A DATA APPROACH TO TRACKING AND EVALUATING ENGINEERING CHANGES

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For my parents, my wife, and Tav

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SUMMARY

Changes are common during any stage of a product life cycle. There are local changes that do not influence other elements of a product. However, there are other changes that can influence different aspects of the product. Consequences of these changes, unless properly anticipated, and accounted for, can be costly. Therefore, it is highly desirable to obtain a mechanism that will be able to anticipate and evaluate product change consequences.

The first task in anticipating and evaluating change consequences is to represent them. The complexity of engineering models make their representation to be rich and semantic. Information data models like EXPRESS provide tools for modeling products. However, the current EXPRESS and other information models do not have a generic methodology to support contextual change representation and propagation.

In this thesis a methodology called Change FAvorable Representation – C-FAR is presented.. C-FAR uses an existing product information model to facilitate change representation, propagation, and qualitative evaluation. The EXPRESS schema's main elements are entities, relations among entities, and attributes that describe the entities.
C-FAR facilitates change and change evaluation to the attribute level.

C-FAR has been evaluated using case studies in structural analysis, bumper design, printed wiring board technology and injection molding process. Results show that C-FAR

is capable of representing change and provides a reasonable qualitative evaluation of the change consequences.

PART I

PROBLEM DEFINITION

Chapter 1

Introduction

Design is a complex and dynamic process [Dym, 1994; Fulton, 1988; Kannapan, 1992, Keller, 1992]. As a result, changes in various design stages influence different aspects of the design. These changes are necessary; they are an integral part of any design. Engineering design, is by nature, an iterative process that evolves until it reaches the optimal point [Cutkosky, 1990]. The optimal design addresses a set of requirements under a certain set of constraints. However, even after reaching this desirable point, the requirements as well as the constraints may change. Our optimal design may no longer be optimal for the new set of requirements. Therefore, the change element should follow the design process from initial conceptual design through maintenance and the entire life cycle of the product [Curtis, 1994; Dagle, 1994; Dym, 1994; Liu, 1993].

Sometimes the change initiator is not aware of the consequences of the changes he or she makes. Changes in requirements may be initiated by an engineering redesign motivated by the customer's ever-evolving needs, by competition, or by the need for internal improvements. The complex design structure includes different data sets that are associated with different parts of the product [Fulton, 1988; Miller, 1996]. Since the design is a complex, elaborate endeavor, the data sets representation emphasizes the design components' interdependency. As a result, a change presented into the system may influence many other aspects of the design [Keller, 1992]. The change initiator has the responsibility to trace the change propagation and evaluate the overall impact that a given change may produce. Eventually, to benchmark the new design, the initiator may compare the new design against the original design.

In this process, four stages have been identified to successfully incorporate a change into a design. The first stage is to introduce the change. The second stage is to trace the change's propagation from the beginning until a stabilized system is achieved. The third stage is to evaluate the new design, and the final stage is to compare the final design with the initial design. The change initiator usually has a good idea of the new elements he or she is going to present to the design. However, this change may trigger a chain of secondary changes that may trigger other changes. The process of change sequences is called "change propagation." The inability to trace or analyze the propagated change over the different design aspects may lead to a faulty new design evaluation and eventually to suboptimal design. Furthermore, it will be difficult, if not impossible, to correct any problems with the new design if there is no way to trace the change propagation.

In order to be able to trace the change propagation, data sets are connected to the design stages, to the requirements, conceptual design, detailed design, analysis and to the evaluation. These data sets are usually built specifically for a narrow aspect for each design stage and serve the designated application. These data sets are in various formats and dimensions. Therefore, making the change propagation is a very difficult task to fulfill. A key element to making the change propagation is the design representation [Dym, 1994; Landis, 1986]. Design representation is a compound of various models that are mathematical, logical, linguistic and graphical. The representation is very important since it can illuminate or confuse certain aspects of the factors in the design process. This may explain the recent resurgence in research in this field (e.g. feature-based design, shape grammars , object-oriented data structures, etc.).

Concurrent engineering [Curtis, 1994; Cutkosky, 1990; Dym, 1994] provides a better framework to make design changes. Concurrent engineering allows feedback from any stage to any other stage in the process design. As opposed to the classical serial design process, the concurrent engineering framework allows for more flexibility in introducing changes along the design. Concurrent engineering is more than an innovative design representation; it is a framework used to capture the evolutionary nature of modern design. This framework facilitates interaction among design stages by identifying, refining, and transforming the requirements and then moving on to structural description and finally to defining a physical plan. However, change investigation and propagation even in concurrent engineering are not emphasized as much as they should be.

The objective of this research is to present a data representation that facilitates change and change propagation in design representation of engineering products. This mechanism will catalyze the redesign process based on the information gathered on the product. The research examines design representation from a data model perspective. There are two parallel outputs in product development: the physical product, which is the traditional design process output, and the information product that describes the physical product. The work suggested in this thesis takes a classical data model and converts it to a Change FAvorable Representation (C-FAR), a new and different methodology of representing design information so that redesign changes can be dynamically anticipated and evaluated. In order to do this, C-FAR will use STEP [Bloor, 1991; Gilbert, 1991; STEP Part 1, 1992; Wang, 1991] (Standard for the Exchange of Product) model data, a well-established data model. The method is to develop an approach -- C-FAR -- that will extract the information from the STEP information model to make the design changes more easily traceable. This methodology will take into consideration the interdependencies among design elements, thus facilitating a deeper understanding of a change consequence and of design parts sensitivity. The methodology for C-FAR will utilize modeling case studies to derive the study and validate results. The first case study is a simple model of an automobile structure [Kamal, 1981]. Next, the model is expanded to include other part views, such as an automobile bumper model. To validate the approach, the methodology will be tested on more case studies such as a Printed Wiring Board (PWB) application and an injection molding application. The significance of this research is to provide a mechanism that will make design information an active agent in the redesign process. The research approach will add to the design ability by turning the information model into a dynamic part of the design. The first stage of redesign change evaluation is to learn who is affected by the initial change. The second stage is to learn to what degree the initial change indeed influenced a given design artifact.

Chapter Two reviews issues dealing with engineering changes on several levels. There is no unique engineering information model that has as its sole purpose to track and evaluate engineering changes. The C-FAR representation offers a methodology that propagates and evaluates engineering changes. The problem scope is described in Chapter Three. This chapter will deal with issues such as what is considered engineering change, what changes the C-FAR approach is suitable for and not suitable for. In Chapter Four, the framework for the thesis objectives is presented. Part II lays down a detailed description of the C-FAR methodology. Part II specifies the validation procedure and illustrate the case studies which C-FAR is examined against. Part III and IV are dedicated to evaluation of the C-FAR methodologies. Several goodness measurements are being stated and examined. Part V presents the conclusion of this research as well as contributions and future work.

Chapter 2

Current Research Issues and Future Challenges

2.1 Literature Survey

This thesis deals partially with *engineering product representation* and the capacity of the representation to deal with *changes*. Change and change propagation are specific and crucial issues in *concurrent engineering* as well in *design evolution*. The first part of the literature survey will deal with this issue. The next part of the survey will converge on some of the methodologies and techniques that are application oriented, namely *product data manger, product data model* and the *STEP model*.

2.1.1 Design Representation

The art of design starts with the manner in which the engineer examines the problem and the problem domain. Therefore, the first step is to represent the elements that are included in the domain. Identifying the participating design elements, understanding their place in the overall framework, as well as exploring the inter-relationship among them are essential parts of a good design representation [Banares-Alcantara, 1991; Dym, 1994; Eastman, 1993; Shah, 1989].

The textual definitions are the straightforward design representation. The definitions can describe objects, requirements, and constrains [Dym, 1994; Ullman, 1993] . A simple textual description facilitates the generalization of design taxonomy [Ullman, 1993] where different levels of design are identified. For example, on a high level there is the problem and the environment in which the problem takes place. On a more specific level are participants, characteristics, and resources for the environment. The initial state and final state and satisfaction criteria correspond to the problem. Also important is the graphical design representation, which adds visual dimension to the artifacts. Finally, the artifact behavior is mostly described by mathematical or logical representation. Behind those representation are the tools: the CAD system for the pictorial representation, analysis tools for the mathematical representation and KBS for the logical representation [Dym, 1994].

In the design representation evolution process , the next step is exploring the design artifacts' characteristics [Bahrami, 1992]. Featured-based design that exploits specific artifacts is an attribute that has added value for the design. A feature may be volume, shape, or, more likely, a more sophisticated attribute of the artifact. For example, the ability of a door to open and close may be used as a feature. This design representation is very appealing since its brings the artifact and their functionality's together [Eastman. 1991].

Object-oriented representation [Banares-Alcantara, 1991] allows the engineer more freedom in the artifact description [Coad, 1991; Shah, 1989]. The notion of objects' attributes and actions is realistic [Buoch, 1992]. Any artifact may be an object structured in such way that it relates to other artifacts via relation and action, and may be described by attributes. The basic object-oriented concept is fairly rudimentary. For example, an “I” beam is a member of a larger class of elements, namely beams. Some generic attributes may be associated with the class called beams, such as section area and moment of inertia. Each “I” beam will have those attributes inherent to it and will have some unique attributes that exist only in “I” beams, namely the flange width “t”, the height “h” and the length “b”. Wegner [Wegner, 1987] describes the conditions that must be met in an object-oriented representation. The first condition is being an object that has certain variables. The next condition is class -- a template or abstraction for a particular class of objects that poses or shares identical behavior and structure. The final condition is inheritance -- the principle of specific attributes of issues such that the siblings are explicitly inheriting the properties of their ancestors[Buoch, 1992].

As discovered in case studies [Sage, 1993], by focusing upon attributes of objects and the relationships between objects , it’s often simple to describe the problem domain. Objects are real-world elements and they possess attributes. The object-oriented (OO) methodologies evolved from the computer science field and were rapidly adapted by design and modeling engineers. In several case [Zhou, 1994] studies it was discovered that the OO representation emphasizes the more stable part of the system, namely the data rather than the function. This facilitates object evolution in a smooth manner. The inherent characteristics of OO representation use powerful abstraction mechanisms that make it easier to deal with complexity. The concept of OO representation relates well to the real world. Modularity is another quality that OO representation demonstrates, therefore allowing minimizing elements representation underlines re-use.

2.1.2 The Change Issue In Engineering Products

The first and foremost goal in product representation is to capture the participating design artifacts [Eastman, 1991, Erens, 1994]. An interesting point is to examine how easy it is in a product representation to represent a change, and moreover, to trace the change and the influence of the change on the whole design.

The questions that arises, then, is what is design change? Who initiates it and what are the mechanisms that participate in a change propagation? It is well-known [Erens, 1994] that design is an evolving process. However, the change that occurs in “design_version_1” that moves it to “design_version_2” is the dynamic part. Therefore, the design change may be one of many elements, namely conceptual change, detailed change, requirement change, or compounds of any of these.

In the classical design process, change definition in this process is expressed in the individual stages and propagates through the feedback to other design process parts. Each part is, in fact, a subprocess. For example, Jamalabad and Langrana [Jamalabad, 1993] suggest the multi-stage iterative feedback. In their suggested approach, the change occurs in the redesign module and is specifically done to improve the analysis input. The meaning of change is implicit. However, it’s clear that the analysis module does not change -- in other words, the change is not structural, but is limited to data sets variation. The first stage in classical design is the “need,” and is described in more details in

Bahrami [Bahrami, 1992] . The “house of quality” facilitates requirements change propagation and allows relations mainly among customer requirements, design requirements and competitive assessments. The house of quality relationship matrix demonstrates how change in the customer requirements will translate to design requirements through matrix elements.

2.1.3 Design Evolution

Design evolution [Landis, 1986; Liu, 1995] is defined by [Thompson, 1990] as a description of the link from conceptual design to the final detailed design. Thompson [Thompson, 1990] developed methodology for design evolution management. In Thompson, the authors explain incremental changes and demonstrate how the final design relates to the initial functional requirements. This is helpful for expressing different design strategies and having the ability to trace them. In Ullman, [Ullman, 1993], the author defines objects, operation relations and behavior and explains how together they can represent an evolutionary process in design.

2.1.4 Concurrent Engineering

Concurrent engineering [Curtin, 1994; Cutkosky, 1990; Dym, 1994; Grigley, 1993] differs from the traditional serial design approach in the following manner. As opposed to the traditional design, concurrent engineering allows feedback from any stage to any other stage in the process design; the design stages are not rigidly defined. Concurrent engineering shortens the development of the lifecycle by automating the product design and manufacturing process [Kannapan, 1992]. The automation can range from the automated generation of process flow chart to systems that automatically design, manufacture and package products. An example of a concurrent engineering data layout is given in [Nebel, 1990]. Integration and sophisticated use of CAE/CAD techniques are essential for concurrent engineering success. Implicitly, the concurrent engineering approach facilitates change propagation by increasing the interconnectivity within the design process. As different processes interact with each other, data schema complexity increases, new issues gain importance, and the need to manage the product information becomes essential. First, there is a need to manage the design information. Next, there is a need to integrate among subprocesses and develop new flexible methods that will be able to react quickly to changes that are so typical to concurrent engineering design.

Essential for the concurrent engineering concept and an important idea by itself is the parametric design [Whybrew, 1991] methodology. The key advantage that the parametric design presents is the concept of full associativity. Full associativity is the ability to make a change to a product design in any phase of its product development process, starting from the conceptual design through the detailing, analysis, and manufacturing, and to propagate this change throughout the different design views.

2.1.5 Product Data Manager

The product data manager is an initial attempt at managing information and information flow in the design process [Curtis, 1994]. The product data manager is a central resource that maintains control over the overall system data, starting from the requirements throughout design, analysis and manufacturing. The product data manager works as an enabler for concurrent engineering in a very practical manner, dealing with distributed data repositories and generating virtual design teams. Change and change tracing are very relevant particle issues that the product data manager of today deals with. A product data manager relies on product data models and data schemas to direct it in the data flow design [Curtis, 1994]. Therefore, the product data manager relies on product data models for its change management.

At the core of the product data manger is the data schema. Therefore, we may find some hints about how change effect is designed from the way the data schema is constructed. Moreover, the product data manager may help us figure out the change propagation trail. Much work has been done in the area of schema evolution [Banerjee, 1987]. CAD systems support the design of engineering models and as such are more likely to be complex and elaborate. Therefore, object-oriented databases are suitable for mapping engineering models [Sciore, 1991]. Few forms for schema evolution have been developed to do this task Landis, 1986]. Most of the research done on schema evolution has been on the methods of keeping the pre-change design in one version and presenting the post-design change as a new version, therefore creating the notion of history. Most of the work has been done using the object-oriented approach, [Jamalabad, 1993; Rumbaugh, 1994] some of it using relational data schema [Liu, 1994] , temporal database approaches [Gal, 1995] or AI techniques, as in case-based reasoning [Grigley, 1993]. Interesting work has been done by Oldberg [Oldberg, 1994] examining the sensitivity of physical database design to change in input. Some work on data schema changes has been done with relation to schemas integration [Batini, 1992]. An interesting methodology for change evolution in ER diagrams has been developed by Liu [Liu, 1994]. Liu developed adaptive schema design for object-oriented databases. He presented a framework of rules and inter-dependency schema to accommodate adaptive OO databases to changing requirements.

2.1.6 Product Data Model

In Warman [Warman, 1984], the authors define the term “product data model” as a model that encompasses global aspects of a part. As CAD systems developed, the amount of information about a product increased dramatically. In the early days, the CAD data was considered to be mainly geometric description. However, nowadays the part information is highly versatile, from requirements information through assembly directions [STEP Part 44, 1992], analysis results and maintenance mechanisms. All this information and more is encapsulated within the product data model.

