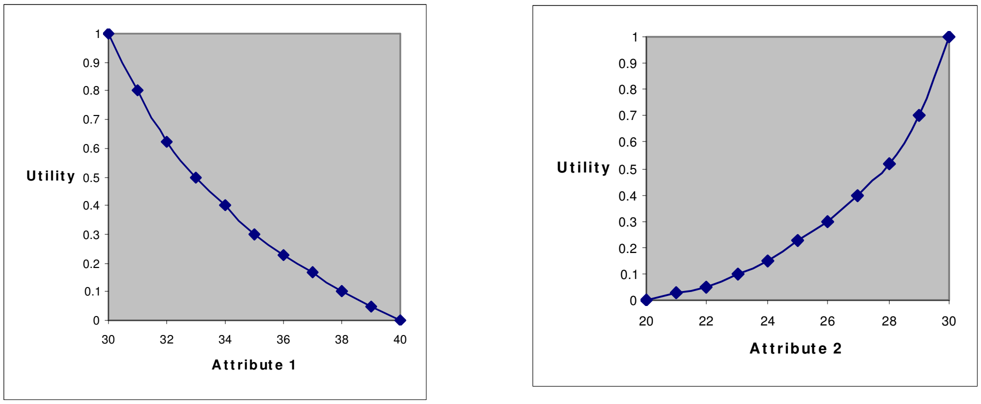
Table 46: Material properties

Unit Attribute	Dimension adaptation strategy	Material adaptation strategy	Combined adaptation strategy
t (inches)	0.7	0.5	0.806
w (inches)	0.7	0.5	0.806
r (inches)	0.5	0.3	0.606
Material modulus (lb/in)	28E6	20E6	20E6
Stiffness (lb/in)	6.1E6	1.8E6	6.1E6
Cost ($)	1.76	0.29	0.79

Table 47: Results gained by implementing the adaptation strategies

A second aspect concerning optimisation is the effect that the timing of design decisions has on attempts to optimize the design utility. Currently the CAFixD method operates on a basic hill climb approach where the local optimum DP/adaptation strategy is chosen for a particular FR, and then the retrieval process moves onto obtaining solutions for the next FR. If presented with two design options at a particular part of the solution progression, then one will be more favorable than the other. However, if the same decision is taken at a later time during the design phase then the outcome may be different because as the design progresses the location of the design within the acceptable performance range for each constraint attribute changes and the preferences at one stage of the design vary from those at another.

Consider for example that a choice has to be made between designs A and B to satisfy a particular FR, both of which make contributions to the performance values of the constraint attributes 1, 2, and 3 for a complete design. For the purposes of the example, it does not matter what these attributes are, but the design preferences for each of them are important and are illustrated in Figure 143. Attribute 1 is a “less-is-better” attribute whereas attributes 2 and 3 are “more-is-better” in nature. The contributions of designs A and B to each of these attribute performance values are presented in Table 48.



Scaling constant values are:
$k_1 = 0.5$;
$k_2 = 0.5$;
$k_3 = 0.1$;

Overall scaling constant $K = -0.2918$

Figure 143: Utility curves for attributes 1, 2, and 3

Design	Attribute 1 contribution	Attribute 2 contribution	Attribute 3 contribution
A	3	3	2
B	1	1	2

Table 48: Contributions of designs A and B to attributes 1, 2, and 3

As the design solution progresses, the attribute performance values for the complete design will change as DPs are chosen for each FR. Remember the approach adopted in the CAFixD method is to incrementally build up the complete design solution by finding individual DP solutions for each FR. Now if a choice is to be made between DPs A and B, then the outcome of that decision will depend upon when the choice is made. Consider two design states. One design state is early on in the solution process, and at that time the attribute performance values for the complete design are 31 (attribute 1), 21 (attribute 2), and 14 (attribute 3). The second design state occurs later on and the performance values for attributes 1, 2, and 3 are 36, 26, and 14 respectively. The two cases are evaluated at both design states. The results of the utility analysis for design state 1 is presented in Table 49, and that for design state 2 in Table 50.

Attribute	Initial value	Design A contribution	Total value	Individual utility	Design B contribution	Total value	Individual utility
1	31	3	34	0.4	1	32	0.62
2	21	3	24	0.15	1	22	0.05
3	14	2	16	0.6	2	16	0.6
			Overall utility	**0.326**		**Overall utility**	**0.387**

Table 49: Design state 1 analysis

Attribute	Initial value	Design A contribution	Total value	Individual utility	Design B contribution	Total value	Individual utility
1	36	3	39	0.05	1	37	0.17
2	26	3	29	0.7	1	27	0.4
3	14	2	16	0.6	2	16	0.6
			Overall utility	**0.43**		**Overall utility**	**0.34**

Table 50: Design state 2 analysis

The important result to note is that at design state 1, DP B is preferable, but at state 2 DP A returns the highest utility. Thus in its current format the CAFixD methodology is unable to understand and handle the dynamic nature of a design solution. To cope with this problem two major tasks must be undertaken:

1. the total number of design states needs to be identified and defined in terms of the attribute performance values for each state;
2. each DP/adaptation strategy option for a particular FR has to be evaluated at each of these design states.

The number of design states is dependent on three items:

1. the number of FRs or groups of FRs for which a solution is sought;
2. the number of candidate DPs for each FR;
3. the number of possible adaptation strategies for each DP.

The number of design states is factorial in nature, and this when added together with the previous suggestion of combining adaptation strategies would result in the need for significant levels of computation in order to optimize the design solution, but the possibility for expanding the method in this way is feasible, if admittedly complex.

Only limited testing of the CAFixD system has been undertaken to date, and specific aspects of the approach require greater levels of validation. In particular various sensitivity analyses need to be performed. These relate to several aspects of the method, but two stand out in particular. The first concerns the utility curves. These curves are currently approximated as cubics and work needs to be done to identify how variation in the accuracy of these curves affects the design outcome. Specifically, the question to be answered is how accurate do the curves have to be. If they are modelled as linear curves instead of cubics, then will that result in a different design solution? Secondly the CAFixD method uses a number of heuristic rules to determine the individual contributions of an adapted design to the global constraint attribute performance levels. Studies need to be performed to determine how accurate these heuristics need to be. For example, the assembly time heuristic assumes a specific time for each assembly operation. During assembly however, these times may not be accurate for the individual person assembling the fixture. The individual may work more or less quickly than the recorded heuristic values. If so, then if this inaccuracy had been incorporated into the design process, would a different solution have been proposed? Such studies have yet to be performed.

Other testing possibilties relate to verifying the accuracy of the unit displacement analysis of clamping and locating units. For example, clamping units are modelled as levers but this represents an approximation of their behaviour. Calculating the stiffness of a clamping unit is a complex issue, and several research efforts are directed towards solving this problem (Zheng, 2005). To evaluate the accuracy of the displacement analysis used in the CAFixD method, experiments need to be performed to compare the measured displacement of a fixture unit with that calculated by the CAFixD method. Depending on the identified accuracy levels, it may be necessary to incorporate a factor of safety into the displacement analysis procedure used in the CAFixD method.

Another form of necessary testing is to compare the fixture designs obtained using the CAFixD method with those generated by an experienced fixture designer, and attempt to determine if the design produced using the CAFixD method is better or worse than that of the designer. Given the limitations of the CAFixD software with regard to workpiece complexity, the workpiece would have to be simple in nature. However, this type of evaluation is very important in determining if the CAFixD method is suited to industrial use. To be used in industry, the CAFixD method needs to be able to design fixtures that instill confidence in those who will use them.

A particularly helpful feature of the system implementation of the CAFixD method is the ability to monitor knowledge levels within the case library through the maintenance facility. Importantly, shortfalls in knowledge can be identified. Currently this is as far as CAFixD goes in terms of evaluating its own knowledge levels but it leaves open the future possibility of the system being able to generate new cases to cover identified shortfalls. Assuming at least one design case already exists within any particular class type, the adaptation knowledge (in the form of adaptation strategies) can be used to generate new cases. The issue to be addressed relates to controlling this process. The adaptation strategies all contain a control module designed to satisfy a specific type FR. Thus to use these adaptation strategies, a new facility would have to be added to the system that would automatically generate FRs that could be passed to the control modules.

Specific challenges in this regard relate to identifying what these FRs should be. One approach may be to randomly generate FRs until the case levels are at the requisite level and then rely on the maintenance mechanism already present within CAFixD to root out cases that are of little benefit. A more targeted approach may be to monitor previous FRs and use these as the basis for generating new cases. For example FR requirements in well populated parts of the library could be copied to sparse areas, and design cases generated to satisfy these FRs. Alternatively if a class type has only two cases in it which satisfy locating unit stiffness values of 20E6 lb/in and 6E6 lb/in, then previous FR values from other parts of the library could be used to determine if it is worthwhile generating::

- a number of cases with stiffness values lower than 6E6 lb/in;
- a number of cases with stiffness values higher than 20E6 lb/in;
- a number of cases with stiffness values between 6E6 lb/in and 20E6 lb/in;
- a number of cases with stiffness values ranging from below 6E6 lb/in to greater than 20E6 lb/in.

A related issue to the case library concerns the maintenance mechanism. Currently a blanket, minimum number of cases is required in each class type, but this could be refined to allow different numbers of cases to be held in different class types. This may be particularly beneficial when working consistently in specific parts of the library. It may be advantageous to allow, within these high activity zones, an increase (which may be only temporary) in the number of allowed cases to increase the likelihood of finding the most satisfactory solution during retrieval.

A second concern with case library 2 is maintaining a diverse range of cases within each class type. The maintenance mechanism can support diversity between class types across the library by virtue of the fact that each class type must have a minimum number of cases within it before maintainenace is performed. However, within a class type no diversity is assured as cases are expunged using criterion based solely upon their retrieval success. This criterion does not include consideration of case diversity. Thus some means of maintining diversity within a class type needs to be determined.

A further refinement may be to offer more guidance when problems occur during design. In the CAFixD software, error messages exist that detail to the user specific problems with the design, and typically these messages will state the likely cause of the problem and offer high level advice on how to correct it. Common examples include errors relating to the generation of any negative tolerance assignments. Figure 144 presents a standard error message displayed by CAFixD. CAFixD will inform the user that a particular tolerance assignment is not achievable due, for example, to the workpiece tolerances or the machine tool accuracy. It does not however fix the problem automatically, but rather makes suggestions and leaves final decisions to the discretion of the user. An alternative approach might be to assume a more proactive role in fixing the problems.

Unable to obtain location tolerance due to a combination of the surface and machine tool tolerances. The machine tool accuracy is the prohibitive factor. Please specify a machine tool with greater accuracy.

Figure 144: An error message displayed by CAFixD

For example, if an unattainable tolerance assignment is observed, CAFixD could automatically attempt to retrieve a machine tool with a suitable level of accuracy from a database of machine tools. A different approach might be to backtrack through the tolerance and sensitivity analyses to identify the workpiece tolerance that is causing the problem, calculate the tolerance value that can be realistically be achieved and request permission to make the change from the user. It is not suggested that CAFixD make these decisions autonomously, but rather provide clear direction for the user. Similarly, adaptation strategies could be refined such that when failure of a strategy occurs, CAFixD may suggest the FR be changed to a performance level at which the strategy can be successfully implemented. Changes of this nature (altering FRs and workpiece tolerances) are essentially a redefinition of the design requirement. Again the purpose here is not to suggest that such changes be implemented automatically by CAFixD. Rather the option should exist whereby CAFixD says to the user:

"The *alter_dimension( )* adaptation strategy has failed for $DP_{2.1.1.1}$. If however the machining force experienced by this DP is reduced from 200 lbs to 150 lbs, then the unit can be successfully modified. Do you wish to make this change?"

Further possibilities for continued research work relate to the third group of FRs, which include requirements for coolant flow channels, tool guides, and error proofing. Currently the adaptation knowledge required for these items has not been generated and the CAFixD tool does not cater for these requirements. The coolant flow channels and tool guides require specific examples of each to be added to the case library, along with the relevant adaptation knowledge. The major difficulty relates to error proofing. The normal solution for such a requirement is to strategically place a number of pins (normally three) on the fixture that will physically prevent the workpiece from being inserted incorrectly into the fixture. Thus the design of the pins and the coordinates of their positions need to be identified. It is difficult to say definitively what the solution to this problem is, but one possible approach might be to generate a grid across the fixture baseplate and vary the position of each error proofing pin by moving it from one grid square to the next. Each time a pin is moved, the workpiece could be virtually inserted into the fixture and an interference analysis performed to ensure that the workpiece is in contact with each of the locators. The analysis would also be performed with the workpiece inserted incorrectly, and the task would be to find the combination of locating pin positions that ensured correct contact with all six locators *only* when the workpiece was oriented correctly.

With respect to the usability of the CAFixD computer software, there are currently limitations. The use of utility analysis is time consuming and although utility curves can be retrieved and reused (for example by stretching them) it is not and is probably never likely to become a standard design tool. The benefit it offers in terms of allowing the expression of a wide range of preferences has not historically outweighed the simplicity of the linear weighting approach (Thurston, 2001). Another feature of CAFixD is that the output is a list of design modifications. Although developed simply as a demonstration tool of the CAFixD method, its appeal to potential users would likely be greatly increased if integrated with a CAD drawing package. This would be a time consuming task but is not necessarily a research issue. An interface program would need to be written to take the written instructions from CAFixD and perform the modifications within the drawing tool. Similarly, integration with a CAPP package has yet to be implemented.

Other issues with the current implementation of CAFixD are that it can only handle simple workpieces consisting of planar surfaces and holes. The inability to cope with complex workpieces is caused by the setup and fixture planning stages, but does not particularly affect the unit design stage. As discussed in chapter 2, much work has been performed by others with respect to these particular aspects of fixture design and has not been repeated here. The contributions of CAFixD with regard to setup and fixture planning have been twofold:

1. the integration of these stages into an overall fixture design method;
2. during the fixture planning stage, the sensitivity and tolerance analyses are targeted towards determining an approximation of the allowed tolerances at each locating point. This is in contrast to the trial-and-error approach adopted by others for example Hu (2001). Having obtained this initial estimate it is suggested that methods such as Hu's be used to refine the solution.

Collision detection has been limited mainly to ensuring that collisions do not occur between the components of individual units. However collisions between individual units and between units and the workpiece or machining toolpath are not considered in

CAFixD. Work on detecting such collisions has been performed by others and has not been repeated here. However a major research issue related to collision detection concerns when it should be performed. Normally such checks are only made when the design is completed. If a problem is found then the obvious implication is that the process must start again. For example if a collision occurs between the workpiece and a clamping unit, then the most obvious options (excluding the possibility of altering the workpiece) are to alter the unit's structure or position. Altering the unit's structure results in a change of stiffness of the unit and altering its position may change the experienced machining force magnitude and possibly the clamping force it has to exert. Either of these effects can result in the need for re-design of the unit.

Ideally such considerations should be included as early as possible to prevent the need for redesign. A possible approach might be to generate a silhouette of a unit when the clamping and locating positions are known, and test that silhouette for any collisions. The silhouette could be generated using domain knowledge, whereby for specific types of units and given the required unit stiffness, the likely overall size of the final design solution can be estimated and this estimate used to check for collision. It is not a foolproof method by any means, and final testing would have to be done using the completed solution at the end of the design process, but the approach would likely reduce the likelihood of collisions occurring.

Comparing the CAFixD system to others developed within the CAFD field, the closest competitors are those created by Joneja & Chang (1999) and Nee & Kumar (1991), both of which assist all four phases of the fixture design process. In terms of supporting setup planning and fixture planning, all systems offer similar levels of functionality. Nee & Kumar do however perform a finite element analysis to determine workpiece deflection caused by machining forces, which is a feature the CAFixD method does not cater for. It can include the workpiece deformation in its tolerance assignment process, but requires a second party to calculate the magnitude of the workpiece deflection. The real advantage of the CAFixD method over these two earlier approaches is the throughness of the unit design and verification phase of CAFixD. These phases are driven by three factors:

- a strong understanding of the fixturing requirement;
- a strong understanding of how units behave;
- a quantitative evaluation mechanism.

During unit design the CAFixD method determines the necessary functions that a unit must perform. For example, the required stiffness at a particular locating or clamping point is calculated and that stiffness, together with an understanding of how a unit behaves, is used to generate units that satisfy this stiffness requirement. Nee & Kumar do not offer this functionality. Stiffness values are assumed for each locating point when performing their finite element analysis of the workpiece. However unit design is based upon satisfying a functional height (as is the case in Joneja & Chang's approach), thus there is no guarantee the unit will provide the required stiffness.

The evaluation process used in the CAFixD method also represents an improvement over these two systems. The most obvious improvement derives from the fact that the CAFixD method incorporates a wider number of design considerations than either Joneja & Chang's or Nee & Kumar's efforts (see Table 2). A second improvement results from the use of utility analysis to support decision making. The earlier research efforts use rules to make decisions between designs. For a limited number of design considerations then this approach may be able to cope adequately with the conflicts of interest that may arise during decision making. However as the number of design considerations increases to the numbers supported by the CAFixD method, then rules are not a particularly practical means of evaluating design options due to the complexities of making tradeoffs between large numbers of design considerations.

A further concern with a rule-based approach is that different designers have different preferences. The preferences stored in these rules are those of the individual who created the rules. They are not necessarily the same rules as the method user: i.e., the fixture designer. Thus these systems impose their own preferences (or more accurately those of the rule-maker) on to the fixture designer, who has no option but to accept them. In contrast, the CAFixD method offers only a means for making decisions in the form of utility analysis. It does not contain any built in preferences and simply responds to the preferences of the designer, making no attempt to impose a will of its own on the user. The designer therefore remains an active member of the design process, and indeed is crucial to the success of the design solution.

7.3 Future Work

On the basis of the discussion in section 7.2, in order to both refine and expand the capability of the CAFixD method, the following suggestions for future work are proffered:

- Investigate means of optimizing the design solution with regard to:
    - combining adaptation strategies during adaptability-based retrieval;
    - accounting for the dynamic nature of the design solution by identifying the optimum point in the process for making design decisions.
- Perform more testing to identify the sensitivity of the CAFixD method to errors in the various heuristics it uses, to approximations in the utility curves, and to simplifications used during the displacement analysis.
- Generate a mechanism whereby, given that the case library can identify its own shortfalls in knowledge, new cases can be generated autonomously to fill these knowledge gaps. The adaptation knowledge exists within the domain knowledge already, thus this task reduces to artificially generating FRs for new design cases.
- Provide a mechanism whereby CAFixD can offer greater levels of guidance when design solutions fail. CAFixD should be able to offer explicit courses of action in times of failure, rather than resorting to high level advice. Such advice may include altering the design requirement in response to a failed adaptation strategy or to an unattainable tolerance assignment.

- Develop the necessary adaptation knowledge that will allow design solutions to be generated for the ergonomic FRs. In particular the significant challenge relates to error proofing fixtures for specific workpieces.
- Create a technique for including verification tasks, such as collision detection, earlier on in the design process to prevent the need for redesign.
- Integrate the current implementation of CAFixD with a CAD to allow it to generate competed drawings. Although not a research issue, this step would greatly improve the “sellability” of CAFixD within the CAFD community.

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Appendix A – FR/DP Skeleton for Plane 3-2-1 Locating Variation 3

FR_{1} – Hold workpiece to the required accuracy
    $FR_{1.1}$ – Locate the workpiece
        $FR_{1.1.1}$ – Provide location directions
            $FR_{1.1.1.1}$ – Provide location direction in y direction
            $FR_{1.1.1.2}$ – Provide location direction in x direction
            $FR_{1.1.1.3}$ – Provide location direction in z direction
            $FR_{1.1.1.4}$ – Provide location orientation around x axis
            $FR_{1.1.1.5}$ – Provide location orientation around y axis
            $FR_{1.1.1.6}$ – Provide location orientation around z axis

        $FR_{1.1.2}$ – Provide contact between locator and workpiece
            $FR_{1.1.2.1}$ – Contact workpiece with locator P1
            $FR_{1.1.2.2}$ – Contact workpiece with locator T1
            $FR_{1.1.2.3}$ – Contact workpiece with locator S1
            $FR_{1.1.2.4}$ – Contact workpiece with locator P2
            $FR_{1.1.2.5}$ – Contact workpiece with locator S2
            $FR_{1.1.2.6}$ – Contact workpiece with locator P3

    $FR_{1.2}$ – Control accuracy of location
        $FR_{1.2.1}$ – Locate workpiece to required drawing tolerances
            $FR_{1.2.1.1}$ – Locate at location point P1 to an accuracy of *xx.xx inches*
            $FR_{1.2.1.2}$ – Locate at location point T1 to an accuracy of *xx.xx inches*
            $FR_{1.2.1.3}$ – Locate at location point S1 to an accuracy of *xx.xx inches*
            $FR_{1.2.1.4}$ – Locate at location point P2 to an accuracy of *xx.xx inches*
            $FR_{1.2.1.5}$ – Locate at location point S2 to an accuracy of *xx.xx inches*
            $FR_{1.2.1.6}$ – Locate at location point P3 to an accuracy of *xx.xx inches*

        $FR_{1.2.2}$ – Compensate for machine misalignment
            $FR_{1.2.2.1}$ – Compensate for machine misalignment *of xx.xx inches* in the y-direction
            $FR_{1.2.2.2}$ – Compensate for machine misalignment *of xx.xx inches* in the x-direction
            $FR_{1.2.2.3}$ – Compensate for machine misalignment *of xx.xx inches* in the z-direction
            $FR_{1.2.2.4}$ – Compensate for machine misalignment *of xx.xx inches* around the x-axis
            $FR_{1.2.2.5}$ – Compensate for machine misalignment *of xx.xx inches* around the y-axis
            $FR_{1.2.2.6}$ – Compensate for machine misalignment *of xx.xx inches* around the z-axis

        $FR_{1.2.3}$ – Compensate for casting variations at locator/workpiece interfaces
            $FR_{1.2.3.1}$ – Compensate for casting variations of *xx.xx inches* at locator P1/workpiece interface

FR$_{1.2.3.2}$ – Compensate for casting variations of *xx.xx inches* at locator T1/workpiece interface
FR$_{1.2.3.3}$ – Compensate for casting variations of *xx.xx inches* at locator S1/ workpiece interface
FR$_{1.2.3.4}$ – Compensate for casting variations of *xx.xx inches* at locator P2/ workpiece interface
FR$_{1.2.3.5}$ – Compensate for casting variations of *xx.xx inches* at locator S2/ workpiece interface
FR$_{1.2.3.6}$ – Compensate for casting variations of *xx.xx inches* at locator P3/ workpiece interface

FR$_{2}$ – Support workpiece against machining forces experienced during machining
FR$_{2.1}$ – Hold workpiece in situ during machining
FR$_{2.1.1}$ – Provide clamping in appropriate directions
FR$_{2.1.1.1}$ – Clamp w/piece against locator P1 with a force of *xx lbs*
FR$_{2.1.1.2}$ – Clamp w/piece against locator T1 with a force of *xx lbs*
FR$_{2.1.1.3}$ – Clamp w/piece against locator S1 with a force of *xx lbs*
FR$_{2.1.1.4}$ - Clamp w/piece against locator P2 with a force of *xx lbs*
FR$_{2.1.1.5}$ - Clamp w/piece against locator S2 with a force of *xx lbs*
FR$_{2.1.1.6}$ - Clamp w/piece against locator P3 with a force of *xx lbs*

FR$_{2.1.2}$ – Support the workpiece during machining
FR$_{2.1.2.1}$ – Ensure locator stiffness at locator P1 is xx lb/in
FR$_{2.1.2.2}$ – Ensure locator stiffness at locator T1 is xx lb/in
FR$_{2.1.2.3}$ – Ensure locator stiffness at locator S1 is xx lb/in
FR$_{2.1.2.4}$ – Ensure clamping stiffness at locator P1 is xx lb/in
FR$_{2.1.2.5}$ – Ensure clamping stiffness at locator T1 is xx lb/in
FR$_{2.1.2.6}$ – Ensure clamping stiffness at locator S1 is xx lb/in
FR$_{2.1.2.7}$ – Ensure locator stiffness at locator P2 is xx lb/in
FR$_{2.1.2.8}$ – Ensure locator stiffness at locator S2 is xx lb/in
FR$_{2.1.2.9}$ – Ensure clamping stiffness at locator P2 is xx lb/in
FR$_{2.1.2.10}$ – Ensure clamping stiffness at locator S2 is xx lb/in
FR$_{2.1.2.11}$ – Ensure locator stiffness at locator P3 is xx lb/in
FR$_{2.1.2.12}$ – Ensure clamping stiffness at locator P3 is xx lb/in

FR$_{2.1.3}$ – Provide clamping points
FR$_{2.1.3.1}$ – Contact workpiece with clamp CP1
FR$_{2.1.3.2}$ – Contact workpiece with clamp CT1
FR$_{2.1.3.3}$ – Contact workpiece with clamp CS1
FR$_{2.1.3.4}$ - Contact workpiece woth clamp CP2
FR$_{2.1.3.5}$ - Contact workpiece with clamp CS2
FR$_{2.1.3.6}$ - Contact workpiece with clamp CP3