2.1.7 STEP- Standard For The Exchange Of Product Model Data

Since 1986 there has been a great international effort to develop an ISO (International Standard Organization) for CAD and engineering data exchange. The STEP [Eastman, 1993; Liu, 1993; Schwab, 1993; STEP Part 44, 1992; STEP Part 11, 1992; STEP Part 1, 1992; Wang, 1991] technology should facilitate concurrent engineering by standardizing the data presentation along the product life cycle. By creating a common approach to the information structure, the need to translate forms of data from one product life stage to another will be minimized. STEP represents its different parts by using a data definition language called EXPRESS [Marche, 1993]. STEP plays a key role in the integration of engineering and manufacturing systems [Miller, 1996]. Key elements in the development of STEP are arranged in three levels: information modeling, exchange format and conceptual modeling. The STEP information is represented by the EXPRESS language, which is a data definition language.

The development of STEP is an ongoing effort that will cover all life cycle and industries domains. Application protocols will hierarchically divide STEP into resource models which will eventually support a specific industry. For example, the way that STEP is set up is that Part 11 in STEP is the definition of the EXPRESS language that is used to describe Part 101, which is drafting resources. Then, Part 101 helps in constructing an application protocol for the automobile industry, which is part 214. The content of STEP reflects the fact that the industry and research communities have an increased understanding of the product data. [Warman, 1984]. Many STEP parts are either completed or on the working group table. Part 1 is an overview, Part 11 is the EXPRESS information modeling language, and Part 21 is a driven data exchange file specification. Parts 22-26 are application programming interfaces, Part 31 is a conformance testing framework, Parts 40-49 are libraries of general purpose information models for geometry, topology, product identification, date, time, etc. Parts 200-299 are industry-specific application protocols, which are built from the library of the general models. Part 201 is explicit drafting, part 202 is associative drafting, part 203 is configuration-controlled 3D assemblies, and part 214 is automotive design.

2.1.8 Reasoning With Qualitative Information

This research deals implicitly with reasoning using qualitative information. The first that is considered when working with qualitative information is representation. The information representation is dependent mostly on the context in which the qualitative information is meant to be used. In Case Based Reasoning, [Kolodner, 1993], the bulk of the information is specified in the form of cases or stories. In the Rule Based approach, [Charniak, 1985], the information scope is pattern driven and consists mostly of highly detailed information. The information characteristics of the Model Based Reasoning, [Schank, 1982] is established on causal models of devices or domains. The information nature of model based reasoning is applicable only when causal models exists and the information is well understood. It can be concluded that the nature of the information representation is derived from the reasoning methodology .

Reasoning with qualitative information has been explored heavily for the past three decades [Charniak, 1985]. Expert system are built mostly using rule based reasoning as a backbone mechanism [Roth, 1983]. In rule based reasoning, rules are inputted by domain experts and are retrieved and matched for input that exactly relate to the rules condition. Rules are applied in an iterative cycle fashion. Rules are mostly small and independent and aspire to cover a consistent piece of domain knowledge. Case based reasoning and model based reasoning are used less frequently than the rule base approach. However, their coverage is wider and they represent reasoning in a more abstract manner. The case based reasoning approach tries to aid users by providing a knowledge reservoir of previous cases and a sophisticated indexing and retrieval mechanism. The model based approach captures knowledge by means of various models that describe views of the desired domain. For example, case based reasoning is applicable even when the knowledge domain is not well understood [Kolodner, 1993]. Model based reasoning provides the means of verifying and justifying its solutions.

2.1.9 Qualitative Information Acquisition And Processing

An important part of this thesis deals with qualitative information acquisition, processing and ranking. For this thesis domain experts were asked to construct significantly large data sets in the form of case studies. On top of that, some of the output that is used to evaluate and verify the methodology has a qualitative flavor to it. Assigning importance values is a major activity in surveying methodologies [Clancey, 1988]. Comparison among choices can be based on placement in an abstract hierarchy, or based on evaluation on a qualitative or quantitative scale, or a comparison based on the degree of their functional role [Ashley 1987]. A classical problem in assigning importance values is how refined the scale should be. On the one hand, a more refined scale potential provides a higher quality of domain coverage understanding. On the other hand, the acquisition process is more tedious when it provides more ranking possibilities. Moreover, for an abstract wide survey domain, a finer ranking system may cause a mediocre evaluation.

A ranking schema based on offering two choices may make the respondent's role easy. However, the richness of information extracted from this acquisition mechanism is doubtful. The quality of the ranking system is dependent mainly on two factors: the domain nature and the characteristics of the ranker. The main problem with ranking is that it is are reliable as long as the ranking estimation is relative [Hunter, 1989]. Namely, for a well defined narrow domain where the problem parameters are clear and limited, it is recommended to introduce a relatively refined ranking schema of five or seven or even nine classes. However, introducing that many ranking possibilities can be counterproductive in an domain with an abstract nature. The house of quality methodology [Clausing, 1988] introduces several ranking schemes. The original schema had three levels: high, medium and low.

2.2 Literature Survey Summary And Current Gaps

The object-oriented representation facilitates relatively complete design representation and, together with the version management, improves design evolution. However, the change in object-oriented representation as well as in any of the design representations is in the best case implicit. In both the serial design process and in concurrent engineering, there is no change-oriented representation. In fact, the data models including STEP tend to suggest that the design is static. Concurrent engineering strives for the design evolution and the dynamic nature of design. Therefore, it is very important to tighten the integration and the communication among different parts of the product. The STEP technology provides the standardization and the data structure umbrella.

Plausible efforts in building a schema evolution mechanism have been described Bouneffa, 1995; BritsGal, 1995; Monk, 1993; 42; Rumbaugh, 1994; Sciore, 1991; Sjoberg, 1993; Skara, 1996; Uneda, 1990; Ullman, 1993]. However, there is still a gap between the design engineering methodologies and the technologies that are supposed to facilitate the concurrent design. For example, the product data manager capabilities are limited to record controlling, and in fact they can be described as merely upgraded file managers [Curtis, 1994]. On the one hand, the design community builds the design methodology that requires intensive and sophisticated technologies, and on the other hand the information modeling community develops the tools to serve these methodologies. The design methodology is running ahead of the technology, and sometimes the methodology is delayed because of a lack of existing technology. Moreover, if the technology could keep up with the design methodology, it would improve the cross fertilization between the two. There is a need to reflect change in design and explore its propagation. For example [ISO TC184/SC4/WG12_ N022. Parametrics. 1997] in the current level of discussion of parametric representation has the following flavor: **How does an increase of a block length dimension influence the two circles that are in it** ? (Figure 2.1)

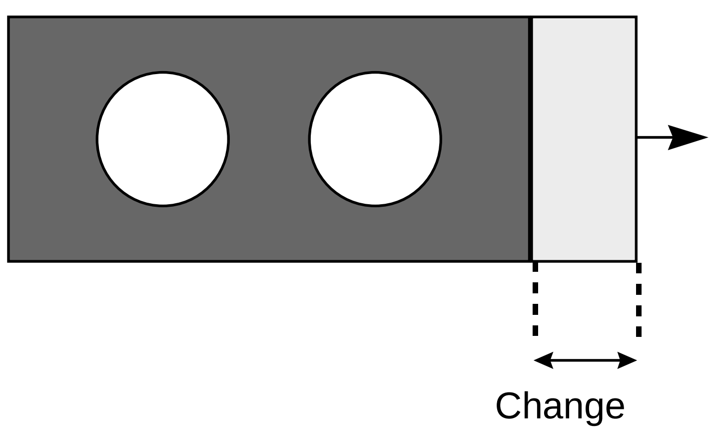


Figure 2.1 Example Pre Change In Block Length Dimension

The 'length' dimension change propagates to other relevant objects via a set of constraints and the possible result is presented in Figure 2.2.

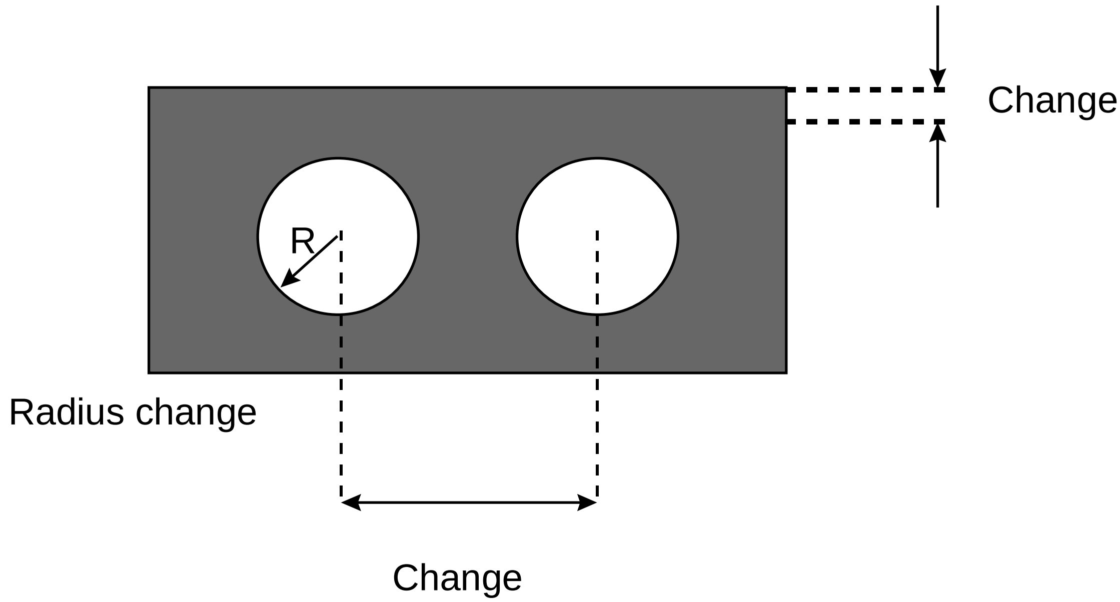


Figure 2.2 Example Post Change In Block Length Dimension

The consequences changes are proportional increase in the block width, relocation of the two centers and proportional increase in the circles radiuses (Figure 2.2). However, the current parametric approach scope does not capture wide aspects of changes. The block in Figure 2.1 represents an aluminum block and the two circles are actually two pockets to be milled by a CNC machine. In this scenario, a whole new dimension on changes can take place. For example, machine parameters change, material changes, etc. Moreover, engineering changes are possible on even more abstract levels, Figure 2.3

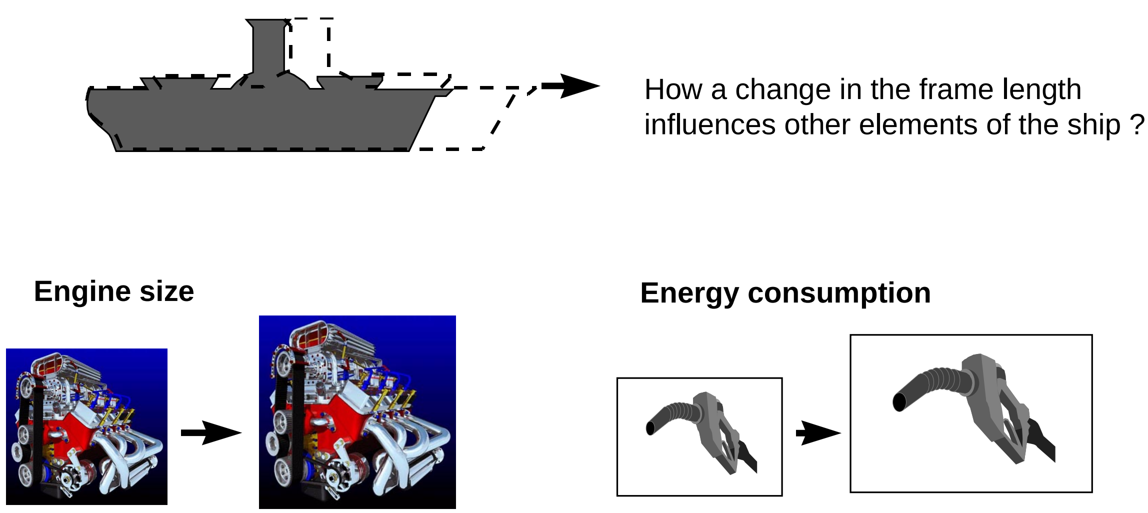


Figure 2.3 Example Possible Ship Length Change Consequences
(Credit Engine Picture to Computerized Engineering Images LTD)

The current parametric approach does not claim to do deal with abstract complex problems that are presented in [ISO TC184/SC4/WG12-N022. Parametrics.]. Clearly engineering changes are not just geometric or functional. Engineering changes are describing engineering objects and therefore are complex and need an abstract semantic mechanism to be adequately described.

Chapter 3

Problem Scope

In this chapter, the problem borders are articulated. The need for an abstract semantic mechanism to describe the domain was established in the previous chapter. The first part of this chapter is dedicated to EXPRESS, since the C-FAR methodology is built on the EXPRESS information model. The next point examined in this chapter is what exactly the EXPRESS information model provides and what it does not provide. Next, a discussion about engineering changes and their reflection in C-FAR is provided. Finally, the notion of redesign is explained as well as redesign's relation to engineering changes.

3.1 EXPRESS - Data Definition Language

To understand the C-FAR methodology, it is helpful to first understand STEP and the language that it uses. STEP encompasses all product data and it is founded on the EXPRESS language [Schenk, 1991], which is an information modeling language. Next, STEP separates the information model from the data instances. Finally, it requires conformance testing of implementations.

EXPRESS is the formal information modeling language used to specify the information requirements of other parts of the STEP. EXPRESS defines schemas objects attributes and behavior. For example, a schema "automobile _bumper" will describe an automobile bumper's objects, attributes, and behavior. EXPRESS is based on the following design goals: the language will be parsable by computers, the language is designed to enable partitioning of the diverse material assessed by this STEP, and the schema is the basis for partitioning and intercommunication. Finally, the language is focused on the definition of entities, which are elements of interests. The definition of entities is in terms of data and behavior. Data represents the properties by which an entity is realized and behavior is represented by constraints. EXPRESS has a graphical subset representation called EXPRESS-G. The EXPRESS-G is a graph-theory type representation method. Although it has been specifically developed for the graphical rendition of information models defined in the EXPRESS language, it may be used as a modeling technology in its own right. The EXPRESS main design goal is to be intuitively understandable, and it is also supposed to support levels of abstraction. An information model is considered to consist of definitions of things (entity, type, function, etc.). For example, the following is an example of a circle description in EXPRESS followed by the same circle represented in EXPRESS-G:

```
SCHEMA circle;
```

```
ENTITY point_3D;
    x1:    REAL;
    x2:    REAL;
    x3:    REAL;
END_ENTITY;

ENTITY circle;
    center_point:   point_3D;
    radius:         REAL;
END_ENTITY
END_SCHEMA;
```

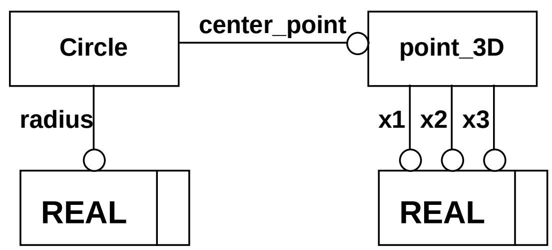


Figure 3.1 Example Of A Circle Description In EXPRESS-G

<u>3.2 EXPRESS Coverage</u>

The Change FAvorable Representation is based on an EXPRESS information model. EXPRESS, part of the STEP standard, is directed to model various product aspects. The following is a case study which illustrates how the EXPRESS information model relates to engineering models. The case study articulates the deliverables of the EXPRESS information model and also what we should not expect to get from it.

3.2.1 Case study Statement

Modeling is a major activity in the design and analysis processes. This case involves modeling an engineering domain problem in two dimensions. One suggested modeling aspect is an idealized mechanical car structural model. A simplified mechanical structure is to be examined. The second modeling aspect is the data that describes the structure or a car structure information model. This case study will include construction of the models and a qualitative comparison between them.

3.2.2 Case Study Framework

One of the earliest attempts at predicting car body behavior used a two-dimensional truss frame as a car side frame representation. The action of vertical loading from the engine and the passenger bay mounts was examined against the reaction of the spring hanger. This model is simple to analyze from a structural perspective and is a good starting point for understanding the main features which car structure presents, and comparing it conveniently with the information model. At the next stage in modeling a car structure, a more elaborate space-frame three-dimensional truss model was adopted. This model characterized the cutting edge of light vehicle space truss design, and was more complex and usually statically indeterminate. These two structural analyses will lead us to an understanding of the main characteristics of truss design within the car chassis vehicle domain and will allow us to develop an information model.

3.2.3 Case Study - Car Profile

In this section a car profile is modeled by 2D truss structure. This problem represents a two-dimensional truss in a vertical loading of the power train transmission passenger bay, with the end rear weight applied on a profile of the car, as illustrated in Figure 3.2. The truss is simply supported as represented by the axle springs, and the loading is static. To find the deflection, the unit dummy load method will be used.

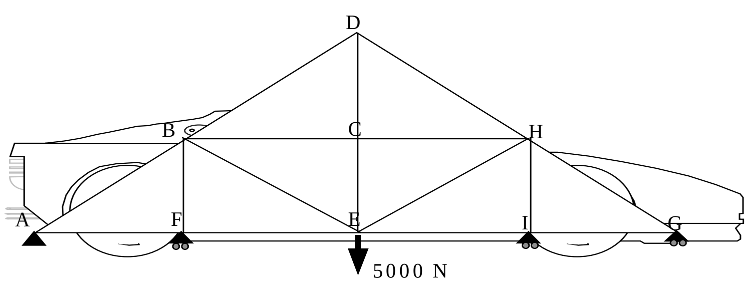


Figure 3.2 Car Profile 2D Truss Structure Model

Problem characteristics are illustrated in Figure 3.2. The load of ten thousand Newtons is applied on the middle of the profile. The problem is symmetrical, and when simplified, the reactions are in the vertical direction.

To enhance the understanding of the problem, the sensitivity of the car profile to various loads applied on this schema will be examined. The flexibility matrix represents how flexible the structure is and how prone to displacement each node is as a result of activating a unit load in the x or y direction**.** The ANSYS software will be used to represent all the test cases. The flexibility matrix can be written in this form:

$[f]\{F\} = \{- D\}$

In the matrix [f], each row “I” represents the influence of applying a unit load on a degree of freedom “I” and the displacement on the rest of the degrees of freedom as a result of this unit load. The flexibility matrix is also called the flexibility influence coefficient. Using the flexibility matrix allows us to analyze the structure independently from the loading. The graph in Figure 3.3 demonstrate the that the more indeterminate the structure, the more stiff it is and less flexible. Using the ANSYS software, we added two and then four more elements and measured the displacement in the Y direction of Node E

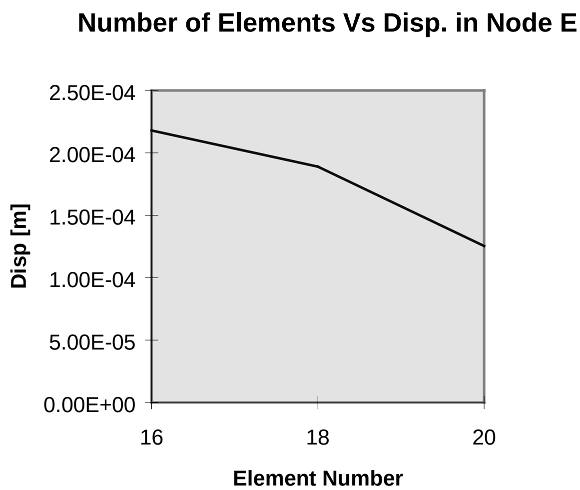


Figure 3.3 Number of Element vs. Node E Displacement

Generally the more elements that are added, the stiffer the structure. The structure will become stiffer as the cross section area of the elements increases. Figure3.4 is an ANSYS software output screens illustrating the deformed car profile.

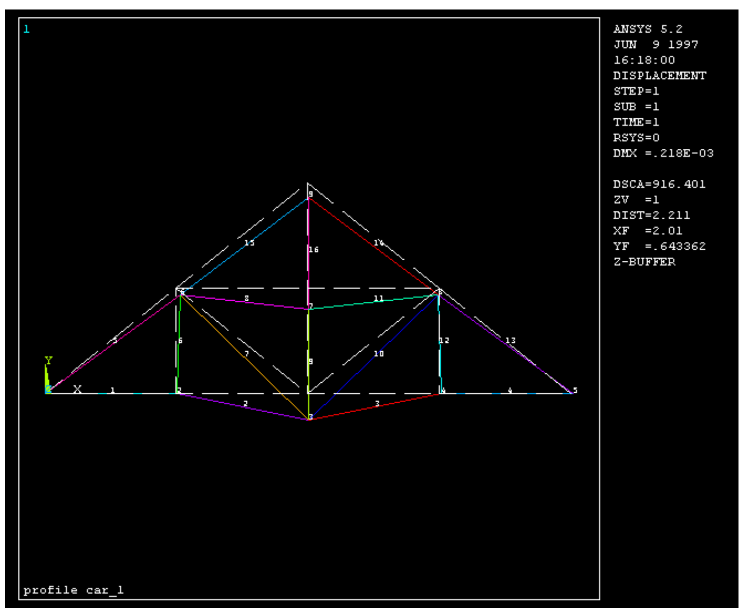


Figure 3.4 Deformed Car Profile.

3.2.4 Case Study - Space Frame

The space frame structure is used to model mainly light, high speed cars This section of the thesis will utilize the classical 3-D space frame as shown in the Figure 3.5

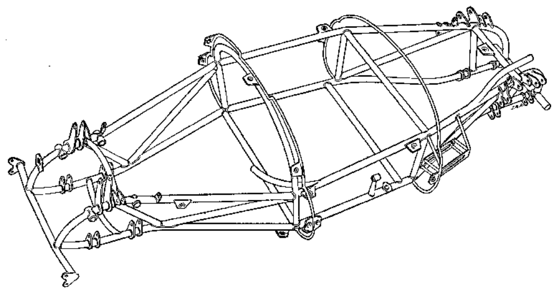


Figure 3.5 Car 3-D Space Frame

(Credit Drawing to Costin & Phipps “Racing and Sports Car Chassis Design”)

For a three-dimensional frame, there is much more difficulty, and the method known as tension coefficient is applied. This is based on the fact that proportionality exists between both result components of length and of force. The tension coefficient is

t = S/L = Fx/X = Fy/Y = Fz/Z

For member force S in the length l projecting force vectors and length component Fx, Fy, Fz, and X,Y,Z on perpendicular coordinate axes. The following is the ANSYS model that analyze this given 3D space frame. Twenty and 50 nodes were used with more than 50 3D elements to analyze this problem. Fig 3.6 is an isometric view with the loads and the geometric constraints

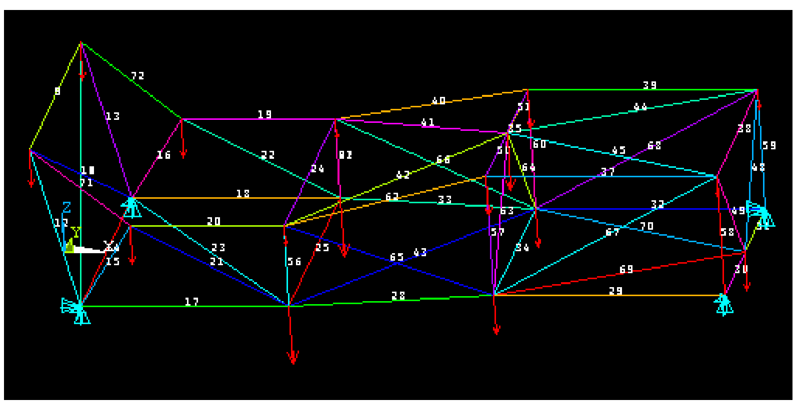


Figure 3.6 ANSYS 3D Space Frame Model

The great majority of vehicle structures are indeterminate. To increase the stiffness, our example is taken from [Costin, 1971] sports car chassis design. The space frame is made up of three main chambers: the engine bay, which carries most of the load; the passenger bay; and the rear, or back, bay. The problem geometry and loads are taken from [Costin, 1971] The problem is solved using ANSYS.

Figure 3.7 illustrates the deflected frame.

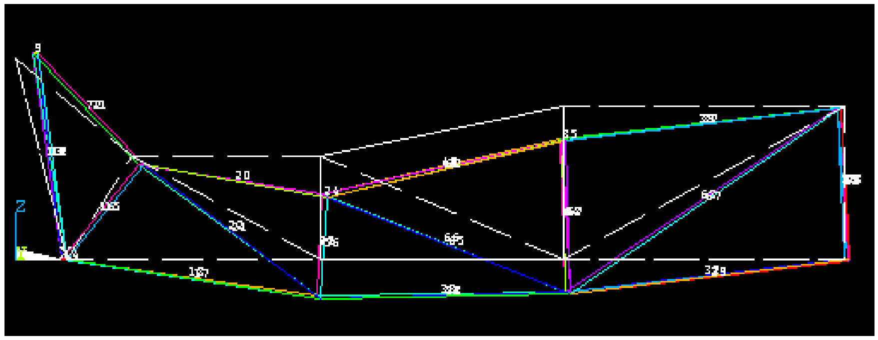


Figure 3.7 Deformed Space Frame Model

3.2.5 Case Study - Car Structure Information Model

The information model used is the express data modeling. This model described in Figure 3.8 concentrates on car structure components. We observe the domain on three levels: the structural level, and then deeper to the analysis level, and then the element node relationship level. We also provide a closer look at the flexibility matrix definition as demonstrated in the next figure. The structure is defined by geometry and our two cases -- car profile and car chassis -- have a structure. The structure is a superclass to force specific subclasses, namely beam structure, element structure, thin-wall structure, and stiff joint frame structure. In the structural analysis case study, we concentrate on the element structure case. In this figure also, the relation between structure and its analysis model is underlined. Specifically in this case study, we use formula-based analysis and finite element analysis. In the following figure, the star near each entity indicates that this entity was investigated in the structural case study.

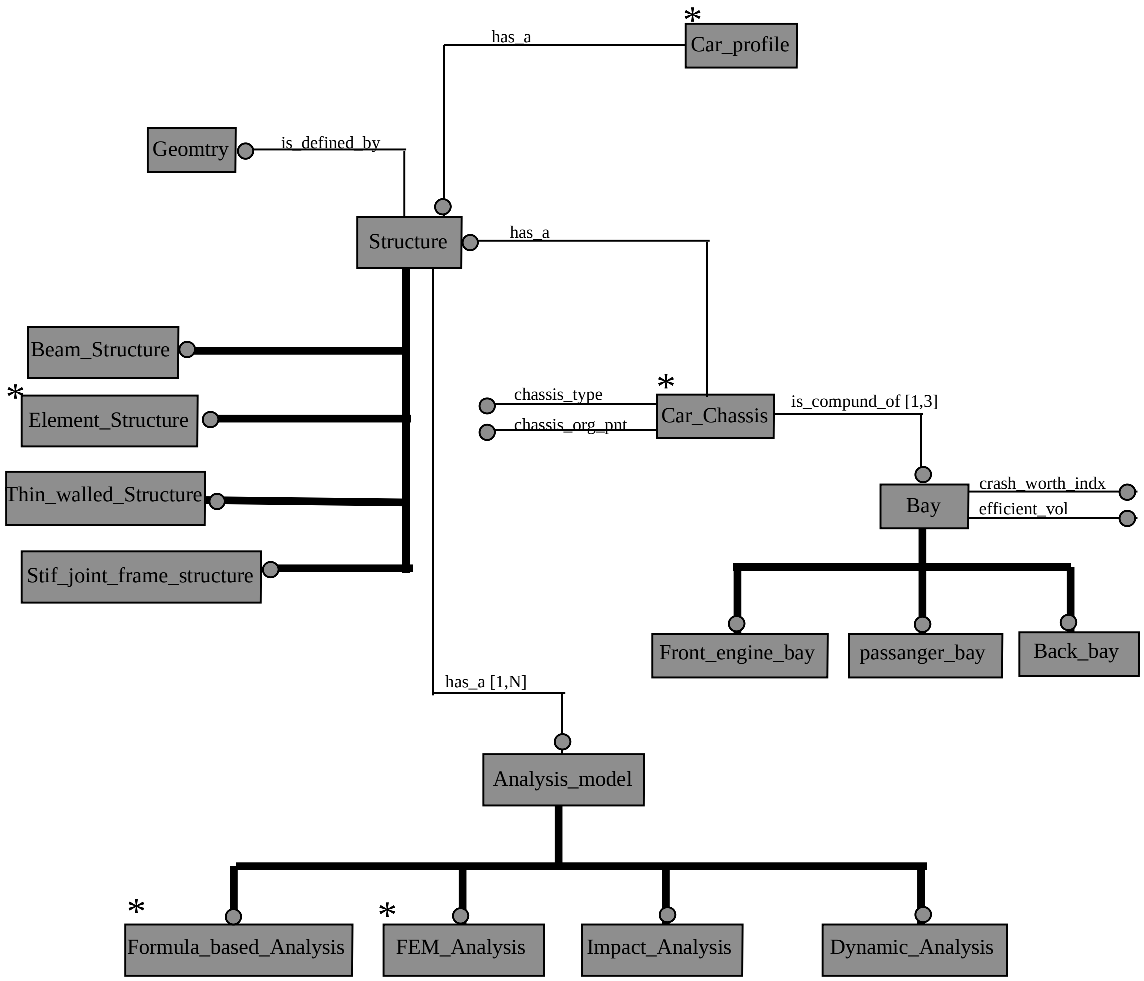


Figure 3.8 Car Structure EXPRESS-G Information Model

Figure 3.9 concentrates on the element structure itself. The element structure is demonstrated as a superclass to the truss entity as well as to the space frame, which is 3D truss. The element structure is compounded of elements and nodes and the element is bounded by the nodes. The subclass elements – link_2D and link_3D – are being used respectively in the car profile case study and the space frame case study. Also, the location of the load action on the structure and the type of loads are underlined.