FR$_{2.1.4}$ – Provide clamping points
FR$_{2.1.4.1}$ – Provide clamping orientation for clamp CP1
FR$_{2.1.4.2}$ – Provide clamping orientation for clamp CT1
FR$_{2.1.4.3}$ – Provide clamping orientation for clamp CS1

FR$_{2.1.4.4}$ - Provide clamping orientation for clamp CP2
FR$_{2.1.4.5}$ - Provide clamping orientation for clamp CS2
FR$_{2.1.4.6}$ - Provide clamping orientation for clamp CP3

FR$_{2.2}$ – Support free end of workpiece

FR$_{3}$ – Ease the use of the fixture
FR$_{3.1}$ – Prevent damage at the fixture/workpiece interface
FR$_{3.1.1}$ – Prevent damage to the workpiece from the fixture
FR$_{3.1.1.1}$ – Protect workpiece surface at P1/surface interface from damage Y/N
FR$_{3.1.1.2}$ – Protect workpiece surface at T1/surface interface from damage Y/N
FR$_{3.1.1.3}$ – Protect workpiece surface at S1/surface interface from damage Y/N
FR$_{3.1.1.4}$ – Protect workpiece surface at P2/surface interface from damage Y/N
FR$_{3.1.1.5}$ – Protect workpiece surface at S2/surface interface from damage Y/N
FR$_{3.1.1.6}$ – Protect workpiece surface at P3`/surface interface from damage Y/N
FR$_{3.1.1.7}$ – Protect workpiece surface at C1/surface interface from damage Y/N
FR$_{3.1.1.8}$ – Protect workpiece surface at C2/surface interface from damage Y/N
FR$_{3.1.1.9}$ – Protect workpiece surface at C3/surface interface from damage Y/N
FR$_{3.1.1.10}$ – Protect workpiece surface at C4/surface interface from damage Y/N
FR$_{3.1.1.11}$ – Protect workpiece surface at C5/surface interface from damage Y/N
FR$_{3.1.1.12}$ – Protect workpiece surface at C6/surface interface from damage Y/N

FR$_{3.1.2}$ – Prevent damage to the fixture from the workpiece
FR$_{3.1.2.1}$ – Prevent abrasion of the locator P1 by the workpiece material Y/N
FR$_{3.1.2.2}$ – Prevent abrasion of the locator T1 by the workpiece material Y/N
FR$_{3.1.2.3}$ – Prevent abrasion of the locator S1 by the workpiece material Y/N
FR$_{3.1.2.4}$ – Prevent abrasion of the locator P2 by the workpiece material Y/N
FR$_{3.1.2.5}$ – Prevent abrasion of the locator S2 by the workpiece material Y/N
FR$_{3.1.2.6}$ – Prevent abrasion of the locator P3 by the workpiece material Y/N
FR$_{3.1.2.7}$ – Prevent abrasion of the clamp C1 by the workpiece material Y/N
FR$_{3.1.2.8}$ – Prevent abrasion of the clamp C2 by the workpiece material Y/N
FR$_{3.1.2.9}$ – Prevent abrasion of the clamp C3 by the workpiece material Y/N
FR$_{3.1.2.10}$ – Prevent abrasion of the clamp C4 by the workpiece material Y/N
FR$_{3.1.2.11}$ – Prevent abrasion of the clamp C5 by the workpiece material Y/N
FR$_{3.1.2.12}$ – Prevent abrasion of the clamp C6 by the workpiece material Y/N

FR$_{3.2}$ – Assist coolant flow during machining
FR$_{3.2.1}$ – Provide chip shedding
FR$_{3.2.1}$ – Provide chip shedding at locator P1 Y/N
FR$_{3.2.2}$ – Provide chip shedding at locator T1 Y/N
FR$_{3.2.3}$ – Provide chip shedding at locator S1 Y/N
FR$_{3.2.4}$ – Provide chip shedding at locator P2 Y/N
FR$_{3.2.5}$ – Provide chip shedding at locator S2 Y/N
FR$_{3.2.6}$ – Provide chip shedding at locator P3 Y/N
FR$_{3.2.7}$ – Provide chip shedding at clamp C1 Y/N

    - FR$_{3.2.8}$ – Provide chip shedding at clamp C2 Y/N
    - FR$_{3.2.9}$ – Provide chip shedding at clamp C3 Y/N
    - FR$_{3.2.10}$ – Provide chip shedding at clamp C4 Y/N
    - FR$_{3.2.11}$ – Provide chip shedding at clamp C5 Y/N
    - FR$_{3.2.12}$ – Provide chip shedding at clamp C6 Y/N

  - FR$_{3.2.1}$ – Provide a channel to remove coolant and chips from specific surfaces Y/N

- FR$_{3.3}$ – Ease loading and unloading of the workpiece from the fixture
  - FR$_{3.3.1}$ – For heavy workpieces only, provide sliding means to allow location in drilled holes Y/N
  - FR$_{3.3.2}$ – Eject the workpiece from the fixture Y/N
  - FR$_{3.3.3}$ – Provide the capability to slide the workpiece into the fixture in the x direction Y/N

- FR$_{3.4}$ – Assist the tool position during machining
  - FR$_{3.4.1}$ – Guide the cutter for machining hole 1 Y/N

- FR$_{3.5}$ – Error proof w/piece
  - FR$_{3.5.1}$ – Prevent LH/RH confusion Y/N
  - FR$_{3.5.2}$ – Prevent loading upside down Y/N
  - FR$_{3.5.3}$ – Prevent loading inside out Y/N

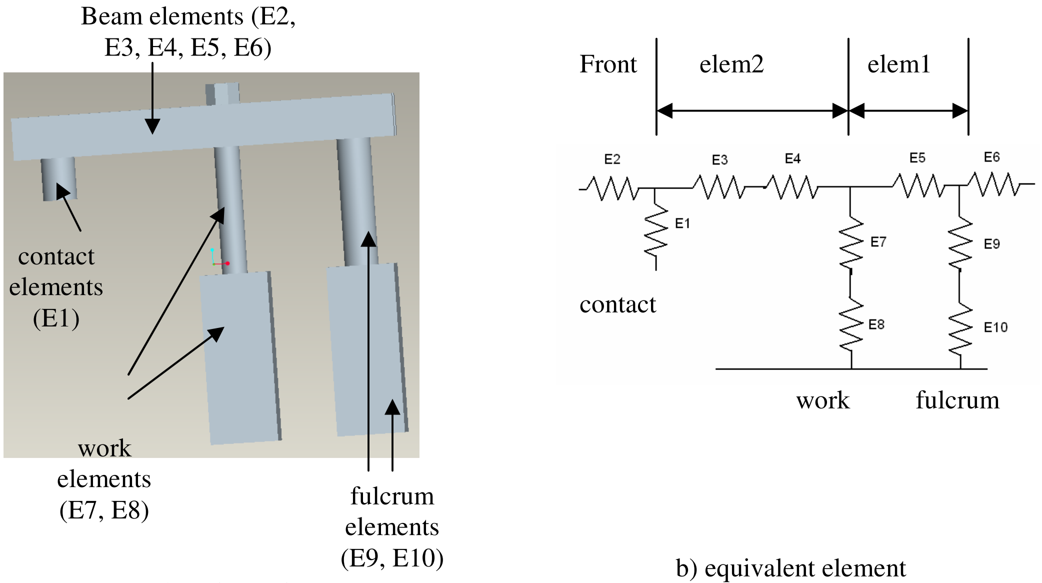
DP_1 Plane	
$DP_{1.1}$ Plane_Var3	
$DP_{1.1.1}$ – Locator/workpiece interface orientation	
$DP_{1.1.1.1}$ – Locator P1/workpiece interface orientation	Surface ID
$DP_{1.1.1.2}$ – Locator T1/workpiece interface orientation	Surface ID
$DP_{1.1.1.3}$ – Locator S1/workpiece interface orientation	Surface ID
$DP_{1.1.1.4}$ – Locator P2/workpiece interface orientation	Surface ID
$DP_{1.1.1.5}$ – Locator S2/workpiece interface orientation	Surface ID
$DP_{1.1.1.6}$ – Locator P3/workpiece interface orientation	Surface ID
$DP_{1.1.2}$ – Workpiece/locator interface contact positions	
$DP_{1.1.2.1}$ – Locator P1 position	Coordinates
$DP_{1.1.2.2}$ – Locator T1 position	Coordinates
$DP_{1.1.2.3}$ – Locator S1 position	Coordinates
$DP_{1.1.2.4}$ – Locator P2 position	Coordinates
$DP_{1.1.2.5}$ – Locator S2 position	Coordinates
$DP_{1.1.2.6}$ – Locator P3 position	Coordinates
$DP_{1.2}$ – Locator unit accuracy parameters	
$DP_{1.2.1}$ – Locator unit tolerances	
$DP_{1.2.1.1}$ - Vertical locating unit tolerance of *xx.xx inches*	Unit ID
$DP_{1.2.1.2}$ - Horizontal locating unit tolerance of *xx.xx inches*	Unit ID
$DP_{1.2.1.3}$ - Horizontal locating unit tolerance of *xx.xx inches*	Unit ID
$DP_{1.2.1.4}$ - Vertical locating unit tolerance of *xx.xx inches*	Unit ID
$DP_{1.2.1.5}$ - Horizontal locating unit tolerance of *xx.xx inches*	Unit ID
$DP_{1.2.1.6}$ - Vertical locating unit tolerance of *xx.xx inches*	Unit ID
$DP_{1.2.2}$ – Spacers between fixture base and machine table	
$DP_{1.2.2.1}$ – Assignment of machine misalignment tolerance of xx.xx inches in the y-direction	Value (inches)
$DP_{1.2.2.2}$ – Assignment of machine misalignment tolerance of xx.xx inches in the x-direction	Value (inches)
$DP_{1.2.2.3}$ – Assignment of machine misalignment tolerance of xx.xx inches in the z-direction	Value (inches)
$DP_{1.2.2.4}$ – Assignment of machine misalignment tolerance of xx.xx radians around the x axis	Value (inches)
$DP_{1.2.2.5}$ – Assignment of machine misalignment tolerance of xx.xx radians around the y axis	Value (inches)
$DP_{1.2.2.6}$ – Assignment of machine misalignment tolerance of xx.xx radians around the z axis	Value (inches)
$DP_{1.2.3}$ – Locator unit spacers at locator/workpiece interfaces	
$DP_{1.2.3.1}$ – Assignment of surface tolerance of xx.xx inches at P1/workpiece interface	Value (inches)
$DP_{1.2.3.2}$ – Assignment of surface tolerance of xx.xx inches at T1/workpiece interface	Value (inches)
$DP_{1.2.3.3}$ – Assignment of surface tolerance of xx.xx inches at S1/workpiece interface	Value (inches)