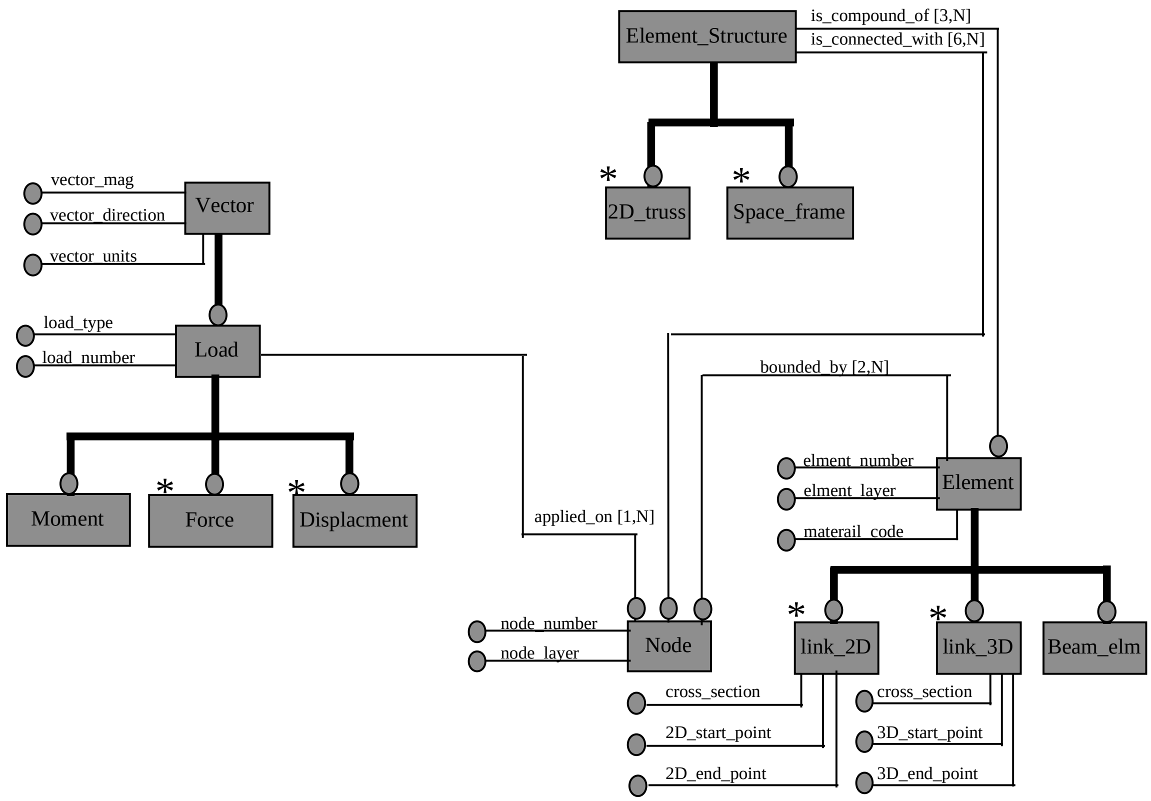


Figure 3.9 EXPRESS-G Structure Finite Element Information Model

Figure 3.8 can be expanded to include a description of the structure flexibility matrix and loads vector. However the EXPRESS schema will not be able to show how a change to any of the analysis instances will affect the structure. EXPRESS was not able to reflect the influence of the number of elements on the nodal displacments.

3.2.6 Case Study - Summary

The case study was divided into two parts. The first was the structural analysis of car structure. This was done in stages. The first stage was a simple car profile of a two-dimensional truss analysis, which facilitates deep investigation into the characteristics of the structure. Next, the space frame analysis was investigated, which is a far more complex multi-element system. To investigate this problem, the ANSYS program was used. The main purpose of undertaking these two case studies was to identify the important parameters and design variables and to examine their relations to one another while modeling idealized car structure. These two models helped us understand the displacement range, the load range, and the cross-section range of the elements needed to tackle this problem. Also, relationship between structure parameters were established.

The second stage of the project was to model this car structural problem using an information model. The information model grasps the structural domain on different levels and it classifies types of structures and analyses. The information model also emphasizes how structures and analyses interact with one another. Important elements of the structural analysis are included, such as the stiffness matrix and its relations to the degrees of freedom and the displacement.

The roles of both models are inherently different. Part of the information engineering model is to help, or even better, to facilitate the high-quality and efficient execution of the structural engineering model. The role of the structural analysis model is to provide a revealing perspective about the way the structure behaves under certain combinations of constraints and load, together with the physical and geometrical input. Table 3.1 describes qualitatively what aspects of the structure are covered and are not covered by the information model.

Engineering Model Functionalities and Properties	**Math Model**	**Load Applied**	**Constraints**	**Geom. Comp.**	**Prob. Solving**	**Sensitivity Analysis**
Structure Information Model Capability to Describe The Engineering Model Functionality	+	+	+	+	-	-

Table 3.1 Information Model Coverage

3.2.7 Case Study - Conclusions

This experiment's purpose was to learn about what aspect of the structural model and the structural model analysis can be covered efficiently using the engineering information model EXPRESS. Two structure case studies were deliberately chosen: the car profile, and the space frame three-dimensional truss. Surprisingly, both of these models nicely fit under the same car structural information model, which suggests a compact nature of this object-oriented flavor EXPRESS data model. Almost entirely, all the aspects of the two structural case studies can be described by the EXPRESS information model in an efficient and modular manner. The information model illustrated an ability to integrate within the data model several aspects of the structure analysis, namely the math model, geometrical aspects, and additional views of the chassis design.

However, there are two main issues that are not covered by the EXPRESS information model. The first issue is a solving problem. EXPRESS does not solve structure analysis problems. The second problem is a sensitivity problem. EXPRESS contains information about the structure elements, but this information is not used to understand how a change in one entity influences another entity. For example, we know from the analysis of the structural model how change in the number of degrees of freedom influences the flexibility matrix. We also know how an increase in the magnitude of a given force vector influences the displacement vector. However, we do not know how the influence of these inter-relationships are being translated into the EXPRESS information model. We know only that there is a relation – we do not know the direction or the nature of the relation.

3.3 C-FAR vs. EXPRESS

The Change FAvorable Representation (C-FAR) attempts to use the knowledge domain that exists in the EXPRESS schema for purposes of exploring changes and their influences. The EXPRESS information model captures the domain artifacts with four main elements: a schema which defines the domain frame; entities, which are the main objects in the domain; relations which describe the connectivity between entities; and attributes, which describe the entities.

C-FAR uses the EXPRESS schema as it currently exists and adds domain knowledge to it. This domain knowledge purpose is to facilitate change and change propagation within the existing objects. However, C-FAR does not expand the EXPRESS schema coverage from a contextual perspective. C-FAR does not add entities, attributes, or relations to the EXPRESS schema.

C-FAR adds to EXPRESS in two main ways. The first is to view an entity as a vector and its attribute as the vector's components. This view focuses the changes of a schema to be changes in the entity's attributes. Next, C-FAR creates matrices between entities that are connected with relations. The C-FAR matrices enable change propagation. The C-FAR mechanism will be further discussed in chapter five and six.

3.4 The Engineering Change Paradigm In C-FAR

The EXPRESS diagram represents data on two levels, the meta-data level and the instances level. The meta data level underlines the schema, entities, relations and attributes. The actual values are compound of the attributes instances. Engineering changes may translate to changes at either of the two levels. Namely, engineering change -- if it is an introduction of a new set of design variables, replacement of complete functional modules, or a value change in a single variable -- are all reflected in two of the representation levels. For example, in the following structural analysis using the EXPRESS schema, a new kind of element is introduced.(Figure 3.10)

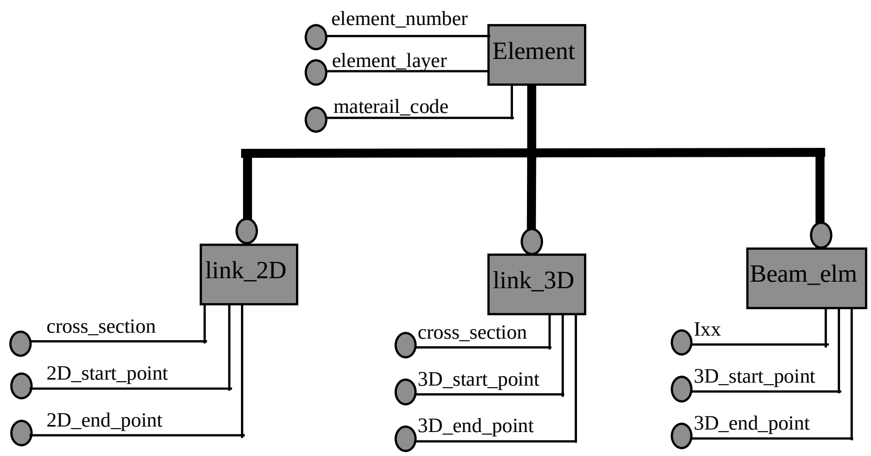


Figure 3.10 Example Three Elements Subtype

A new type of element is added, Solid9Pnt. (Figure 3.11)

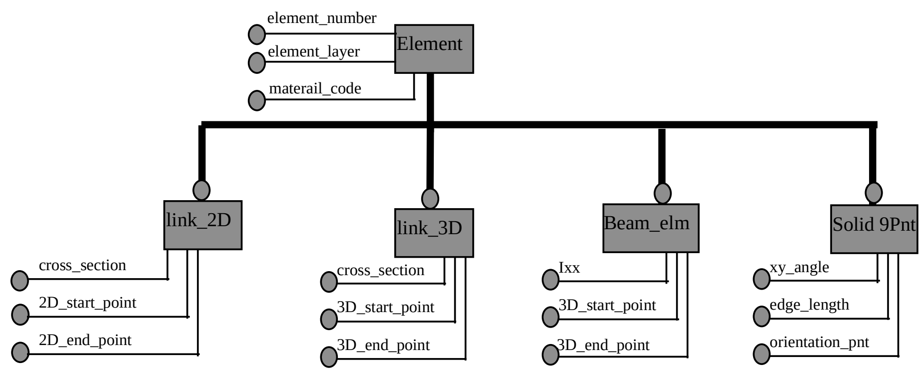


Figure 3.11 Example Four Elements Subtype

Solid9P is a subtype of the entity element, therefore Solid9P is equivalent to link_2D, link_3D and Beam_elm. Adding the Solid9P entity has also added its three attributes, xy_angle, edge_length, and orientation_pnt. Therefore, an introduction of a new element in this case has translated in EXPRESS to one entity, one relation and three attributes.

A second kind of change is a change of an attribute value. From a semantic perspective there is no change within the meta data schema. For example, a change in the 2D_start_point value for the link_2D element from 0.00 to 1.00 is not reflected in the EXPRESS schema. Within the STEP framework, Part number 21 holds the information of the instances of the EXPRESS meta data schema.

An interesting question is, once we introduce an engineering change, can we know if this change affects the data, meta-data, or both? Since we assume that we have an EXPRESS schema that covers the engineering domain adequately, it is not a difficult task to check all the current attributes and values and examine the proposed change. If the complete proposed change can be described with changing any of the existing attribute or values, then it can be said that the change is meta-data change independent. However, if it is impossible to reflect the engineering change only via the existing attributes, then the engineering change causes a manipulation of the meta data EXPRESS schema. Therefore, given the meta-data schema and the proposed change, it is feasible to classify the engineering changes as meta-data change independent and meta-data change dependent It is important to emphasize that the schema definition is no less important than the engineering change in determining if a change is meta-data independent or not. The following is an example that demonstrates this point.

Consider the introduction of Solid9P element to this schema:

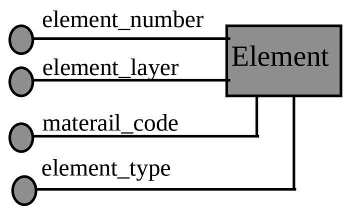


Figure 3.12 Example Element Entity

In this case, the element type Solid9P represents a change of value of element_type and subsequently does not represent a change in the meta data, unlike the example in Figure 3.11. Therefore, whether the change is meta-data change independent or not is a function of both the schema and the change itself. Redesign activity can be observed as a sequence of one or more changes. From a data perspective, these redesign triggered changes will be meta-data independent or meta-data dependent. **C-FAR deals with changes that are meta-data independent**. By not considering the meta data dependent changes, the C-FAR research directs its efforts towards engineering changes of semantically parametric nature. Considering meta-data independent changes avoids going into schema evolution theory. Moreover, it creates a disjointed state between the unchanged EXPRESS schema and C-FAR and the proposed engineering changes. Namely, the engineering change initiator should not have a knowledge of EXPRESS or how to build an EXPRESS or C-FAR schema. C-FAR will be a black box for the engineering change initiator and change initiator will be exposed only to the measurable quantities of the schema.

3.5 Engineering Redesign and C-FAR

The notion of engineering redesign in the thesis framework is defined as a set of prescribed engineering changes that are applied to a system in a given initial state and these changes then transform this initial state into a final, post-change state. Within the C-FAR framework, the system description is given via EXPRESS and the C-FAR enrichments. Therefore, the engineering redesign scope is actually a set of changes that are applied to a C-FAR specific model. Since the C-FAR scope is limited to changes that are meta data independent, engineering redesign activities may not be covered completely by it. However, given a C-FAR model of an engineering application and a suggested engineering change, it is trivial to determine whether the given engineering redesign can be modeled by C-FAR or not. There is one criteria that is used to determine if the redesign can be represented by C-FAR: the absence of meta data changes. If the suggested redesign activity can be stated by using only non meta data attributes, then the redesign activity can be modeled by C-FAR. Non meta data attributes constitute the measurable parameters of the problem domain. Given an EXPRESS schema, the non meta data attributes are trivial to detect. A detailed explanation about the methodology is provided in chapter five and six.

3.6 Problem Scope Summary

C-FAR is a methodology that uses the EXPRESS information model as a baseline. EXPRESS does not provide a mechanism that reflects change or change propagation.
C-FAR's aim is to enable the representation of engineering changes that are meta-data independent, to facilitate these change propagations through the schema, and to supply a mechanism that estimates qualitatively the propagated change consequences.
C-FAR is built to serve as an aid for a redesign activity. The notion of redesign activity in this thesis is a set of prescribed engineering changes that moves the problem description from one state prior to the changes to a second state after the suggested changes have been made. The following is an example that illustrate the scope domain.
Following is a structure in Figure 3.13:

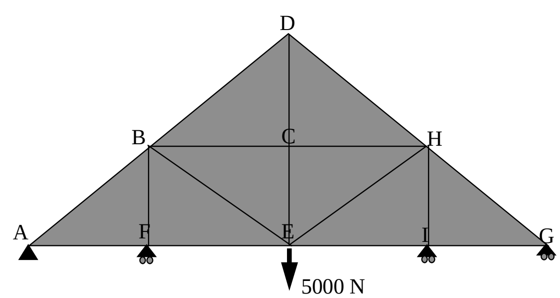


Figure 3.13 Example 2D Truss Structure Model

The corresponding EXPRESS schema is given in Figure 3.14

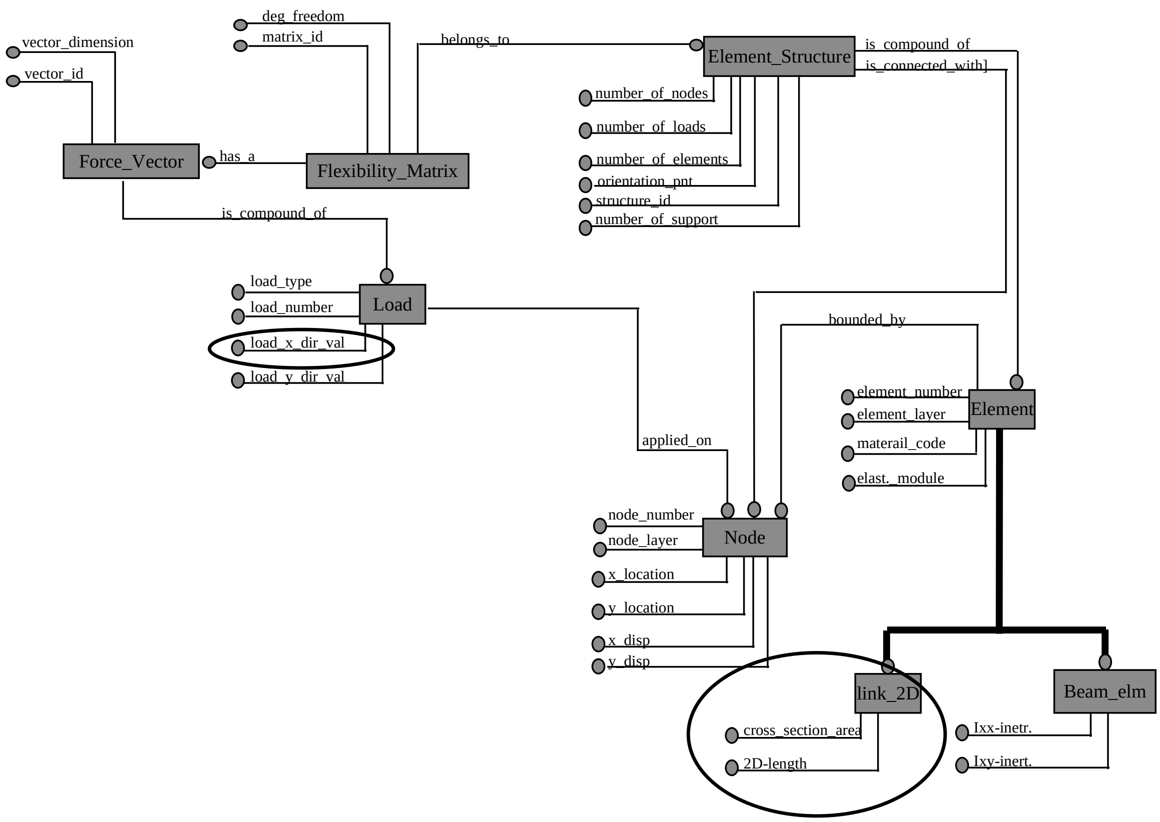


Figure 3.14 Example EXPRESS-G Model

Following is an example of an engineering change scenario:

How would a change to the Load_x_dir_val attribute of the entity load will influence the entity link_2D ? in Figure 3.14. Will this change strongly influences it, somewhat influence it, or not influence the Node's attributes at all?

PART II

C-FAR CHANGE FAVORABLE REPRESENTATION

Chapter 4

C-FAR Objectives

The overall objective of this work is to devise a methodology which will aid engineering redesign by enabling engineering change representation and change propagation activity. In this section, a description of the thesis objectives is specified.

Relevancy of Coverage

The first objective of the research work concerns the relevance to various engineering disciplines in general and the product-related engineering field in specific. In other words, the thesis output should be relevant to existing engineering domains and their corresponding applications and products.

The C-FAR methodology achieves relevancy of coverage by building the C-FAR methodology on top of the STEP standard. The C-FAR methodology is tailored for the EXPRESS information model, which is used to describe the STEP parts. STEP parts are geared to model a wide range of engineering domains, e.g. engineering drawing, finite element methods, automobile applications etc.

Enable Engineering Change Representation

The methodology should specifically support engineering change representation. Engineering change representation means the ability to express the change in a problem domain from one state to another. The C-FAR methodology should conceptually capture an event, namely engineering change. Engineering redesign activity is compounded of one or more engineering changes. Change representation is one of the two cornerstones that the C-FAR methodology uses to build on top of the EXPRESS model.

Enable Change Propagation

The methodology should provide a mechanism to facilitate an initial change propagation throughout the problem domain description. A change propagation mechanism is an essential part of the C-FAR methodology. Change propagation is the second cornerstone that the C-FAR methodology uses to build on top of the EXPRESS model.

Correctness

The methodology should adequately reflect the proposed change of an EXPRESS attribute linkage to another EXPRESS attribute. Therefore the correctness of the C-FAR approach is dependent on the goodness of change representation, matrix construction and change propagation.

Hypothesis:

If the work of this thesis can meet the objectives described above, if it has relevancy of coverage, if it enables engineering change representation and change propagation, and achieves these goals with a reasonable level of correctness, then the work of this thesis can be claimed to be a successful research effort for “data approach to track and evaluate engineering changes.” A discussion on hypothesis fulfillment is provided in chapter 19.

Chapter 5

C-FAR Approach for Capturing Change

5.1 Overview

The Change FAvorable Representation methodology -- C-FAR -- represents the notion of change and facilitates change propagation in the engineering information model framework. While existing information models provide a comprehensive product description, they are not able to represent change or indicate change consequences.

C-FAR's purpose is to transform the information model to a contributing active participant in exploration of the product's engineering characteristics. The C-FAR methodology achieves this by estimating change consequences. For example, given an information model about automobile bumper components, C-FAR is able to indicate and qualitatively estimate whether a change in the automobile height would change the choice of a bumper component.

This chapter provides an overview of the C-FAR methodology, components and assumptions. Chapter six describes the C-FAR implementation, construction and usage.

The Change FAvorable Representation methodology is based on EXPRESS (Appendix F). The EXPRESS information model was created to define engineering products and support management of key engineering data. Specifically, EXPRESS provides linkages between engineering elements. EXPRESS defines its main artifacts as objects or entities. In turn, these entities are described via their attributes. For example, an entity "Circle" is described by its radius and center point. At the very heart of EXPRESS is the notion of a *relation*. EXPRESS ties relevant entities into a relation. The entities that are in this relation have a certain contextual importance to one another.

EXPRESS serves its purpose of modeling engineering products, well but it falls short in another way. EXPRESS only links entities -- it has no mechanism to describe the linkages between the attributes of the entities. C-FAR represents entities as vectors and their attributes as components of a vector. A matrix called a C-FAR matrix provides links between the attributes of one entity and the attributes of another entity. The components used to construct the C-FAR matrix are called **linkage values.** A linkage value represents the relation between two attributes, one from each entity. Since C-FAR is geared towards the notion of change, a linkage value between two attributes is assigned to answer the following question: How would a change to the attribute in one entity affect the attribute of the second entity ? This question is answered by a domain expert and the answer is 'high' if the entity is strongly affected, 'medium' if it is affected somewhat, and 'low' if it is not affected.

By creating the notion of a C-FAR matrix, more information about the product is being represented, and this information is geared towards change. However, a C-FAR matrix only provides linkages between the attributes of two entities that are connected by a relation. A new question may arise: How would a change in one entity influence a third entity which is not directly connected to a changed entity? One answer to this question is to ask a domain expert to build linkages between all the possible entities. Even though this would be feasible, doing this poses some problems. First, consider a schema with n entities and 3n relations. If a domain expert were to build linkages between all possible entities, this would increase the number of matrices describing linkages from O(n) matrices to $O(n^{\wedge 2})$. This would clearly increase the complexity of the job. There is another problem with having experts build linkages between entities. Considering that an EXPRESS schema can be across several engineering domains, many knowledgeable domain experts may be required to make linkages between entities.

There is an alternative to having domain experts make these linkages. Instead, a change propagation mechanism could be used. C-FAR provides a change propagation mechanism, which is explained in detail in the following sections. Fortified with a combination of improved data dependency description and a mechanism to propagate its linkages, C-FAR's aim is to qualitatively evaluate the affect of engineering change that is made from one attribute's entity to another.

5.2 Introduction

In this chapter, the C-FAR methodology is presented and explained. First, the C-FAR representation technique is described. The representation technique is composed of two main components: a view of the entities as vectors and the establishment of a linkage matrix between two vectors. Next, C-FAR's change propagation mechanism is illustrated. This mechanism facilitates a qualitative evaluation of the linkage between objects in the engineering domain that is covered by the given schema. Finally, the graph theory prospective of C-FAR is explored.

5.3 C-FAR As A Representation Technique

5.3.1 C-FAR Vector Representation

To facilitate engineering change representation, C-FAR uses the EXPRESS schema, which has entities, attributes and relations. The following is a description of the C-FAR interpretation of a given EXPRESS schema. Within C-FAR, an entity is a **vector**, and the vector's dimension is the number of attributes of the entity. For example, Figure 5.1 describes the EXPRESS entity and attributes for a bottle.

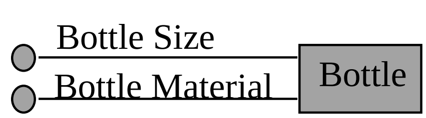


Figure 5.1 Example Bottle Entity in EXPRESS

The C-FAR meta-data representation for the entity load is the following:
[Bottle Size, Bottle Material]
The following is an example of data representation of this entity:
Bottle[3, Glass]

The bottle vector is defined by the value of its attributes. In this case, the bottle size is 3 liters and the bottle material is glass.

5.3.2 C-FAR Vector Change Representation

A change in any of the bottle vector attributes values will create a new bottle vector. For example, assume a change to the bottle size:

Bottle[Δ , 0]

This is a change vector for the bottle vector where the changed attribute is the bottle size. The notion of change in this research describes whether the attribute is subjected to a change or not. It does not speculate on the type of change, e.g. large, small, increase or decrease. In chapter 19 a further discussion about the notion of change is provided .

5.3.3 C-FAR Relation Representation

C-FAR matrix relates each component of one vector to the components of the other vector. In the EXPRESS information model, a relation connects two entities. Therefore, a two dimensional matrix is sufficient to represent an EXPRESS relation. The matrix components are called linkage values and their role is to qualitatively illustrate how a change in one attribute will influence the other. The matrix dimensions are n*m where n is the dimension of one vector and m is the dimension of the second.

5.3.4 C-FAR Linkage Value

Linkage values can be, H, representing high linkage between the attributes; M, representing medium linkage; and L, representing low linkage between the attributes. Clearly the optimal situation would be to have an absolute knowledge source provide a normalized number in the interval 0 to 1 to symbolize linkage between two attributes. However, since in the engineering domain mere humans have to estimate linkage values, providing a limited choice of linkage values options is a better approach. Many sociological and psychological discussions have been held on how to refine the number of choices given to a respondent [Guinta, 93], [Bicknell, 96]. In this research, arguments for various types of ranking systems were considered, and the house of quality [Clausing, 88], [Bahrami, 1992] using three classifications -- high, medium and low – was selected. The house of quality relates engineering attributes to each other using high, medium and low linkage values. A low linkage value between Element A and Element B means that a change to Element A does not influence Element B. A medium linkage value between Element A and Element B means that a change to Element A somewhat influences Element B. A high linkage value between Element A and Element B means that a change to Element A strongly influences Element B.

The following is an example illustrating this terminology. Figure 5.2 illustrates a bottle containing a liquid. The relation to be examined is between the bottle itself and the liquid.

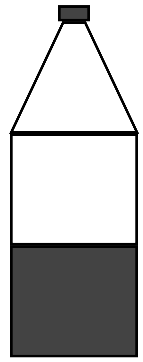


Figure 5.2 Bottle and Liquid

The bottle attributes are:

1 Bottle Size
2 Bottle Material (glass, plastic, etc.)

The liquid attributes are:

1 Liquid Type (wine, beer, water, soft drink, oil, milk, etc.)
2 Liquid Quantity

This example illustrates how to determine the linkage values between all the liquid attributes and all the bottle attributes. Then the question can be asked how, for example, a change in the liquid type would influence the bottle attributes.

	Influences Bottle Size	**Influences** Bottle Material (Glass, Plastic, etc.)
How change in Liquid Type	**Medium**	**High**

Table 5.1 Example Linkage Value

Table 5.1 contents explanations:
1. A change in the liquid type is somewhat related to the bottle size. There are different liquid types that have the same bottle size and there are liquid types with unique bottle sizes. It cannot be said that there is no linkage at all between liquid type and bottle size. However, it cannot be said that say there is a strong linkage between them, the label for this linkage value is **Medium.**
2. A change in the liquid type is strongly related to the choice of bottle material. For example, milk comes in a plastic bottle, alcoholic beverages come in glass, etc. Therefore, it can be said that there is a strong linkage between them, so the label for this linkage value is **High.**

	Influences bottle size	**influences** bottle material (Glass, Plastic, etc.)
How change in liquid quantity	**High**	**Low**

Table 5.2 Example Linkage Value

The following explains the contents of Table 5.2:
1. Since a change in the liquid quantity is strongly related to the bottle size, we can say there is a strong linkage between them. Therefore, the label for this linkage value is **High.**

2. A change in the liquid quantity is not related to the choice of bottle material. For example, drinking water comes in plastic containers of all sizes. We can say there is no linkage between them. Therefore, the label for this linkage value is **Low.**

Generally, the medium linkage value will be assigned to a relation when in some instances there will be linkages between attributes, but in other instances the relation will be low or irrelevant. It is possible to reverse the roles of the attributes in Tables 5.1 and 5.2. Table 5.3 illustrates how a change in the bottle's attributes influences the liquid's attributes. The reverse matrix does not necessarily contains the same linkage values.

Liquid Bottle	**influences** liquid type	**influences** liquid quantity
How change in bottle size	**Medium**	**High**
How change in bottle material	**High**	**Low**

Table 5.3 Example Linkage Value

Tables 5.1, 5.2 and 5.3 can be combined to one representation, which is provided in Table 5.4:

Bottle Liquid	Bottle Size	Bottle Material
Liquid Type	**M/M**	**H/H**
Liquid Quantity	**H/H**	**L/L**

Table 5.4 Example Double Linkage Value

As illustrated in Table 5.4, each linkage value table slot contains two linkage values. The left linkage value in each slot indicates how a change in the liquid's attributes influences the bottle's matching attributes and the right linkage in each slot value indicates how a change in the bottle's attributes influences the liquid's attributes.

5.3.5 C-FAR Matrix

The C-FAR matrix represents a relation between two entities and defines the influence of a change of one on the other in either directions. The number of rows in the C-FAR matrix is the number of attributes in one entity and the number of columns is the number of attributes in the second entity. The C-FAR matrix elements are linkage values. Each element in the C-FAR matrix is a compound of two linkage values. One linkage value represents how a change in one attribute of Entity A influences the attributes in Entity B. The second linkage value represents how a change in one attribute of Entity B influences an attribute in Entity A. For example, Figure 5.3 illustrates a C-FAR matrix with two linkage value for each slot.

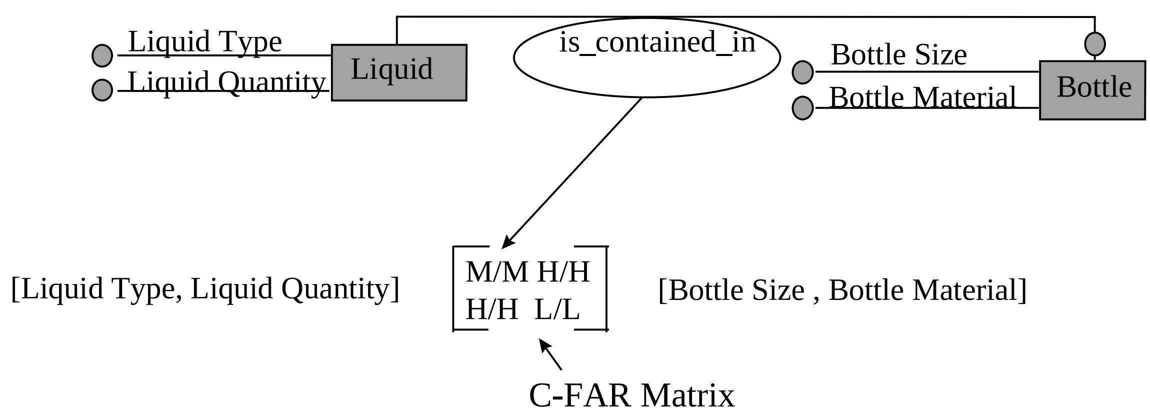


Figure 5.3 Example C-FAR Matrix

The left linkage value in each slot indicates how a change in the liquid's attributes influences the bottle's matching attribute and the right linkage value in each slot indicates how a change in the bottle's attributes influences the liquids' attributes. This C-FAR matrix was derived from Table 5.4.

5.3.6 Semi C-FAR Matrix

The semi C-FAR matrix between Entity A and Entity B is denoted as C(A,B). Unlike the C-FAR matrix where each matrix element includes two linkage values, C(A,B) has only one linkage value per element. The linkage value represents how a change in one attribute of Entity A influences the attributes in Entity B. C(B,A) is a corresponding semi C-FAR matrix in the opposite direction between Entity B and Entity A. Each element value in C(B,A)represents how a change in one attribute of Entity "B" influences the attributes in Entity "A".

5.4 C-FAR Change Propagation

5.4.1 Source Entity

A source entity is an entity where one of its attributes has been changed by the user. In Figure 5.4 entity A is the source entity and the goal is to measure the change originated at this entity.