DP$_{1.2.3.4}$ – Assignment of surface tolerance of xx.xx inches at P2/workpiece interface	Value (inches)
DP$_{1.2.3.5}$ – Assignment of surface tolerance of xx.xx inches at S2/workpiece interface	Value (inches)
DP$_{1.2.3.6}$ – Assignment of surface tolerance of xx.xx inches at P3/workpiece interface	Value (inches)
DP$_{2}$ – Fixture unit force capabilities	
DP$_{2.1}$ – Clamping unit force capabilities	
DP$_{2.1.1}$ – Clamping unit forces	
DP$_{2.1.1.1}$ – Vertical clamp CP1 opposing workpiece/P1 interface with clamping force of *xx lbs*	Unit ID
DP$_{2.1.1.2}$ – Horizontal clamp CT1 opposing workpiece/T1 interface with clamping force of *xx lbs*	Unit ID
DP$_{2.1.1.3}$ – Horizontal clamp CS1 opposing workpiece/S1 interface with clamping force of *xx lbs*	Unit ID
DP$_{2.1.1.4}$ - Vertical clamp CP2 opposing workpiece/P2 interface with clamping force of *xx lbs*	Unit ID
DP$_{2.1.1.5}$ - Horizontal clamp CS2 opposing workpiece/S2 interface with clamping force of *xx lbs*	Unit ID
DP$_{2.1.1.6}$ - Vertical clamp CP3 opposing workpiece/P3 interface with clamping force of *xx lbs*	Unit ID
DP$_{2.1.2}$ – Unit stiffness	
DP$_{2.1.2.1}$ – Locator P1 stiffness of *xx.xx lbs/in*	Unit ID
DP$_{2.1.2.2}$ – Locator T1 stiffness of *xx.xx lbs/in*	Unit ID
DP$_{2.1.2.3}$ – Locator S1 stiffness of *xx.xx lbs/in*	Unit ID
DP$_{2.1.2.4}$ – Clamping unit CP1 stiffness of *xx.xx lbs/in*	Unit ID
DP$_{2.1.2.5}$ – Clamping unit CT1 stiffness of *xx.xx lbs/in*	Unit ID
DP$_{2.1.2.6}$ – Clamping unit CS1 stiffness of *xx.xx lbs/in*	Unit ID
DP$_{2.1.2.7}$ – Locator unit P2 stiffness of *xx.xx lbs/in*	Unit ID
DP$_{2.1.2.8}$ – Locator unit S2 stiffness of *xx.xx lbs/in*	Unit ID
DP$_{2.1.2.9}$ – Clamping unit CP2 stiffness of *xx.xx lbs/in*	Unit ID
DP$_{2.1.2.10}$ – Clamping unit CS2 stiffness of *xx.xx lbs/in*	Unit ID
DP$_{2.1.2.11}$ – Locator unit P3 stiffness of *xx.xx lbs/in*	Unit ID
DP$_{2.1.2.12}$ – Clamping unit CP3 stiffness of *xx.xx lbs/in*	Unit ID
DP$_{2.1.3}$ – Clamping points	
DP$_{2.1.3.1}$ – Clamp CP1 position	Coordinates
DP$_{2.1.3.2}$ – Clamp CT1 position	Coordinates
DP$_{2.1.3.3}$ – Clamp CS1position	Coordinates
DP$_{2.1.3.4}$ - Clamp CP2position	Coordinates
DP$_{2.1.3.5}$ - Clamp CS2 position	Coordinates
DP$_{2.1.3.6}$ - Clamp CP3position	Coordinates
DP$_{2.1.3}$ – Clamping points	
DP$_{2.1.4.1}$ – Clamp CP1/workpiece interface orientation (workpiece surface)	Surface ID
DP$_{2.1.4.2}$ – Clamp CT1/workpiece interface orientation (workpiece surface)	Surface ID

DP$_{2.1.4.3}$ – Clamp CS1/workpiece interface orientation (workpiece surface)	Surface ID
DP$_{2.1.4.4}$ - Clamp CP2/workpiece interface orientation (workpiece surface)	Surface ID
DP$_{2.1.4.5}$ - Clamp CS2/workpiece interface orientation (workpiece surface)	Surface ID
DP$_{2.1.4.6}$ - Clamp CP3/workpiece interface orientation (workpiece surface)	Surface ID
DP$_{2.2}$ – External support unit	Unit ID
DP$_{3}$ – ergonomic design features	
DP$_{3.1}$ – fixture/workpiece interface treatment	
DP$_{3.1.1}$ – fixture interface parameters	
DP$_{3.1.1.1}$ – cross sectional area of contact at P1/workpiece interface	Inches^2
DP$_{3.1.1.2}$ – cross sectional area of contact at T1/workpiece interface	Inches^2
DP$_{3.1.1.3}$ – cross sectional area of contact at S1/workpiece interface	Inches^2
DP$_{3.1.1.4}$ – cross sectional area of contact at P2/workpiece interface	Inches^2
DP$_{3.1.1.5}$ – cross sectional area of contact at S2/workpiece interface	Inches^2
DP$_{3.1.1.6}$ – cross sectional area of contact at P3/workpiece interface	Inches^2
DP$_{3.1.2.7}$ – cross sectional area of contact at C1/workpiece interface	Inches^2
DP$_{3.1.2.8}$ – cross sectional area of contact at C2/workpiece interface	Inches^2
DP$_{3.1.2.9}$ – cross sectional area of contact at C3/workpiece interface	Inches^2
DP$_{3.1.2.10}$ – cross sectional area of contact at C4/workpiece interface	Inches^2
DP$_{3.1.2.11}$ – cross sectional area of contact at C5/workpiece interface	Inches^2
DP$_{3.1.2.12}$ – cross sectional area of contact at C6/workpiece interface	Inches^2
DP$_{3.1.2}$ – fixture hardness parameters	
DP$_{3.1.2.1}$ – manufacture P1 from carbide	Y/N
DP$_{3.1.2.2}$ – manufacture T1 from carbide	Y/N
DP$_{3.1.2.3}$ – manufacture S1 from carbide	Y/N
DP$_{3.1.2.4}$ – manufacture P2 from carbide	Y/N
DP$_{3.1.2.5}$ – manufacture S2 from carbide	Y/N
DP$_{3.1.2.6}$ – manufacture P3 from carbide	Y/N
DP$_{3.1.2.7}$ – flame harden contact area of C1	Y/N
DP$_{3.1.2.8}$ – flame harden contact area of C2	Y/N
DP$_{3.1.2.9}$ – flame harden contact area of C3	Y/N
DP$_{3.1.2.10}$ – flame harden contact area of C4	Y/N
DP$_{3.1.2.11}$ – flame harden contact area of C5	Y/N
DP$_{3.1.2.12}$ – flame harden contact area of C6	Y/N
DP$_{3.2}$ – Coolant channels	
DP$_{3.2.1}$ – V slopes on fixture units	
DP$_{3.2.1}$ – V groove on locator P1	Y/N
DP$_{3.2.2}$ – V groove on locator T1	Y/N

DP$_{3.2.3}$ – V groove on locator S1	Y/N
DP$_{3.2.4}$ – V groove on locator P2	Y/N
DP$_{3.2.5}$ – V groove on locator S2	Y/N
DP$_{3.2.6}$ – V groove on locator P3	Y/N
DP$_{3.2.7}$ – V groove on clamp C1	Y/N
DP$_{3.2.8}$ – V groove on clamp C2	Y/N
DP$_{3.2.9}$ – V groove on clamp C3	Y/N
DP$_{3.2.10}$ – V groove on clamp C4	Y/N
DP$_{3.2.11}$ – V groove on clamp C5	Y/N
DP$_{3.2.12}$ – V groove on clamp C6	Y/N
DP$_{3.2.1}$ – Coolant channels to individual features	Unit ID
DP $_{3.3}$ – workpiece loading/unloading mechanisms	
DP $_{3.3.1}$ – Disappearing locating pins	Pin ID
DP $_{3.3.2}$ – ejector mechanism	Unit ID
DP $_{3.3.3}$ – Open end of fixture	Unit ID
DP $_{3.4}$ – Tool guides	
DP $_{3.4.1}$ – tool guide for feature 1	Unit ID
DP $_{3.5}$ – Interference pin arrangement	
DP $_{3.5.1}$ – position of interference pin #1	Coordinates
DP $_{3.5.2}$ – position of interference pin #2	Coordinates
DP $_{3.5.3}$ – position of interference pin #3	coordinates

Appendix B – Storing a Case in Case Library 2



a) clamping unit

b) equivalent element representation

Figure B-1: A clamping unit and its equivalent element skeleton

Clamping unit attribute	Value	Comment
Class type	VC0132	Class type within case library 2
Unit ID	VC0132C1	Identifying name for unit
Stiffness FR performance	17765 lb/in	Unit stiffness
Clamping force FR performance	35 lb	Unit clamping force
Acting height	3 inches	Contact point with workpiece is 3 inches from the base of the unit
Chip shedding ability	No	Does the unit have a chip shedding ability?
Unit cost	$ 1.825566	-
Unit weight	1.199557 lb	-
Loading time associated with unit	0.583333 mins	-
Unit assembly time	4.816667 mins	-
Unloading time associated with unit	0.45 mins	-
Force actuation	TO1A	Threaded bolt force actuation
Total no. of elements	10	Total number of elements within the unit
No. of fulcrum elements	2	Number of elements in the fulcrum limb
No. or work elements	2	Number of elements in the work limb
No.of length BeamE1 elements	1	Number of elements in beam_elem1
No.of length BeamE2 elements	2	Number of elements in beam_elem2
Length of L1	1.5 inches	
Length of L2	2 inches	
(Work) L2 beam element	4	Beam element to which work limb connects
(Fulcrum) L1 beam element	5	Beam element to which fulcrum limb connects
C beam element	2	Beam element to which contact limb connects
Work limb max thickness	0.8 inches	Maximum thickness in the work limb
Fulcrum limb maximum thickness	0.8 inches	Maximum thickness in the fulcrum limb
Contact limb max thickness	0.4 inches	Maximum thickness in the contact limb
Work element	7	Work element that contacts strap beam
Fulcrum element	9	Fulcrum element that contacts strap beam
Contact element	1	Contact element that contacts strap beam

Table B-1: Case schema

Element attribute	Value	Comment
Element #	1	Element number
Limb element no.	0	Position along limb
Structure type	Cylinder	Cross section
Element type	contact	Limb element situated in
Dist from end	0	Distance element is from the end of beam_elem2
Length	0.5 inches	Element length
Start CS b or radius	0.4 inches	Element thickness at start of element
End CS b or radius	0.4 inches	Element thickness at end of element
Start CS h or radius	0.4 inches	Element width at start of element
End CS h or radius	0.4 inches	Element width at end of element
Material mod	StSteel304	Material type
Height adjust	No	Is the element subject to a height adjustment?
Slot consideration	No	Is there a slot in the element?
Slot width	0	Width of slot
Available slot length	0	Length of slot
Connection to next element	Screw	Screw connection
No. of connections	1	1 screw only
Offset distance	0	Centered on element
Mated from	0	N/A
Mated to	2	Mates to element 2
Connection diameter	0.1 inches	-

Table B-2: Element 1 schema

Element attribute	Value	Comment
Element #	2	Element number
Limb element no.	0	Position along limb
Structure type	Block	Cross section
Element type	Front	Limb element situated in
Dist from end	0	Distance element is from the end of beam_elem2
Length	0.5 inches	Element length
Start CS b or radius	0.5 inches	Element thickness at start of element
End CS b or radius	0.5 inches	Element thickness at end of element
Start CS h or radius	0.6 inches	Element width at start of element
End CS h or radius	0.6 inches	Element width at end of element
Material mod	StSteel304	Material type
Height adjust	No	Is the element subject to a height adjustment?
Slot consideration	No	Is there a slot in the element?
Slot width	0	Width of slot
Available slot length	0	Length of slot
Connection to next element	None	Not a real component so the connection type is none (connection details are not applicable to this element)
No. of connections	0	Not applicable to this element
Offset distance	0	Not applicable to this element
Mated from	1	Mates from element 1
Mated to	3	Mates to element 5
Connection diameter	0	Not applicable to this element

Table B-3: Element 2 schema

Element attribute	Value	Comment
Element #	3	Element number
Limb element no.	1	Position along limb
Structure type	Block	Cross section
Element type	beam_elem2	Limb element situated in
Dist from end	0 inches	Distance element is from the end of beam_elem2
Length	1.5 inches	Element length
Start CS b or radius	0.5 inches	Element thickness at start of element
End CS b or radius	0.5 inches	Element thickness at end of element
Start CS h or radius	0.6 inches	Element width at start of element
End CS h or radius	0.6 inches	Element width at end of element
Material mod	StSteel304	Material type
Height adjust	N	Is the element subject to a height adjustment?
Slot consideration	N	Is there a slot in the element?
Slot width	0	Width of slot
Available slot length	0	Length of slot
Connection to next element	0	Not a real component so the connection type is none (connection details are not applicable to this element)
No. of connections	0	Not applicable to this element
Offset distance	0	Not applicable to this element
Mated from	2	Mates from element 2
Mated to	4	Mates to element 4
Connection diameter	0	Not applicable to this element

Table B-4: Element 3 schema

Element attribute	Value	Comment
Element #	4	Element number
Limb element no.	2	Position along limb
Structure type	Block	Cross section
Element type	beam_elem2	Limb element situated in
Dist from end	1.5 inches	Distance element is from the end of beam_elem2
Length	0.5 inches	Element length
Start CS b or radius	0.5 inches	Element thickness at start of element
End CS b or radius	0.5 inches	Element thickness at end of element
Start CS h or radius	0.6 inches	Element width at start of element
End CS h or radius	0.6 inches	Element width at end of element
Material mod	StSteel304	Material type
Height adjust	No	Is the element subject to a height adjustment?
Slot consideration	Yes	Is there a slot in the element?
Slot width	0.3 inches	Width of slot
Available slot length	0.5 inches	Length of slot
Connection to next element	None	Not a real component so the connection type is none (connection details are not applicable to this element)
No. of connections	0	Not applicable to this element
Offset distance	0	Not applicable to this element
Mated from	3	Mates from element 3
Mated to	5	Mates to element 5
Connection diameter	0	Not applicable to this element

Table B-5: Element 4 schema

Element attribute	Value	Comment
Element #	5	Element number
Limb element no.	1	Position along limb
Structure type	Block	Cross section
Element type	Beam_elem1	Limb element situated in
Dist from end	0 inches	Distance element is from the end of beam_elem1
Length	1.5 inches	Element length
Start CS b or radius	0.5 inches	Element thickness at start of element
End CS b or radius	0.5 inches	Element thickness at end of element
Start CS h or radius	0.6 inches	Element width at start of element
End CS h or radius	0.6 inches	Element width at end of element
Material mod	StSteel304	Material type
Height adjust	N	Is the element subject to a height adjustment?
Slot consideration	Y	Is there a slot in the element?
Slot width	0.3 inches	Width of slot
Available slot length	1.5 inches	Length of slot
Connection to next element	0	Not a real component so the connection type is none (connection details are not applicable to this element)
No. of connections	0	Not applicable to this element
Offset distance	0	Not applicable to this element
Mated from	4	Mates from element 4
Mated to	6	Mates to element 6
Connection diameter	0	Not applicable to this element

Table B-6: Element 5 schema

Element attribute	Value	Comment
Element #	6	Element number
Limb element no.	0	Position along limb
Structure type	Block	Cross section
Element type	Back	Limb element situated in
Dist from end	0 inches	Distance element is from the end of this limb
Length	0.5 inches	Element length
Start CS b or radius	0.5 inches	Element thickness at start of element
End CS b or radius	0.5 inches	Element thickness at end of element
Start CS h or radius	0.6 inches	Element width at start of element
End CS h or radius	0.6 inches	Element width at end of element
Material mod	StSteel304	Material type
Height adjust	N	Is the element subject to a height adjustment?
Slot consideration	Y	Is there a slot in the element?
Slot width	0.3 inches	Width of slot
Available slot length	1.5 inches	Length of slot
Connection to next element	3	Alignment connection only
No. of connections	1	1 alignment connection only
Offset distance	0	-
Mated from	5	Mates from element 5
Mated to	9	Mates to element 9
Connection diameter	0	Not applicable to this element

Table B-7: Element 6 schema

Element attribute	Value	Comment
Element #	7	Element number
Limb element no.	2	Position along limb
Structure type	Cylindrical	Cross section
Element type	Work	Limb element situated in
Dist from end	2 inches	Distance element is from the end of work limb
Length	1.5 inches	Element length
Start CS b or radius	0.3 inches	Element thickness at start of element
End CS b or radius	0.3 inches	Element thickness at end of element
Start CS h or radius	0.3 inches	Element width at start of element
End CS h or radius	0.3 inches	Element width at end of element
Material mod	StSteel304	Material type
Height adjust	Y	Is the element subject to a height adjustment?
Slot consideration	N	Is there a slot in the element?
Slot width	0	Width of slot
Available slot length	0	Length of slot
Connection to next element	7	Nut and bolt connection
No. of connections	1	1 bolt only
Offset distance	0	Connection centered on element
Mated from	4	Mates from element 4
Mated to	8	Mates to element 8
Connection diameter	0.3 inches	Bolt diameter

Table B-8: Element 7 schema

Element attribute	Value	Comment
Element #	8	Element number
Limb element no.	1	Position along limb
Structure type	Block	Cross section
Element type	Work	Limb element situated in
Dist from end	0 inches	Distance element is from the end of beam_elem2
Length	2 inches	Element length
Start CS b or radius	0.8 inches	Element thickness at start of element
End CS b or radius	0.8 inches	Element thickness at end of element
Start CS h or radius	0.8 inches	Element width at start of element
End CS h or radius	0.8 inches	Element width at end of element
Material mod	StSteel304	Material type
Height adjust	Y	Is the element subject to a height adjustment?
Slot consideration	N	Is there a slot in the element?
Slot width	0	Width of slot
Available slot length	0	Length of slot
Connection to next element	2	Threaded bolt connection
No. of connections	2	2 bolts
Offset distance	0.6 inches	Bolts on a diameter of 0.6 inches from central axis
Mated from	7	Mates from element 7
Mated to	0	Mates to baseplate
Connection diameter	0.1 inches	Bolt diameter

Table B-9: Element 8 schema

Element attribute	Value	Comment
Element #	9	Element number
Limb element no.	2	Position along limb
Structure type	Cylindrical	Cross section
Element type	Fulcrum	Limb element situated in
Dist from end	2 inches	Distance element is from the end of limb
Length	1.5 inches	Element length
Start CS b or radius	0.4 inches	Element thickness at start of element
End CS b or radius	0.4 inches	Element thickness at end of element
Start CS h or radius	0.4 inches	Element width at start of element
End CS h or radius	0.4 inches	Element width at end of element
Material mod	StSteel304	Material type
Height adjust	Y	Is the element subject to a height adjustment?
Slot consideration	N	Is there a slot in the element?
Slot width	0	Width of slot
Available slot length	0	Length of slot
Connection to next element	1	Pin connection
No. of connections	1	1 connection only
Offset distance	0	Centered connection
Mated from	6	Mates from element 6
Mated to	10	Mates to element 10
Connection diameter	0.4 inches	Pin diameter

Table B-10: Element 9 schema

Element attribute	Value	Comment
Element #	10	Element number
Limb element no.	1	Position along limb
Structure type	1	Cross section
Element type	3	Limb element situated in
Dist from end	0 inches	Distance element is from the end of limb
Length	2 inches	Element length
Start CS b or radius	0.8 inches	Element thickness at start of element
End CS b or radius	0.8 inches	Element thickness at end of element
Start CS h or radius	0.8 inches	Element width at start of element
End CS h or radius	0.8 inches	Element width at end of element
Material mod	StSteel304	Material type
Height adjust	Y	Is the element subject to a height adjustment?
Slot consideration	N	Is there a slot in the element?
Slot width	0	Width of slot
Available slot length	0	Length of slot
Connection to next element	2	Threaded bolt connections
No. of connections	2	2 connections
Offset distance	0.6 inches	Bolts positioned on diameter from central axis
Mated from	9	Mates from element 9
Mated to	0	Mates to baseplate
Connection diameter	0.1 inches	Bolt diameter

Table B-11: Element 10 schema

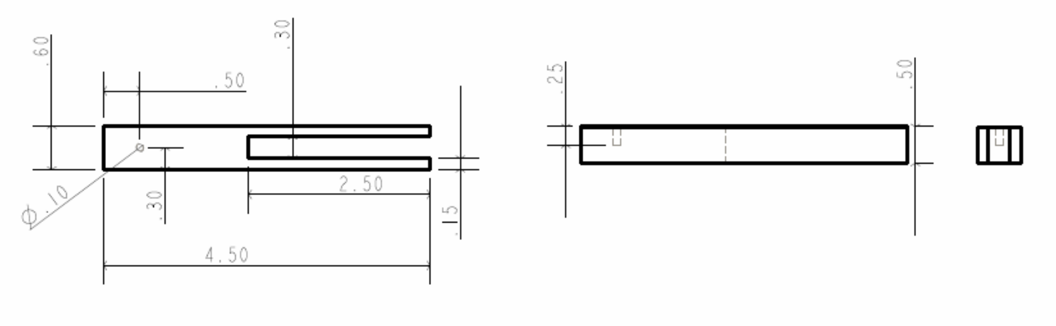


Figure B-2: Beam dimensions (elements 2, 3, 4, 5, 6)

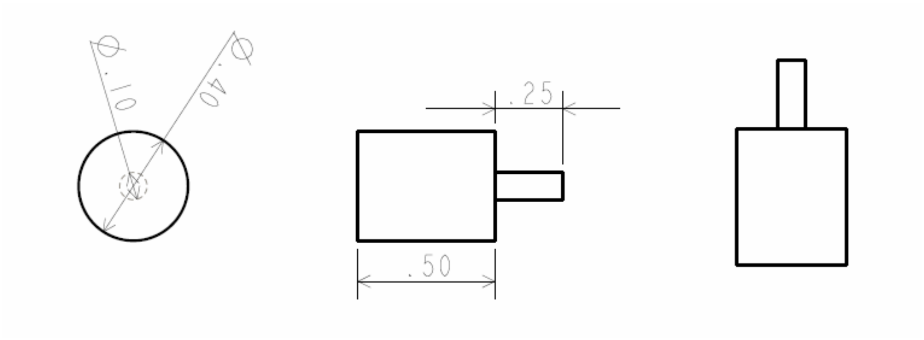


Figure B-3: The contact limb (element 1)

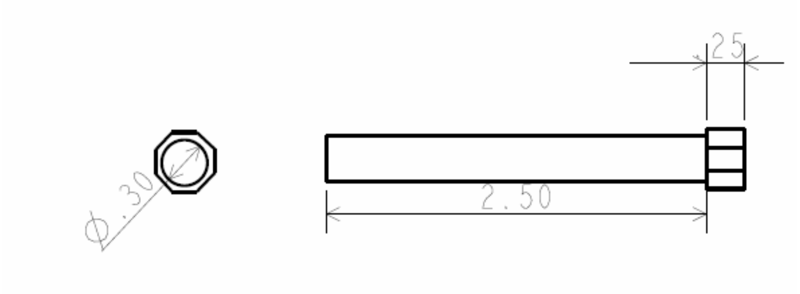


Figure B-4: The work component (element 7)

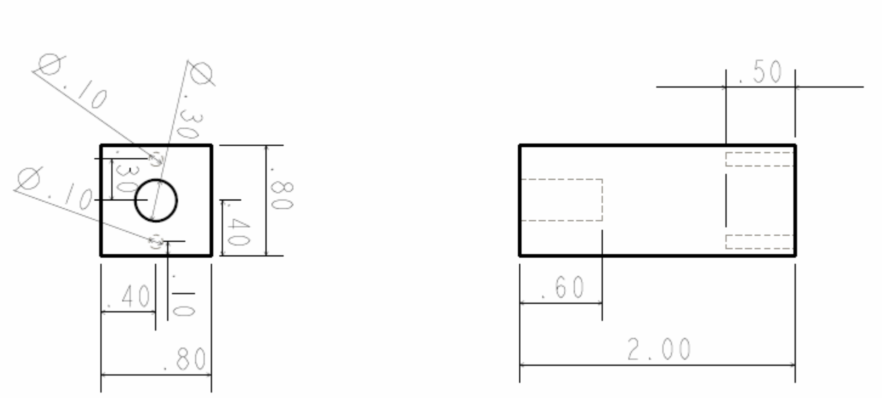


Figure B-5: The work support component (element 8)

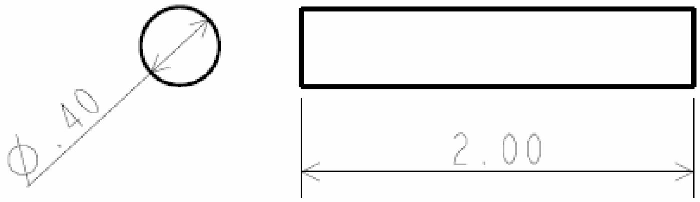


Figure B-6: The fulcrum component (element 9)