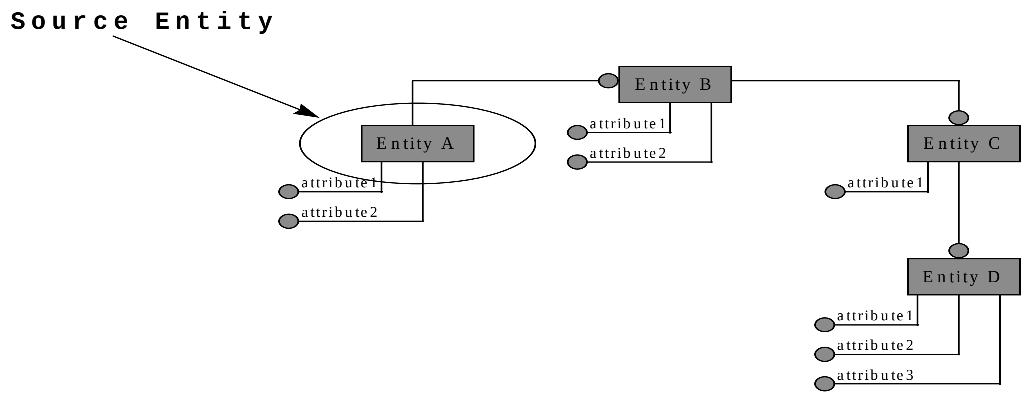


Figure 5.4 Source Entity Example

5.4.2 Target Entity

The target entity is defined as an entity that is influenced by the source entity and has been selected for examination. In Figure 5.5, a change in Attribute1 in Entity C is measured.

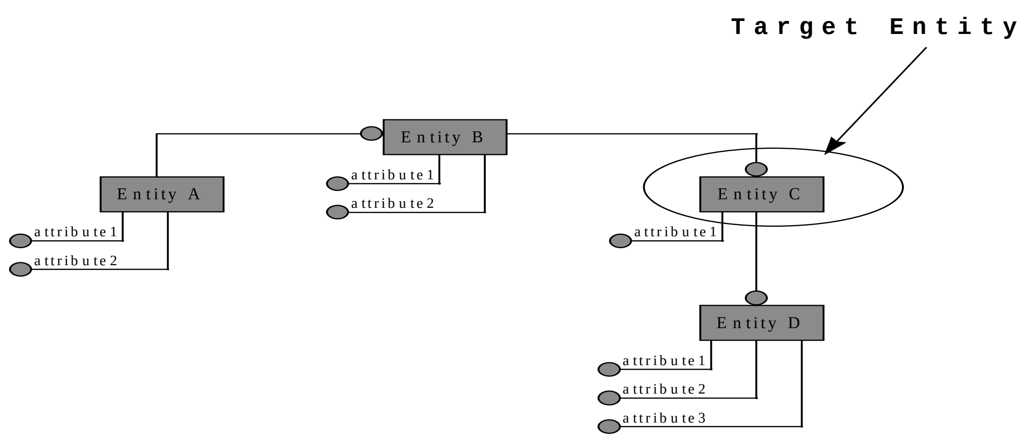


Figure 5.5 Target Entity Example

5.4.3 Change Propagation Characteristics

Change propagation is an important part of the C-FAR methodology. This mechanism is used for calculating the consequences of a change from a source entity to a target entity. A simple path that leads from the source entity to the target entity is called a simple influence path. Further discussion about C-FAR paths is given in section 5.5. An example of a simple influence path is given in Figure 5.6. The simple influence path starts at the source entity, which is the load, and ends at the target entity, which is the element. An influence path is composed of a series of relations that can be represented as a series of semi C-FAR matrices. Consider an influence path with n entities, n-1 semi C-FAR matrices and an initial change vector of Δ vector(1).

A change propagation is defined as the following set of multiplication:

Δ vector(2) = Δ vector(1) * C(Entity_1, Entity_2)

Δ vector(3) = Δ vector(2) * C(Entity_2, Entity_3)

.

.

Δ vector(n) = Δ vector(n-1) * C(Entity_n-1, Entity_n)

Δ vector(n) represents the change consequences of Δ vector(1) along a single influence path. An example of the change propagation is given in Figure 5.6. A change in the influence of the load magnitude on the element length is examined. The example illustrates two semi C-FAR matrices along one influence path.

The change consequences of Δ vector(1) on the target entity is Δ [H*H+L*L].

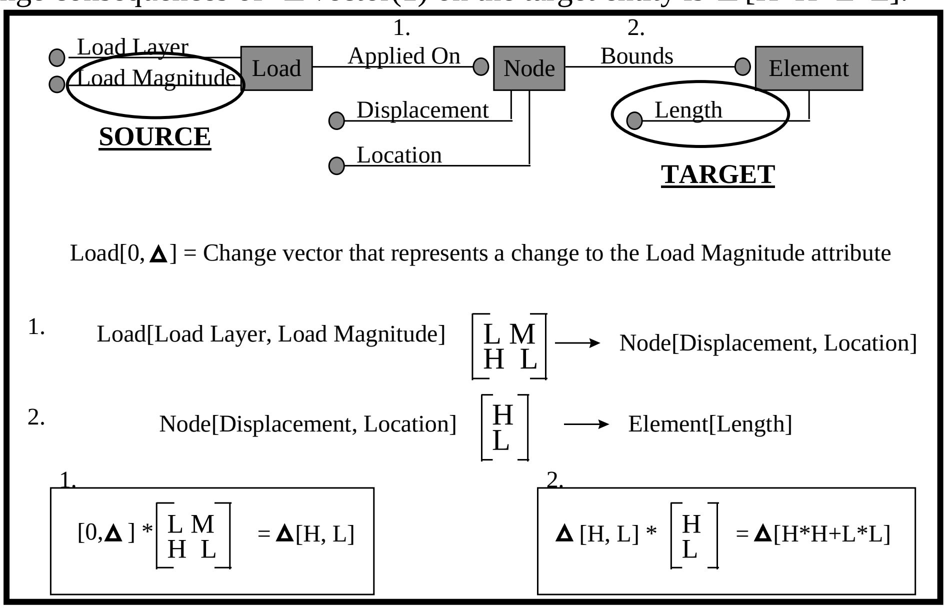


Figure 5.6 Example, Simple Change Propagation

5.4.4 Numeric Values For Linkage Values

A sender entity is an entity along the influence path. A sender entity propagates the change vector through its attributes. All the entities along the influence path, except the target entity, are at one time sender entities. A receiver entity is also an entity along the influence path. A receiver entity receives the change through its attributes. A low linkage value (“L”) means that a change in an attribute of a sender entity does not influence an attribute of the receiving entity. Considering this, the following are two propagation assumptions. A change vector element that is multiplied by the linkage value “L” is equal to “L”. A change vector element that is added to the linkage value “L” is equal to itself.

The numeric value of a low linkage value is zero. Therefore, a minimum linkage value is low. The high (“H”) linkage value means that a change in an attribute to a sender entity strongly influences an attribute of the receiving entity. The numeric value for the high linkage value has been chosen to be 0.9. The “M” linkage value means that a change in an attribute to a sender entity somewhat influences an attribute of the receiving entity. The numeric value for the “M” linkage value has been selected to be 0.3. The numeric choices for the “M” and “H” rankings were influenced by the recommendations in the House of Quality method [Clausing, 88], [Bahrami, 1992]. Choosing a value of 0.9 for “H” means that for each element with each propagation, the accumulated change effect is going down by a factor of at least 0.9. EXPRESS relates relevant entities with relations. Therefore, it is assumed that the longer the influence path, the less likely it is that there is a strong linkage between the source and the target, which explains the choice of 0.9 to represent “H.” The value of “M” is 0.3 and is equal approximately to ten consecutive propagations of the “H” linkage value.

5.4.5 Change Propagation Redundancy

Generally, attributes describe different aspects of the entity to which they belong. Attributes of a given entity may or may not relate to one another. For example, the bottle entity may be described by the bottle material and the bottle size. Between these two attributes, there is a low linkage; in other words, a change in the bottle size does not influence the bottle material. These attributes are called **orthogonal attributes** because when one of them is changed, there is no effect on the other. However, when the bottle weight attribute is added to the bottle entity description, there is a linkage between the weight attribute with the bottle size and material. Therefore, the entity bottle weight and bottle size are not orthogonal. In the same manner, the attributes for bottle weight and bottle material are not orthogonal. In the case of non-orthogonal attributes, the change propagation description given in section 5.4.3 may create a superficially enhanced impact of the initial change on the target entity. For example, in Figure 5.7, a change to the plate holder holding mechanism attribute is examined.

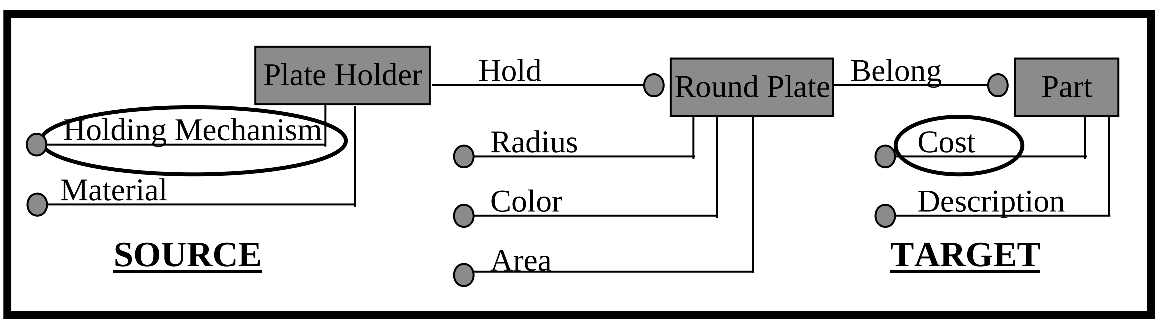


Figure 5.7 Example Change Propagation Redundancy

The target attribute is the part’s cost. The semi C-FAR matrices that relates the plate holder to the round plate and the round plate to the part are:

C(Plate Holder, Round Plate) = $\begin{bmatrix} M & L & M \\ L & L & L \end{bmatrix}$

C(Round Plate, Part) = $\begin{bmatrix} H & L \\ M & L \\ H & L \end{bmatrix}$

The source change vector represents a change to the holding mechanism as illustrated in the following equation:

Δ vector(1) = [Δ , 0]

The following is a calculation of the influence of the given change on the target entity:

Δ vector(2) = Δ vector(1) * C(Plate Holder, Round Plate) = [Δ , 0] * $\begin{bmatrix} M\ L\ M \\ L\ \ L\ \ L \end{bmatrix}$ =

Δ [$M\ L\ M$]

Δ vector(3) = Δ [$M\ L\ M$] * C(Round Plate, Part) = Δ [$M\ L\ M$] * $\begin{bmatrix} H & L \\ M & L \\ H & L \end{bmatrix}$ =

$$\Delta \begin{bmatrix} M*H+L*M+M*H \\ M*L+L*L+M*L \end{bmatrix}$$

In section 5.4.4, the numeric values for the linkage values are discussed. The linkage value “L” is mapped to the value zero, M is “0.3” and H is “0.9”. Therefore Δ vector(3) =

$$\Delta \begin{bmatrix} M*H+M*H \\ L \end{bmatrix} = \Delta \begin{bmatrix} 0.27+0.27 \\ 0 \end{bmatrix}$$

The terms “0.27 + 0.27” represents the degree of influence of the plate holder mechanism on the part’s cost via the change to plate radius and the plate area. The schema designer has chosen to represent both the round plate radius and the plate area. Assuming that the plate area can be calculated by its radius, a change to the plate radius means a change to the plate area. However, the change propagation treats these two terms as if they are not related, and adds the change influence of both of them to the part cost attribute. The C-FAR change propagation mechanism does not incorporate the knowledge that a change to the plate radius is actually a change to the plate area. The notion of change propagation redundancy is originates from multiple attributes that belong to one entity and describe similar contextual ideas.

The example provided in Figure 5.8 illustrates the same schema with one change. Instead of the attribute area, the round plate has an attribute material.

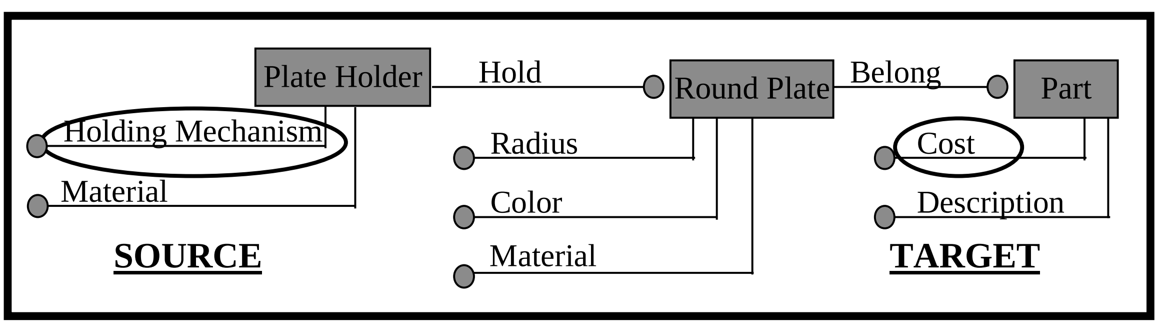


Figure 5.8 Example Change Propagation Redundancy

A change to the plate holder holding mechanism attribute is examined in this example again. The target attribute is the parts' cost. The semi C-FAR matrix between plate holder to round plate and round plate to part are:

C(Plate Holder, Round Plate) = $\begin{bmatrix} M & L & M \\ L & L & H \end{bmatrix}$

C(Round Plate, Part) = $\begin{bmatrix} H & L \\ M & L \\ H & L \end{bmatrix}$

The source change vector, represents a change to the holding mechanism

Δ vector(1) = [Δ , 0]

The following is a calculation of the influence of the given change on the target entity:

Δ vector(2) = Δ vector(1) * C(Plate Holder, Round Plate) = [Δ , 0] * $\begin{bmatrix} M & L & M \\ H & L & L \end{bmatrix}$ =

Δ [$M\ L\ M$]

Δ vector(3) = Δ [$M\ L\ M$] * C(Round Plate, Part) = Δ [$M\ L\ M$] * $\begin{bmatrix} H & L \\ M & L \\ H & L \end{bmatrix}$ =

$$\Delta \begin{bmatrix} M*H+L*M+M*H \\ M*L+L*L+M*L \end{bmatrix}$$

Δ vector(3) = $\Delta \begin{bmatrix} M*H+M*H \\ L \end{bmatrix} = \Delta \begin{bmatrix} 0.27+0.27 \\ 0 \end{bmatrix}$

The terms "0.27 + 0.27" represents the influence of the plate holder mechanism on the part's cost via the change to plate radius and the plate material. In this example the round plate attributes do not describe similar contextual ideas. Therefore there is no propagation redundancy.

In this example, the term "0.27 + 0.27" is justified since there is no relation between the change to the plate material and the plate radius. They are orthogonal attributes.

In these two examples, the same change propagation mechanism was deployed and the same results were achieved. However, in the first case, where the attributes were not orthogonal, the part cost linkage to the plate holder mechanism was unjustifiably enhanced.

In the case illustrated in Figure 5.7, it was not necessary to add the contribution of the area linkage value to the cost since the radius linkage value already considered it. However, in the case illustrated by Figure 5.8, the contribution of both radius and material linkage value is needed. The next section provides an approach that deals with this problem

5.4.6 Change Propagation Redundancy Compensation

The propagation redundancy phenomenon occurs when entity is described with non-orthogonal attributes.