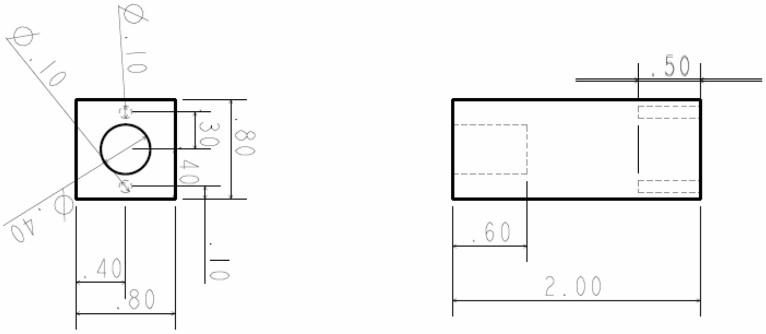
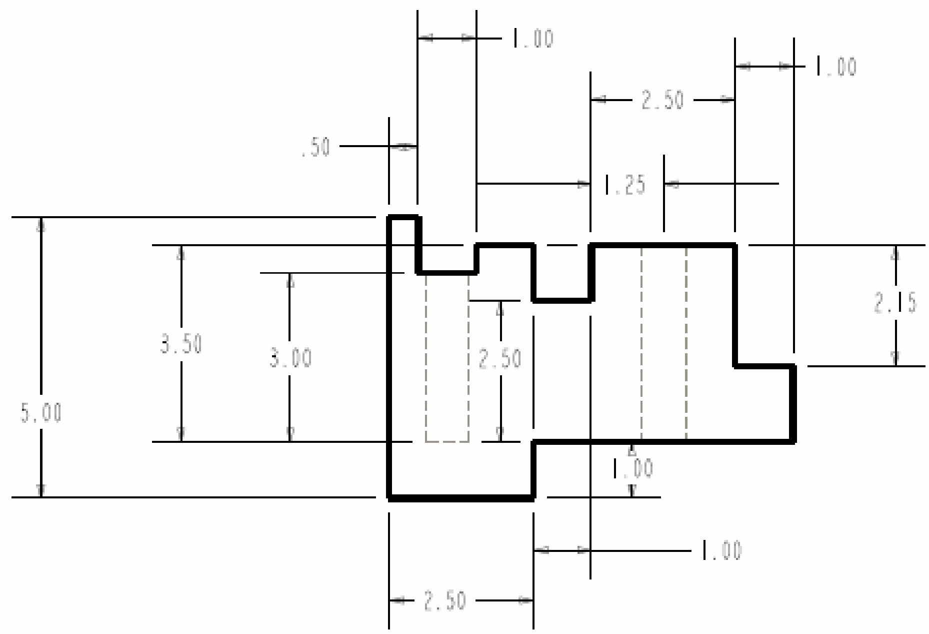
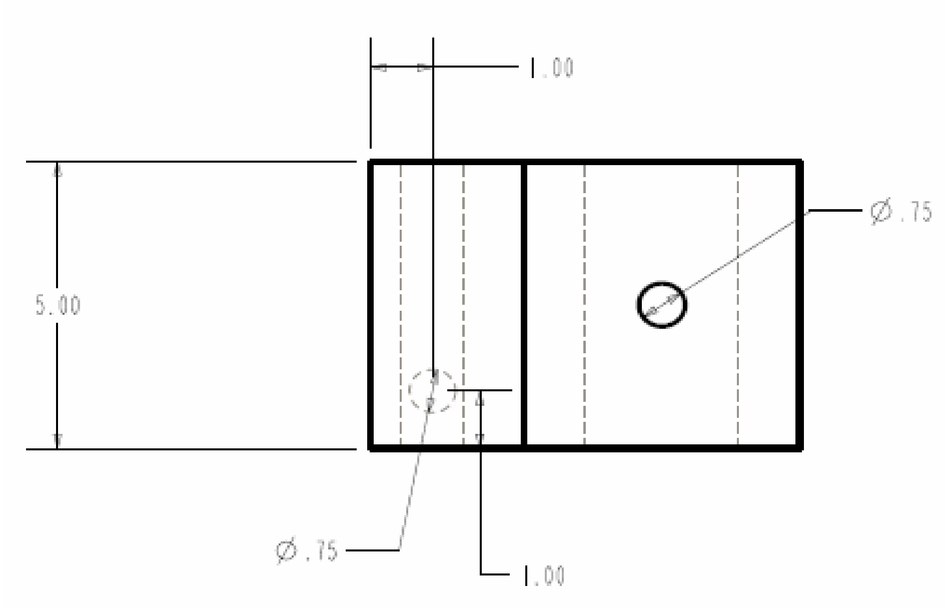
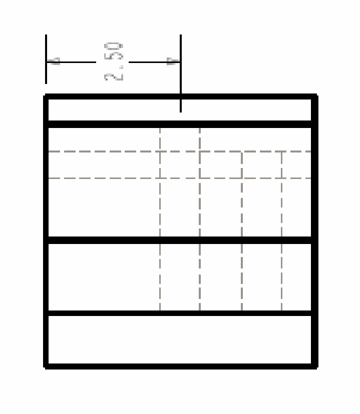


Figure B-7: The fulcrum support element (element 10)

Appendix C – Workpiece Geometry






2.50

Appendix D - Completed FR/DP Skeleton (FRs 1 and 2)

FR$_{1}$ – Hold workpiece to the required accuracy	
FR$_{1.1}$ – Locate the workpiece	
FR$_{1.1.1}$ – Provide location directions	
FR$_{1.1.1.1}$ – Provide location direction in y direction	(0,1,0)
FR$_{1.1.1.2}$ – Provide location direction in x direction	(1,0,0)
FR$_{1.1.1.3}$ – Provide location direction in z direction	(0,0,1)
FR$_{1.1.1.4}$ – Provide location orientation around x axis	(0,1,0)
FR$_{1.1.1.5}$ – Provide location orientation around y axis	(1,0,0)
FR$_{1.1.1.6}$ – Provide location orientation around z axis	(0,1,0)
FR$_{1.1.2}$ – Provide contact between locator and workpiece	
FR$_{1.1.2.1}$ – Contact workpiece with locator P1	
FR$_{1.1.2.2}$ – Contact workpiece with locator T1	
FR$_{1.1.2.3}$ – Contact workpiece with locator S1	
FR$_{1.1.2.4}$ – Contact workpiece with locator P2	
FR$_{1.1.2.5}$ – Contact workpiece with locator S2	
FR$_{1.1.2.6}$ – Contact workpiece with locator P3	
FR$_{1.2}$ – Control accuracy of location	
FR$_{1.2.1}$ – Locate workpiece to required drawing tolerances	
FR$_{1.2.1.1}$ – Locate at location point P1 to an accuracy of *xx.xx inches*	0.0100 inches
FR$_{1.2.1.2}$ – Locate at location point T1 to an accuracy of *xx.xx inches*	0.0025 inches
FR$_{1.2.1.3}$ – Locate at location point S1 to an accuracy of *xx.xx inches*	0.0028 inches
FR$_{1.2.1.4}$ – Locate at location point P2 to an accuracy of *xx.xx inches*	0.0100 inches
FR$_{1.2.1.5}$ – Locate at location point S2 to an accuracy of *xx.xx inches*	0.0028 inches
FR$_{1.2.1.6}$ – Locate at location point P3 to an accuracy of *xx.xx inches*	0.0100 inches
FR$_{1.2.2}$ – Compensate for machine misalignment	
FR$_{1.2.2.1}$ – Compensate for machine misalignment *of xx.xx inches* in the y-direction	2E-005 inches
FR$_{1.2.2.2}$ – Compensate for machine misalignment *of xx.xx inches* in the x-direction	2E-005 inches
FR$_{1.2.2.3}$ – Compensate for machine misalignment *of xx.xx inches* in the z-direction	2E-005 inches
FR$_{1.2.2.4}$ – Compensate for machine misalignment *of xx.xx radians* around the x-axis	8.7266E-005
FR$_{1.2.2.5}$ – Compensate for machine misalignment *of xx.xx radians* around the y-axis	8.7266E-005
FR$_{1.2.2.6}$ – Compensate for machine misalignment *of xx.xx radians* around the z-axis	8.7266E-005
FR$_{1.2.3}$ – Compensate for casting variations at locator/workpiece interfaces	
FR$_{1.2.3.1}$ – Compensate for casting variations of *xx.xx inches* at locator P1/workpiece interface	0.002 inches
FR$_{1.2.3.2}$ – Compensate for casting variations of *xx.xx inches* at	0.002 inches

locator T1/workpiece interface

FR$_{1.2.3.3}$ – Compensate for casting variations of *xx.xx inches* at locator S1/ workpiece interface	0.002 inches
FR$_{1.2.3.4}$ – Compensate for casting variations of *xx.xx inches* at locator P2/ workpiece interface	0.002 inches
FR$_{1.2.3.5}$ – Compensate for casting variations of *xx.xx inches* at locator S2/ workpiece interface	0.002 inches
FR$_{1.2.3.6}$ – Compensate for casting variations of *xx.xx inches* at locator P3/ workpiece interface	0.002 inches

FR$_{2}$ – Support workpiece against machining forces experienced during machining

FR$_{2.1}$ – Hold workpiece in situ during machining

FR$_{2.1.1}$ – Provide clamping in appropriate directions

FR$_{2.1.1.1}$ – Clamp w/piece against locator P1 with a force of *xx lbs*	50 lbs
FR$_{2.1.1.2}$ – Clamp w/piece against locator T1 with a force of *xx lbs*	50 lbs
FR$_{2.1.1.3}$ – Clamp w/piece against locator S1 with a force of *xx lbs*	50 lbs
FR$_{2.1.1.4}$ - Clamp w/piece against locator P2 with a force of *xx lbs*	50 lbs
FR$_{2.1.1.5}$ - Clamp w/piece against locator S2 with a force of *xx lbs*	50 lbs
FR$_{2.1.1.6}$ - Clamp w/piece against locator P3 with a force of *xx lbs*	50 lbs

FR$_{2.1.2}$ – Support the workpiece during machining

FR$_{2.1.2.1}$ – Ensure locator stiffness at locator P1 is xx lb/in	37417 lb/in
FR$_{2.1.2.2}$ – Ensure locator stiffness at locator T1 is xx lb/in	252543 lb/in
FR$_{2.1.2.3}$ – Ensure locator stiffness at locator S1 is xx lb/in	231810 lb/in
FR$_{2.1.2.4}$ – Ensure clamping stiffness at locator P1 is xx lb/in	29934 lb/in
FR$_{2.1.2.5}$ – Ensure clamping stiffness at locator T1 is xx lb/in	222971 lb/in
FR$_{2.1.2.6}$ – Ensure clamping stiffness at locator S1 is xx lb/in	204666 lb/in
FR$_{2.1.2.7}$ – Ensure locator stiffness at locator P2 is xx lb/in	37417 lb/in
FR$_{2.1.2.8}$ – Ensure locator stiffness at locator S2 is xx lb/in	231810 lb/in
FR$_{2.1.2.9}$ – Ensure clamping stiffness at locator P2 is xx lb/in	29934 lb/in
FR$_{2.1.2.10}$ – Ensure clamping stiffness at locator S2 is xx lb/in	204666 lb/in
FR$_{2.1.2.11}$ – Ensure locator stiffness at locator P3 is xx lb/in	37417 lb/in
FR$_{2.1.2.12}$ – Ensure clamping stiffness at locator P3 is xx lb/in	29934 lb/in

FR$_{2.1.3}$ – Provide clamping points

FR$_{2.1.3.1}$ – Contact workpiece with clamp CP1

FR$_{2.1.3.2}$ – Contact workpiece with clamp CT1

FR$_{2.1.3.3}$ – Contact workpiece with clamp CS1

FR$_{2.1.3.4}$ - Contact workpiece woth clamp CP2

FR$_{2.1.3.5}$ - Contact workpiece with clamp CS2

FR$_{2.1.3.6}$ - Contact workpiece with clamp CP3

FR$_{2.1.4}$ – Provide clamping points

FR$_{2.1.4.1}$ – Provide clamping orientation for clamp CP1	(0,-1,0)
FR$_{2.1.4.2}$ – Provide clamping orientation for clamp CT1	(-1,0,0)
FR$_{2.1.4.3}$ – Provide clamping orientation for clamp CS1	(0,0,-1)
FR$_{2.1.4.4}$ - Provide clamping orientation for clamp CP2	(0,-1,0)

$FR_{2.1.4.5}$ - Provide clamping orientation for clamp CS2	(-1,0,0)
$FR_{2.1.4.6}$ - Provide clamping orientation for clamp CP3	(0,-1,0)
DP_1 Plane	
$DP_{1.1}$ Plane_Var3	
$DP_{1.1.1}$ – Locator/workpiece interface orientation	
$DP_{1.1.1.1}$ – Locator P1/workpiece interface orientation	2
$DP_{1.1.1.2}$ – Locator T1/workpiece interface orientation	16
$DP_{1.1.1.3}$ – Locator S1/workpiece interface orientation	3
$DP_{1.1.1.4}$ – Locator P2/workpiece interface orientation	2
$DP_{1.1.1.5}$ – Locator S2/workpiece interface orientation	3
$DP_{1.1.1.6}$ – Locator P3/workpiece interface orientation	1
$DP_{1.1.2}$ – Workpiece/locator interface contact positions	
$DP_{1.1.2.1}$ – Locator P1 position	(6.75,1,0.25)
$DP_{1.1.2.2}$ – Locator T1 position	(0,2.5,2.5)
$DP_{1.1.2.3}$ – Locator S1 position	(0.25,2.25,0)
$DP_{1.1.2.4}$ – Locator P2 position	(3.639,1,4.75)
$DP_{1.1.2.5}$ – Locator S2 position	(5.75,2.25,0)
$DP_{1.1.2.6}$ – Locator P3 position	(0.25,0,0.25)
$DP_{1.2}$ – Locator unit accuracy parameters	
$DP_{1.2.1}$ – Locator unit tolerances	
$DP_{1.2.1.1}$ - Vertical locating unit tolerance of *xx.xx inches*	Unit ID
$DP_{1.2.1.2}$ - Horizontal locating unit tolerance of *xx.xx inches*	Unit ID
$DP_{1.2.1.3}$ - Horizontal locating unit tolerance of *xx.xx inches*	Unit ID
$DP_{1.2.1.4}$ - Vertical locating unit tolerance of *xx.xx inches*	Unit ID
$DP_{1.2.1.5}$ - Horizontal locating unit tolerance of *xx.xx inches*	Unit ID
$DP_{1.2.1.6}$ - Vertical locating unit tolerance of *xx.xx inches*	Unit ID
$DP_{1.2.2}$ – Spacers between fixture base and machine table	
$DP_{1.2.2.1}$ – Assignment of machine misalignment tolerance of xx.xx inches in the y-direction	2E-005 inches
$DP_{1.2.2.2}$ – Assignment of machine misalignment tolerance of xx.xx inches in the x-direction	2E-005 inches
$DP_{1.2.2.3}$ – Assignment of machine misalignment tolerance of xx.xx inches in the z-direction	2E-005 inches
$DP_{1.2.2.4}$ – Assignment of machine misalignment tolerance of xx.xx radians around the x axis	8.7266E-005 radians
$DP_{1.2.2.5}$ – Assignment of machine misalignment tolerance of xx.xx radians around the y axis	8.7266E-005 radians
$DP_{1.2.2.6}$ – Assignment of machine misalignment tolerance of xx.xx radians around the z axis	8.7266E-005 radians
$DP_{1.2.3}$ – Locator unit spacers at locator/workpiece interfaces	
$DP_{1.2.3.1}$ – Assignment of surface tolerance of xx.xx inches at P1/workpiece interface	0.002 inches
$DP_{1.2.3.2}$ – Assignment of surface tolerance of xx.xx inches at T1/workpiece interface	0.002 inches