The first step in solving this issue is to know whether attributes are orthogonal or not. A way to express the attributes orthogonality is via linkage values. High linkage value indicates low orthogonality, medium linkage value indicates some orthogonality, and low linkage value indicates a strong orthogonality. This inter entity knowledge is necessary to solve the redundancy problem. The orthogonality knowledge is captured via an orthogonality matrix. For example, the following matrix is an orthogonality matrix representing the entity round plate in Figure 5.7

$$\text{Orthogonality(Round Plate)} = \begin{bmatrix} - & L & H \\ L & - & L \\ H & L & - \end{bmatrix}$$

This orthogonality matrix is derived from the Table 5.5

Round Plate Round Plate	**influences** round plate radius	**influences** round plate color	**influences** round plate area
How a change in round plate radius	-	Low	High
How a change in round plate color	Low	-	Low
How a change in round plate area	High	Low	-

Table 5.5 Example of C-FAR Orthogonality Matrix Construction

The elements in the orthogonality matrix are called orthogonality linkage values. The “-“ indicates the irrelevancy of a change of an attributes influence on itself.

An estimation mechanism that uses the orthogonality information is also needed.

The C-FAR methodology suggests an estimation mechanism that compensates for the redundancy. This estimation mechanism uses orthogonality weights. Orthogonality weights represent numeric values for the orthogonality linkage values. Low orthogonolity value weight has been chosen to be 9. Medium orthogonality linkage value has been chosen to be 3. High orthogonality linkage value has been chosen to be 1. The larger gap between the low orthogonality linkage value and the medium orthogonality linkage value emphasizes the importance of the low linkage value as oppose to medium or high.

The second step in addressing the change propagation redundancy phenomenon is using an estimation mechanism that uses the orthogonality weights to approximate the overall orthogonality among the sender’s attributes. In turn, the sender’s orthogonality weights are used in a linear approximation to estimate the compensated change vector.

The Approximated Collective Orthogonality (ACO) of an entity in the context of a specific change is defined as the summation of the orthogonality weights of all its component attributes that contribute to that change.

Let the equation
y = ax + b
represent the change in a certain attribute of the receiving entity, given the ACO, x, of the sender entity.
Two extreme cases of change can be identified:
Equation 5.1: Maximum: y1 = ax1 + b
Equation 5.2: Minimum: y2 = ax2 + b
Let establish y1 and y2 of a change in the receiver entity be attributed to the maximum and minimum estimation x1 and x2 of ACO of the sender entity. From Equation 5.1 and Equation 5.2 it is possible to derive coefficients a and b.
The following is an example illustrating the estimation mechanism:
Consider an example with the sender change vector, $\Delta\,[M\,M\,L\,L\,M\,H]$ and

the semi C-FAR matrix: $\begin{bmatrix} L\,H \\ L\,M \\ L\,M \\ L\,M \\ L\,M \\ L\,M \end{bmatrix}$

Therefore the receiver vector change is: $\Delta\,[M\,M\,L\,L\,M\,H] * \begin{bmatrix} L\,H \\ L\,M \\ L\,M \\ L\,M \\ L\,M \\ L\,M \end{bmatrix} =$

$$\Delta \begin{bmatrix} M*H + M*M + L*M + L*M + M*M + H*M \\ M*L + M*L + L*L + L*L + M*L + H*L \end{bmatrix} =$$

$$\Delta \begin{bmatrix} 0.27 + 0.09 + 0.09 + 0.27 \\ 0 \end{bmatrix}$$

The maximum value of the receiver change vector corresponds to maximum orthogonality among the attributes of the sender entity. For the receiver change vector, the maximum influence of change is given by y1:
y1 = 0.27 + 0.09 + 0.09 + 0.27 = 0.72
y1 occurs when the senders six orthogonality linkage values that indicate the orthogonality among the contributing sender’s attributes are low (giving a value of 9 to each of them).
Therefore the Maximum ACO is: 6 * 9 = 54 = x1

The minimum value occurs when the senders six orthogonality linkage values that indicate the orthogonality among the contributing sender's attributes are high (giving a value of 1 to each of them).

Therefore the Minimum ACO is: 6 * 1 = 6 = x2

The corresponding receiver change vector, y2, is:

Max(0.27, 0.09, 0.09, 0.27) = 0.27 = y2

Where Max(A, B, C) returns the largest among A, B, C.

Equations 5.1 and 5.2 become

54a + b = 0.72

6a + b = 0.27

Solving for a and b yields: a = 0.009375, b = 0.21375.

Therefore the linear approximation equation for this example is:

Equation 5.3: 0.009375x + 0.21375 = y

The compensation operation on the vector receiver vector Δ vector is defined as -Orth(Δ vector)

Consider an example where three of the orthognality linkage values are high, two are medium and one is low. The overall summation for these orthogonality weights is:

3*1 + 2*3 + 1*9 = x = 18

Substitute x in Equation 5.3 yields y = 0.3825

Therefore, Orth(Δ vector) = $\begin{bmatrix} 0.3825 \\ L \end{bmatrix}$

5.4.7 Compensated Change Propagation

Compensated change propagation is defined as compensating change vectors multiplied by semi C-FAR matrices. Consider an influence path with n entities, n-1 semi C-FAR matrices and an initial change vector of Δ vector(1).

A change propagation is defined as the following set of multiplication

Δ vector(1) * C(Entity_1, Entity_2) = Δ vector(2)

Orth(Δ vector(2)) * C(Entity_2, Entity_3) = Δ vector(3)

.

.

Orth(Δ vector(n-1)) * C(Entity_n-1, Entity_n) = Δ vector(n)

Δ vector(n) represents the change consequences of Δ vector(1) along a single influence path. The C-FAR methodology uses the compensated change propagation as its propagation mechanism.

5.5 Graph Theory Perspective And C-FAR

The two previous sections explained the main mechanism that are the building blocks of C-FAR. C-FAR change propagation mechanism includes the notion of influence paths. This section explores and justifies the choice and impact of these possible paths.

5.5.1 C-FAR Simplified Model

To focus on the graph algorithmic nature of the problem. The C-FAR schema will be converted to a simpler graph, as described in Figure 5.9. Each relation will be an edge, and all the attributes but one will be discarded.

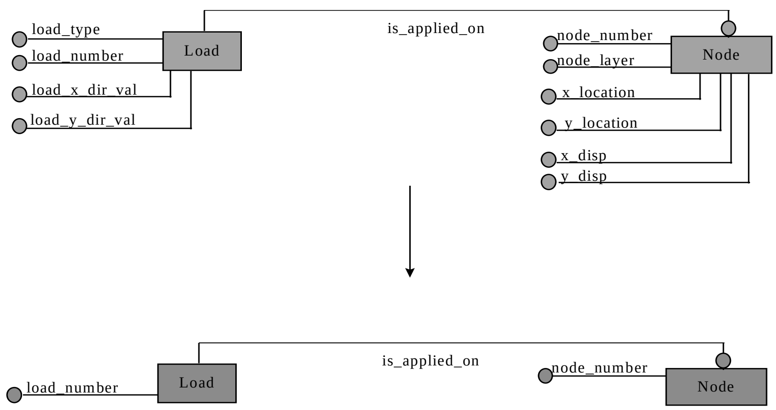


Figure 5.9 Example Graph Simplification

The relation will be replaced with the C-FAR value that corresponds to the linkage between the two attributes. In the example given in Figure 5.9, the values will assumed to be high. The graph is illustrated in Figure 5.10

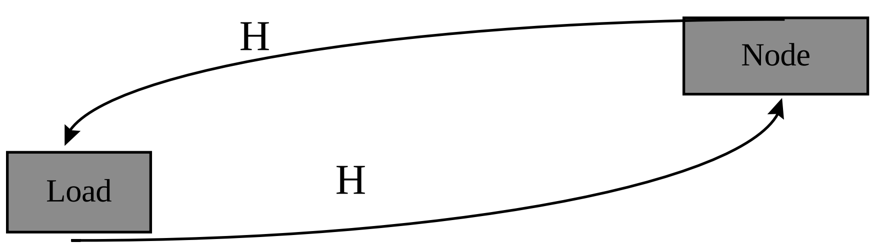


Figure 5.10 Example Linkage Values

Next, the linkage propagation will be examined. Figure 5.11 describes an addition of another entity. The “Force_Vector” entity is connected to the “Load” entity with the low linkage value. The low linkage value means that there is a low linkage between the “Load” and the “Force_Vector”.

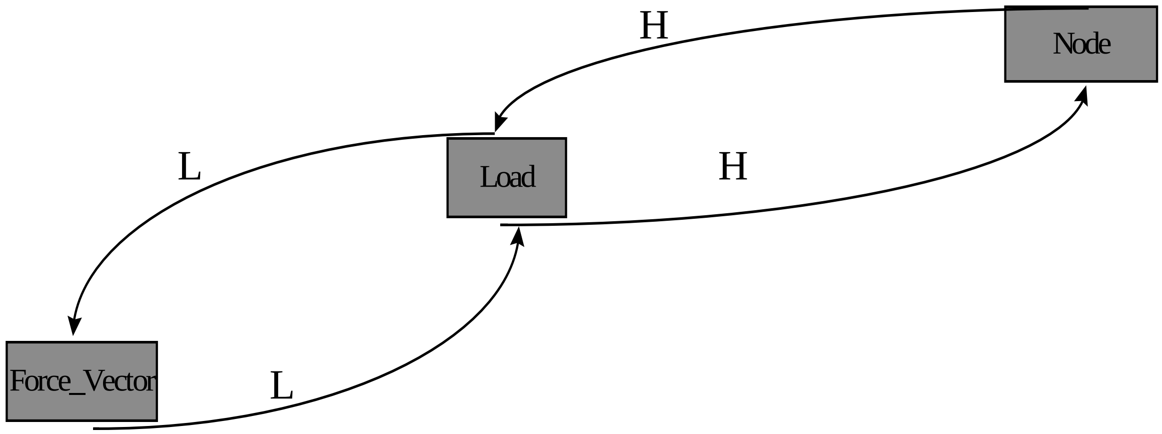


Figure 5.11 Example Chaining Linkage Values

The linkage between “Force_Vector” and “Load” is low and the linkage between “Load” and “Node” is high. The linkage between “Force_Vector” and “Node” is defined as L * H.

The C-FAR computed linkage between non-directly connected entities is computed as multiplication of the linkages values on the path that leads from the source entity to the target entity.

5.5.2 Simple Paths vs. Cycles

A path is considered to be simple path if it passes through an entity only once. A non-simple path is called a cyclic path. Should cyclic influence paths be considered in this framework? Consider the example in Figure 5.12. A possible cyclic path is Flexibility_Matrix-Force_Vector-Load- Force_Vector- Load. Another possible cyclic path is Flexibility_Matrix-Force_Vector-Load- Force_Vector- Flexibility_Matrix-Force_Vector-Load. In fact, there are an infinite number of cyclic paths. The linkage value from the last cyclic path is H * L * M * H * H * L.

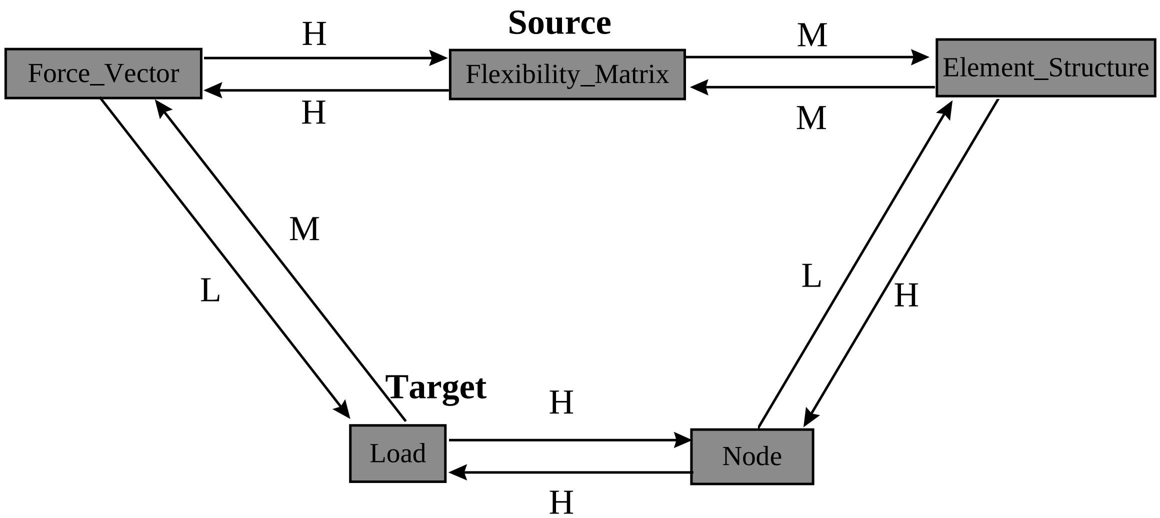


Figure 5.12 Example Simple vs. Cyclic Paths

This result reflects a secondary linkage, which is a linkage between the target and one of the entities in the path and back to the target. This secondary linkage represents a repeat of a linkage already used. In the same manner, one can produce more paths with secondary, tertiary, etc. linkages. EXPRESS is a semantic model that captures information at various levels of abstractions. The C-FAR matrix provides a quantification mechanism to a problem domain that is mostly abstract with a dominating semantic notion. Therefore, the first order linkage is generally more important than the secondary tertiary, etc. linkage types. For example, the "Load" attribute that is represented in this example is "load_number" and the "Node" attribute is "node_number". In this case, secondary and tertiary linkages do not have much meaning. As a result, the focus of the algorithm will be on simple paths. The problem in dealing with secondary or tertiary change order is mainly of a contextual notion.

5.5.3 C-FAR Approach for Adding Influence Path Contribution

An interesting issue is: What if there is more than one simple path that leads from the source entity to the target entity? The solution to this question is not unique; it is given in terms of an interval of total influences. The upper bound of the total influences interval is reached by the summation of all the influence paths. The lower bound on this interval is achieved by picking up the path with the highest influence. For example, assume three simple paths: path1, path2 and path3. Path1's influence is 0.1, path2's influence is 0.6, and path3's influence is 0.05. The upper bound of the interval of total influence is:

0.6 + 0.1 + 0.05 = 0.75

The lower bound of the interval of total influence is:

Max(0.6, 0.1, 0.05) = 0.6

The contextual meaning of the upper bound of the total linkage value is that the influence of a change along any path is not related or correlated to a change influence of the other paths.
However, contextual meaning of the total linkage value lower bound is that the influence of a change along any path is strongly correlated to a change influence of the other paths.
The interval of calculated total influences presents a range of possible total influence values.

5.6 Summary

In this chapter, the core of the C-FAR methodology was explained. C-FAR's major components and definitions were specified as well as C-FAR's general approach and assumptions. In a sense, the C-FAR matrix represented an expert subjective opinion about a relation between two entities. Dealing with subjective, non-precise information pulled the C-FAR approach in two directions: towards simplicity and towards caution. It is tempting to view the information schema and its entities as an interdependent construct. Once a change was introduced to any of its elements, other elements changed their values in an iterative manner until the change influence eventually faded and a new equilibrium is reached. Unfortunately, engineering problem models are contextually complex and a simple, somehow less ambitious approach is at least initially preferable. Therefore, C-FAR considered only simple paths in the linkage value calculation procedure. This chapter carefully illustrated the C-FAR building blocks for facilitating change representation and change propagation.

Chapter 6

C-FAR Implementation

As seen in Figure 6.1, C-FAR implementation has two main stages: C-FAR construction and C-FAR usage. C-FAR construction is an activity which enriches the EXPRESS schema with knowledge from an expert domain. This knowledge is translated to a C-FAR matrix, which provides a qualitative linkage measure to relations in the EXPRESS schema. The second main stage of the C-FAR approach is usage. After the C-FAR schema is built, a user can query the schema and ask what the consequences are of a given change. In this chapter the C-FAR implementation is explained. First the C-FAR Construction is illustrated followed by a detailed explanation of C-FAR usage. This chapter also include discussion about C-FAR algorithmic implantation.