DP $_{1.2.3.3}$ – Assignment of surface tolerance of xx.xx inches at S1/workpiece interface	0.002 inches
DP $_{1.2.3.4}$ – Assignment of surface tolerance of xx.xx inches at P2/workpiece interface	0.002 inches
DP $_{1.2.3.5}$ – Assignment of surface tolerance of xx.xx inches at S2/workpiece interface	0.002 inches
DP $_{1.2.3.6}$ – Assignment of surface tolerance of xx.xx inches at P3/workpiece interface	0.002 inches
DP $_{2}$ – Fixture unit force capabilities	
DP $_{2.1}$ – Clamping unit force capabilities	
DP $_{2.1.1}$ – Clamping unit forces	
DP $_{2.1.1.1}$ – Vertical clamp CP1 opposing workpiece/P1 interface with clamping force of *xx lbs*	Unit ID
DP $_{2.1.1.2}$ – Horizontal clamp CT1 opposing workpiece/T1 interface with clamping force of *xx lbs*	Unit ID
DP $_{2.1.1.3}$ – Horizontal clamp CS1 opposing workpiece/S1 interface with clamping force of *xx lbs*	Unit ID
DP $_{2.1.1.4}$ - Vertical clamp CP2 opposing workpiece/P2 interface with clamping force of *xx lbs*	Unit ID
DP $_{2.1.1.5}$ - Horizontal clamp CS2 opposing workpiece/S2 interface with clamping force of *xx lbs*	Unit ID
DP $_{2.1.1.6}$ - Vertical clamp CP3 opposing workpiece/P3 interface with clamping force of *xx lbs*	Unit ID
DP $_{2.1.2}$ – Unit stiffness	
DP $_{2.1.2.1}$ – Locator P1 stiffness of *xx.xx lbs/in*	Unit ID
DP $_{2.1.2.2}$ – Locator T1 stiffness of *xx.xx lbs/in*	Unit ID
DP $_{2.1.2.3}$ – Locator S1 stiffness of *xx.xx lbs/in*	Unit ID
DP $_{2.1.2.4}$ – Clamping unit CP1 stiffness of *xx.xx lbs/in*	Unit ID
DP $_{2.1.2.5}$ – Clamping unit CT1 stiffness of *xx.xx lbs/in*	Unit ID
DP $_{2.1.2.6}$ – Clamping unit CS1 stiffness of *xx.xx lbs/in*	Unit ID
DP $_{2.1.2.7}$ – Locator unit P2 stiffness of *xx.xx lbs/in*	Unit ID
DP $_{2.1.2.8}$ – Locator unit S2 stiffness of *xx.xx lbs/in*	Unit ID
DP $_{2.1.2.9}$ – Clamping unit CP2 stiffness of *xx.xx lbs/in*	Unit ID
DP $_{2.1.2.10}$ – Clamping unit CS2 stiffness of *xx.xx lbs/in*	Unit ID
DP $_{2.1.2.11}$ – Locator unit P3 stiffness of *xx.xx lbs/in*	Unit ID
DP $_{2.1.2.12}$ – Clamping unit CP3 stiffness of *xx.xx lbs/in*	Unit ID
DP $_{2.1.3}$ – Clamping points	
DP $_{2.1.3.1}$ – Clamp CP1 position	(6.75,2.35,0.25)
DP $_{2.1.3.2}$ – Clamp CT1 position	(6,2.5,2.5)
DP $_{2.1.3.3}$ – Clamp CS1position	(0.25,2.25,5)
DP $_{2.1.3.4}$ - Clamp CP2position	(2,4.5,4.75)
DP $_{2.1.3.5}$ - Clamp CS2 position	(5.75,2.25,5)
DP $_{2.1.3.6}$ - Clamp CP3position	(0.25,5,0.25)
DP $_{2.1.3}$ – Clamping points	
DP $_{2.1.4.1}$ – Clamp CP1/workpiece interface orientation (workpiece surface)	5

DP$_{2.1.4.2}$ – Clamp CT1/workpiece interface orientation (workpiece surface)	6
DP$_{2.1.4.3}$ – Clamp CS1/workpiece interface orientation (workpiece surface)	17
DP$_{2.1.4.4}$ - Clamp CP2/workpiece interface orientation (workpiece surface)	7
DP$_{2.1.4.5}$ - Clamp CS2/workpiece interface orientation (workpiece surface)	17
DP$_{2.1.4.6}$ - Clamp CP3/workpiece interface orientation (workpiece surface)	15

Appendix E – Constraint attribute Performance Values for Existing Cases

Case	Cost ($)	Weight (lbs)	Loading time (mins)	Assembly time (mins)	Unloading time (mins)
VL011C1	4.112	0.4	0	1.9	0
HL013C1	5.56	0.7	0	2.3	0
VC0132C1	1.799	1.172	0.5833	4.82	0.45
HC021C1	1.41	0.8	0.45	3.5	0.4
VC021C1	1.799	1.172	0.5833	4.82	0.45

Table E-1: Constraint attribute performance values for reference design solution

Appendix F – Drawings for Updated Clamp

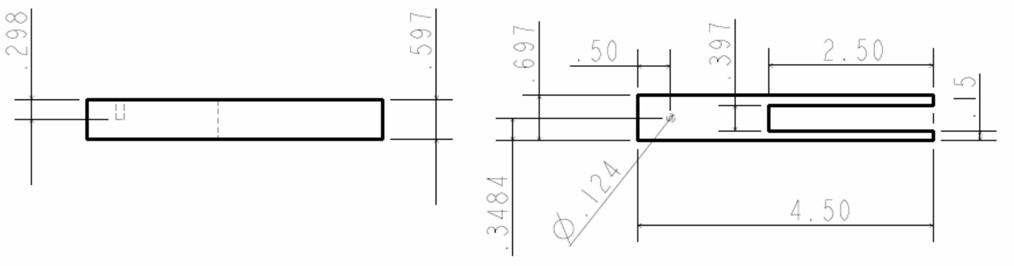


Figure F-1: Beam dimensions (elements 2, 3, 4, 5, 6)

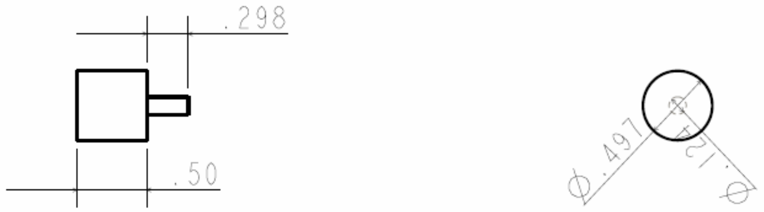


Figure F-2: The contact limb (element 1)

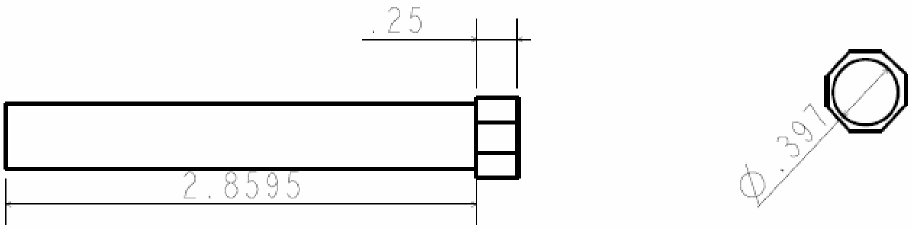


Figure F-3: The work component (element 7)

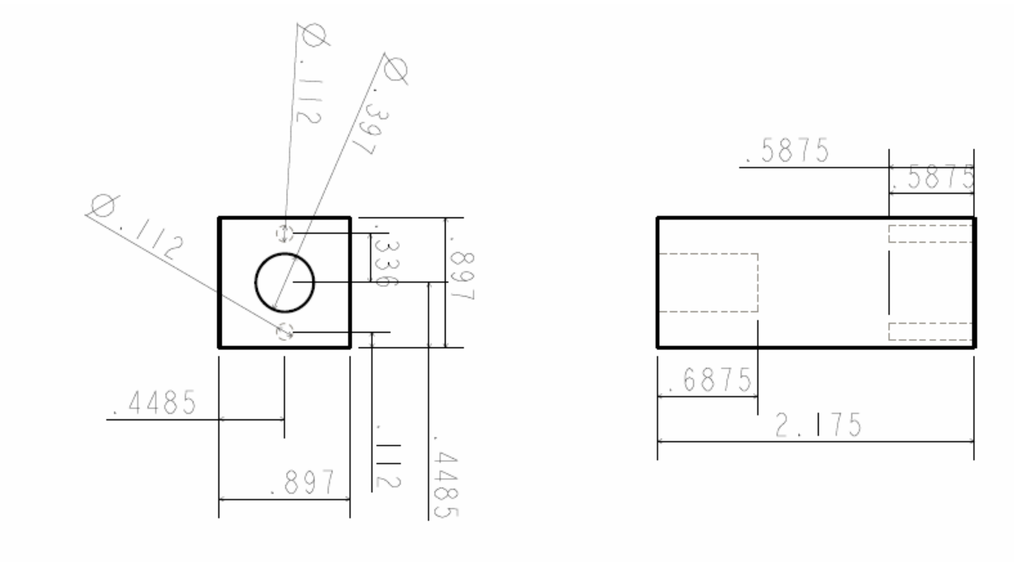


Figure F-4: The work support component (element 8)

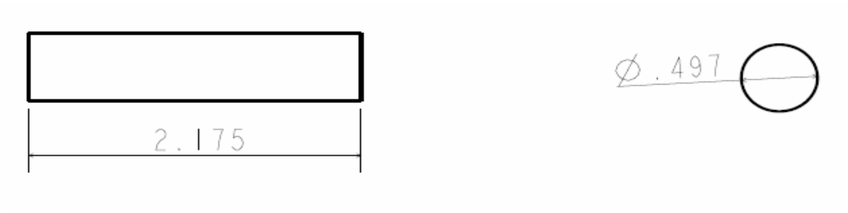


Figure F-5: The fulcrum component (element 9)

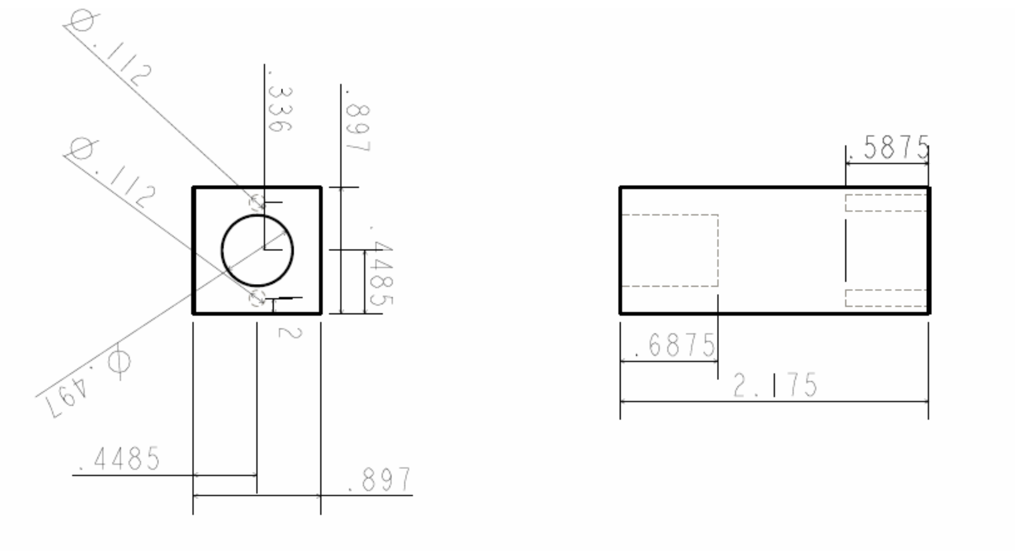
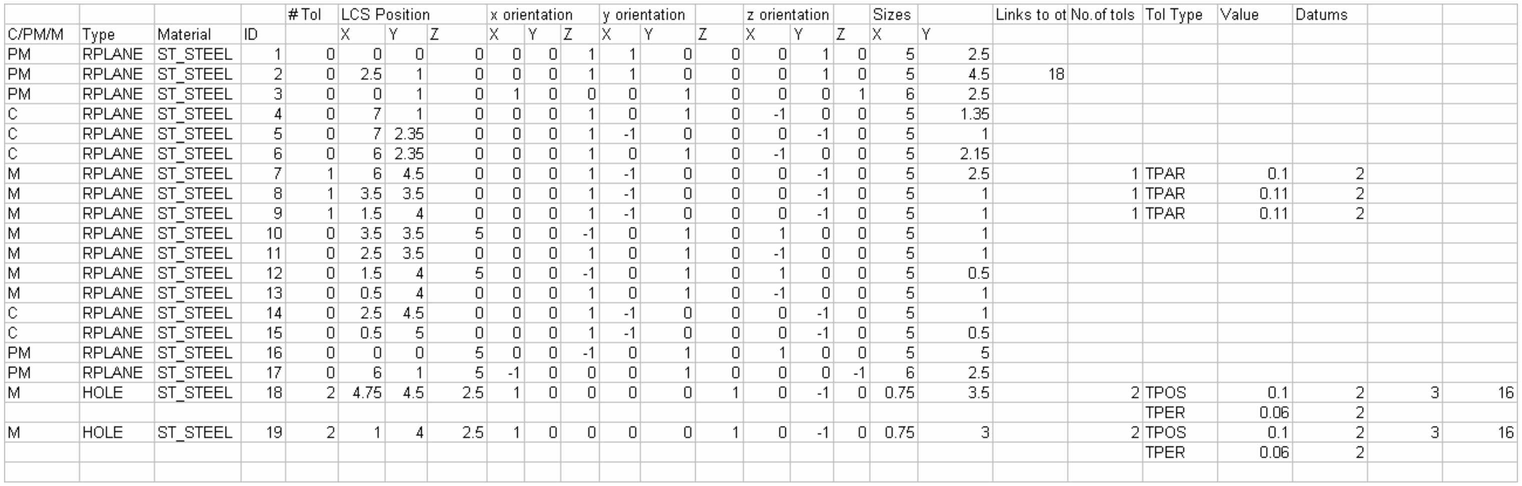


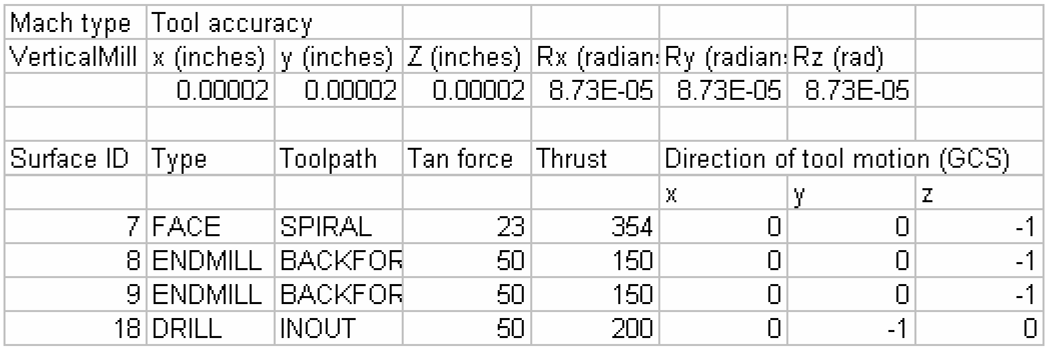
Figure F-6: The fulcrum support element (element 10)

Appendix G – Workpiece .xls File



				# Tol	LCS Position			x orientation			y orientation			z orientation			Sizes		Links to ot	No.of tols	Tol Type	Value	Datums		
C/PM/M	Type	Material	ID		X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y							
PM	RPLANE	ST_STEEL	1	0	0	0	0	0	0	1	1	0	0	0	1	0	5	2.5							
PM	RPLANE	ST_STEEL	2	0	2.5	1	0	0	0	1	1	0	0	0	1	0	5	4.5	18						
PM	RPLANE	ST_STEEL	3	0	0	1	0	1	0	0	0	1	0	0	0	1	6	2.5							
C	RPLANE	ST_STEEL	4	0	7	1	0	0	0	1	0	1	0	-1	0	0	5	1.35							
C	RPLANE	ST_STEEL	5	0	7	2.35	0	0	0	1	-1	0	0	0	-1	0	5	1							
C	RPLANE	ST_STEEL	6	0	6	2.35	0	0	0	1	0	1	0	-1	0	0	5	2.15							
M	RPLANE	ST_STEEL	7	1	6	4.5	0	0	0	1	-1	0	0	0	-1	0	5	2.5		1	TPAR	0.1	2		
M	RPLANE	ST_STEEL	8	1	3.5	3.5	0	0	0	1	-1	0	0	0	-1	0	5	1		1	TPAR	0.11	2		
M	RPLANE	ST_STEEL	9	1	1.5	4	0	0	0	1	-1	0	0	0	-1	0	5	1		1	TPAR	0.11	2		
M	RPLANE	ST_STEEL	10	0	3.5	3.5	5	0	0	-1	0	1	0	1	0	0	5	1							
M	RPLANE	ST_STEEL	11	0	2.5	3.5	0	0	0	1	0	1	0	-1	0	0	5	1							
M	RPLANE	ST_STEEL	12	0	1.5	4	5	0	0	-1	0	1	0	1	0	0	5	0.5							
M	RPLANE	ST_STEEL	13	0	0.5	4	0	0	0	1	0	1	0	-1	0	0	5	1							
C	RPLANE	ST_STEEL	14	0	2.5	4.5	0	0	0	1	-1	0	0	0	-1	0	5	1							
C	RPLANE	ST_STEEL	15	0	0.5	5	0	0	0	1	-1	0	0	0	-1	0	5	0.5							
PM	RPLANE	ST_STEEL	16	0	0	0	5	0	0	-1	0	1	0	1	0	0	5	5							
PM	RPLANE	ST_STEEL	17	0	6	1	5	-1	0	0	0	1	0	0	0	-1	6	2.5							
M	HOLE	ST_STEEL	18	2	4.75	4.5	2.5	1	0	0	0	0	1	0	-1	0	0.75	3.5		2	TPOS	0.1	2	3	16
																					TPER	0.06	2		
M	HOLE	ST_STEEL	19	2	1	4	2.5	1	0	0	0	0	1	0	-1	0	0.75	3		2	TPOS	0.1	2	3	16
																					TPER	0.06	2		

Appendix H – Machining .xls File



Mach type	Tool accuracy						
VerticalMill	x (inches)	y (inches)	Z (inches)	Rx (radian	Ry (radian	Rz (rad)	
	0.00002	0.00002	0.00002	8.73E-05	8.73E-05	8.73E-05	
Surface ID	Type	Toolpath	Tan force	Thrust	Direction of tool motion (GCS)		
					x	y	z
7	FACE	SPIRAL	23	354	0	0	-1
8	ENDMILL	BACKFOR	50	150	0	0	-1
9	ENDMILL	BACKFOR	50	150	0	0	-1
18	DRILL	INOUT	50	200	0	-1	0

Appendix I – Modification file for clamping unit

Subject case:	VC021C1
Element number:	1
Set diameter dimension to:	0.49678089
Modify connector length (mate_to connector) by:	0.048390445
Set 'mate to' connector diameter to:	0.124195223
Set 'mate to' connector hole diameter to:	0.124195223
Set connector offset (mate to) diameter to:	0
Element number:	2
Set start_b dimension to:	0.59678089
Dimension measured:	Across local central axis
Set 'mate from' connector hole diameter to:	0.124195223
Modify connector hole (mates from) length by:	0.048390445
Set connector offset (mate from) diameter to:	0
Set end_b dimension to:	0.59678089
Dimension measured:	Across local central axis
Set start_h dimension to:	0.69678089
Dimension measured:	Across local central axis
Set end_h dimension to:	0.69678089
Dimension measured:	Across local central axis
Element number:	3
Set start_b dimension to:	0.59678089
Dimension measured:	Across local central axis
Set end_b dimension to:	0.59678089
Dimension measured:	Across local central axis
Set start_h dimension to:	0.69678089

Dimension measured:	Across local central axis
Set end_h dimension to:	0.69678089
Dimension measured:	Across local central axis
Element number:	4
Set start_b dimension to:	0.59678089
Dimension measured:	Across local central axis
Set end_b dimension to:	0.59678089
Dimension measured:	Across local central axis
Set start_h dimension to:	0.69678089
Dimension measured:	Across local central axis
Set end_h dimension to:	0.69678089
Dimension measured:	Across local central axis
Set slot width to:	0.39678089
Element number:	5
Set start_b dimension to:	0.59678089
Dimension measured:	Across local central axis
Set end_b dimension to:	0.59678089
Dimension measured:	Across local central axis
Set start_h dimension to:	0.69678089
Dimension measured:	Across local central axis
Set end_h dimension to:	0.69678089
Dimension measured:	Across local central axis
Set slot width to:	0.39678089
Element number:	6
Set start_b dimension to:	0.59678089

Dimension measured:	Across local central axis
Set end_b dimension to:	0.59678089
Dimension measured:	Across local central axis
Set start_h dimension to:	0.69678089
Dimension measured:	Across local central axis
Set end_h dimension to:	0.69678089
Dimension measured:	Across local central axis
Set slot width to:	0.39678089
Element number:	7
Set position to:	2.175
Position axis:	Unit y positive
Set length to:	1.675
Modify connector length by:	0.18428089
Set diameter dimension to:	0.39678089
Set 'mate to' connector diameter to:	0.39678089
Set 'mate to' connector hole diameter to:	0.39678089
Set connector offset (mate to) diameter to:	0
Element number:	8
Set length to:	2.175
Modify connector hole depth by:	0.0875
Connector hole depth measured from:	'Mating to' surface:
Modify connector length by:	0.0875
Modify connector hole depth by:	0.0875
Connector hole depth measured from:	'Mating from' surface:
Set start_b dimension to:	0.89678089
Dimension measured:	Across local central axis
Set 'mate to' connector diameter to:	0.112097611
Set 'mate to' connector hole diameter to:	0.112097611

Set connector offset (mate to) diameter to:	0.672585668
Set 'mate from' connector hole diameter to:	0.39678089
Set connector offset (mate from) diameter to:	0
Set end_b dimension to:	0.89678089
Dimension measured:	Across local central axis
Set start_h dimension to:	0.89678089
Dimension measured:	Across local central axis
Set end_h dimension to:	0.89678089
Dimension measured:	Across local central axis
Element number:	9
Set position to:	2.175
Position axis:	Unit y positive
Set length to:	1.675
Modify connector hole depth by:	0.0875
Connector hole depth measured from:	'Mating to' surface:
Modify connector length by:	0.175
Set diameter dimension to:	0.49678089
Set 'mate to' connector diameter to:	0.49678089
Set 'mate to' connector hole diameter to:	0.49678089
Set connector offset (mate to) diameter to:	0
Element number:	10
Set length to:	2.175
Modify connector hole depth by:	0.0875
Connector hole depth measured from:	'Mating to' surface:
Modify connector length by:	0.0875
Modify connector hole depth by:	0.0875
Connector hole depth measured from:	'Mating from' surface:
Set start_b dimension to:	0.89678089
Dimension measured:	Across local central axis

Set 'mate to' connector diameter to:	0.112097611
Set 'mate to' connector hole diameter to:	0.112097611
Set connector offset (mate to) diameter to:	0.672585668
Set 'mate from' connector hole diameter to:	0.49678089
Set connector offset (mate from) diameter to:	0
Set end_b dimension to:	0.89678089
Dimension measured:	Across local central axis
Set start_h dimension to:	0.89678089
Dimension measured:	Across local central axis
Set end_h dimension to:	0.89678089
Dimension measured:	Across local central axis