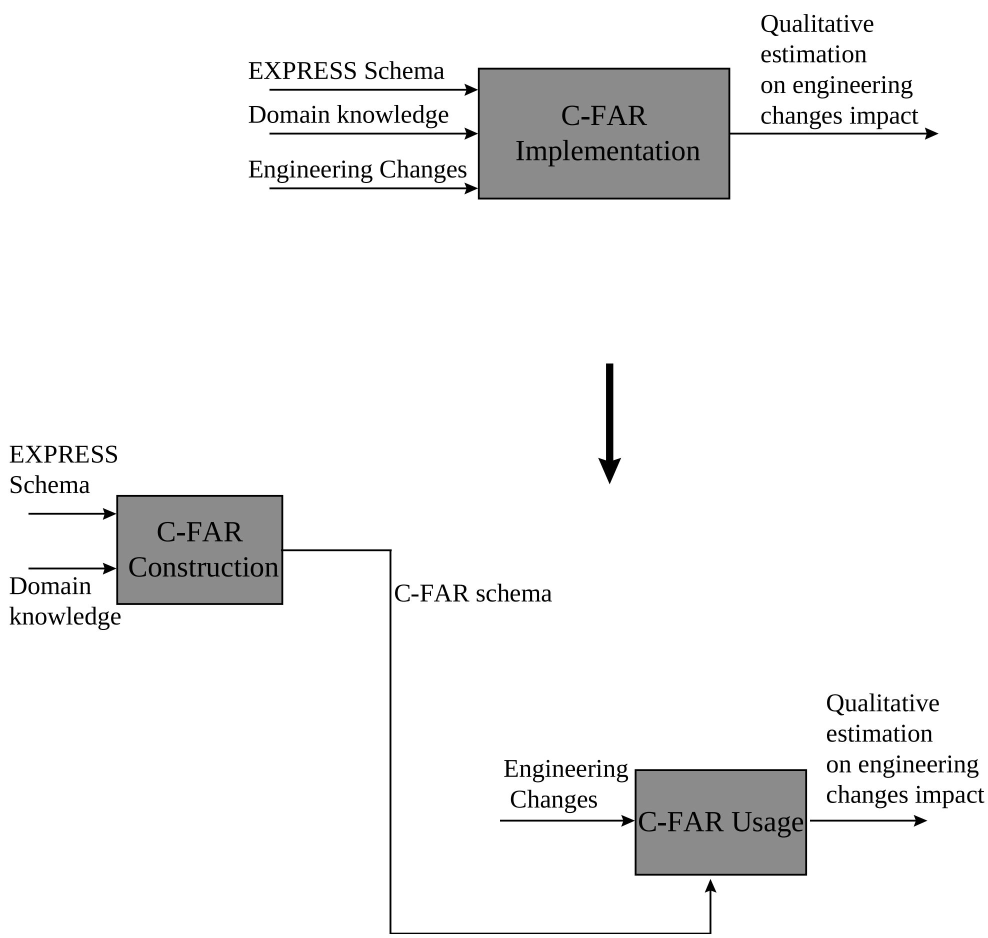


Figure 6.1 C-FAR Implementation

6.1 C-FAR Construction

C-FAR construction can be divided into two main stages. The first is the scoping stage, where the EXPRESS data schema is manipulated to facilitate incorporation of the C-FAR matrices. The second stage involves building a C-FAR matrix for any two entities that have a relation between them. Figure 6.2

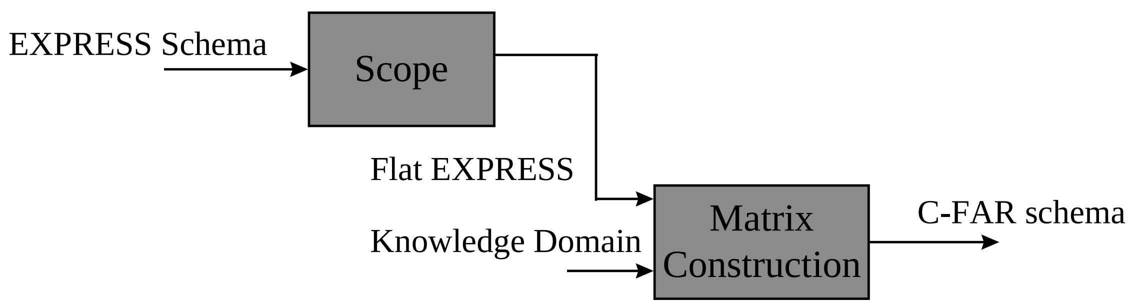


Figure 6.2 C-FAR Construction

6.1.1 EXPRESS Schema Scoping

The purpose of the scoping stage is to prepare a schema for C-FAR matrices. The preparation is made up of two main steps. The first step is to isolate the entities' attributes and the relations in the EXPRESS schema. An EXPRESS schema may also incorporate constraints and functions. In this stage, C-FAR does not use these components of EXPRESS. For example, the force_vector entity has a constraint set that prevents a vector component from being larger than the overall vector magnitude.

```
ENTITY force_vector;
    i_dir:      REAL;
    j_dir:      REAL;
    k_dir:          REAL:
    magnitude  REAL;
    units      unit_list;
where
    ABS(magnitude) >= ABS(i_dir);
    ABS(magnitude) >= ABS(j_dir);
    ABS(magnitude) >= ABS(k_dir);
```

END_ENTITY

The scoping action will extract the entity relations and attribute information and will have the following form:

```
force_vector {
    attribute i_dir;
    attribute j_dir;
    attribute k_dir;
    attribute magnitude
    attribute units
};
```

A second main action in the scoping stage is ‘folding’ a supertype subtype relationship as explained in the following section.

6.1.2 Supertype Subtype Relations

The EXPRESS schema supports the notion of relations between entities as well as the special supertype subtype relationship. C-FAR treats the supertype subtype relation as an exception. The supertype subtype relation does not require a matrix to relate the attributes of the supertype to the subtype entities’ attributes. The attributes of the supertype are the attributes of the subtype as well. Therefore, C-FAR considers the supertype attribute to be the subtype attributes for any relation the subtype entity has with any other entity in the schema. For example Figure 6.3. The element entity attributes are considered also to be attributes of its subtype link_2D entity. Therefore, the C-FAR matrix between the entity Node and entity link_2D has a dimension of 6X6.

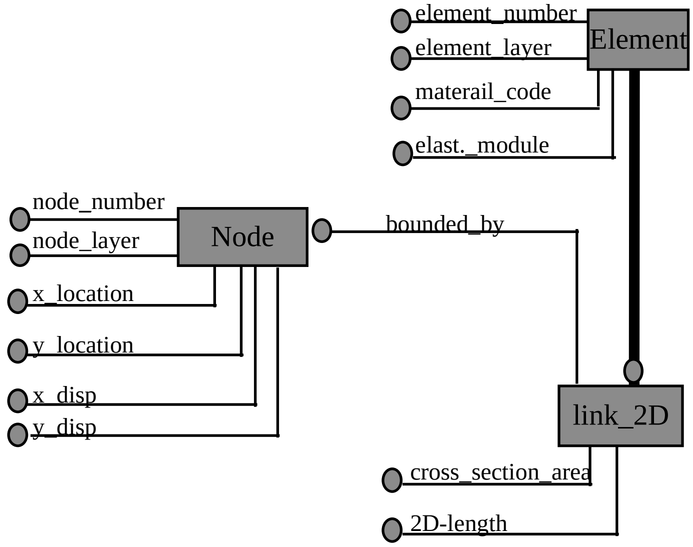


Figure 6.3 Example Supertype Subtype Relations

In Figure 6.3 a thicker line represents a supertype subtype relationship. The entity element is a supertype of the entity “link_2D.” The supertype subtype relationship in EXPRESS has several characteristics. The first issue is whether a supertype can be instanced without simultaneously instancing one of its subclasses. The answer to the question is yes. The framework of this thesis does not treat the constraint network of EXPRESS. However, in this special case, C-FAR will treat the a type of supertype subtype relationships. In some cases, a supertype entity cannot be instanced without simultaneously instancing one of its subclasses For example in Figure 6.4 the entity Element has to be accompanied with one of its subtypes, link_2D or Beam_elm

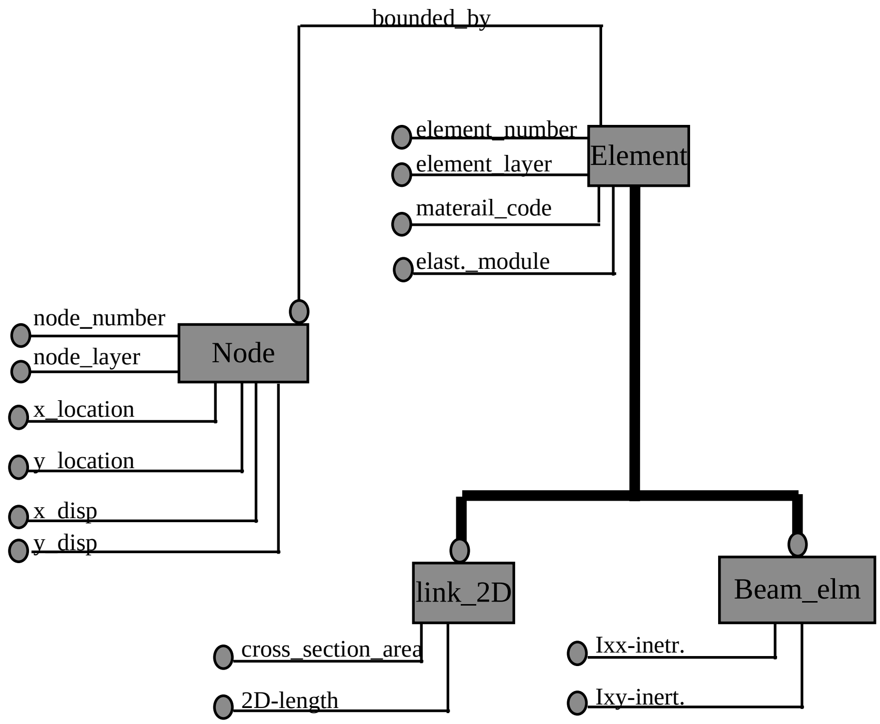


Figure 6.4 Supertype Relations With Two Subtypes

For the EXPRESS schema in Figure 6.4 C-FAR will create two new schemes that have the form in Figure 6.5.

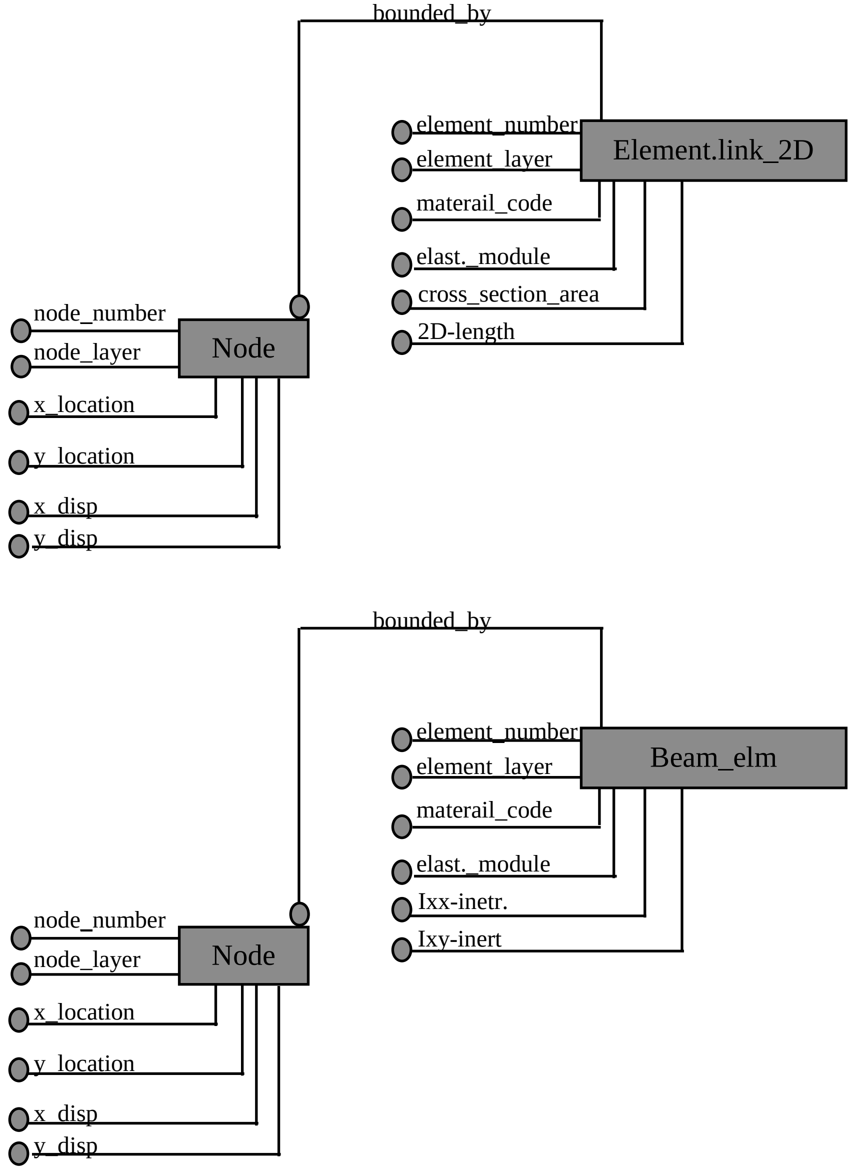


Figure 6.5 Example Elimination of Supertype Subtype Relation

C-FAR distinguishes between two kinds of non-instanced supertype relationships: the "One-Of" relationship and the non "One-Of" relationship. In example above, only one of the subtypes can be instanced at the same point. This condition is called a "One-Of" supertype subtype relationship. In these relationship, C-FAR assumes that a change in one of the subtypes cannot influence any other subtype in the same inheritance relationship. However, for non "One-Of" supertype subtype relationships, a change in one of the subtypes can eventually propagate to its peers.

Once the knowledge domain is translated to the C-FAR matrices, the C-FAR construction is completed. C-FAR construction is supposed to be done by an expert who is knowledgeable in the schema area. For the framework of this research, the construction activity is done only once and the usage is independent of it.

6.1.3 C-FAR Matrix Construction

The C-FAR matrix is the main element that is added to the EXPRESS schema. Domain experts are responsible for building the matrices. Each C-FAR matrix encapsulates two semi-C-FAR matrices. A semi-C-FAR matrix represents how a change in any of the attributes of the sender entities influences the attributes of any of the attributes of the receiver entity. The second semi C-FAR matrix switches between the sender and the receiver matrices. The domain expert should evaluate each relation between two entities. For each attribute, the expert should ask himself how a change in this attribute influences any of the attributes of the reclining attributes. Specifically, the expert should first ask him or herself if a change in the attribute does not influence the receiving entity attribute. If the answer is positive, then the linkage value of “L” is attached to the relevant slot in the semi C-FAR matrix. If the answer is negative, the next question should be the following: Does a change in this attribute strongly influence the receiver entity attribute? If the answer is positive, then the linkage value of “H” is attached to the relevant slot in the semi C-FAR matrix. However, in case the answer is negative again, then the change of the attribute only somewhat influences the receiving entity attribute.

The orthogonality matrix provides an insight into the interrelationship between attributes of an entity. The procedure for building the orthogonality matrix is the same as for a regular C-FAR matrix. Figure 6.6 illustrates an EXPRESS relation and three C-FAR matrices relevant for this construct (Tables 6.1-3). There is one C-FAR matrix that represents the relation, and there are two orthogonal matrices, one for each entity.

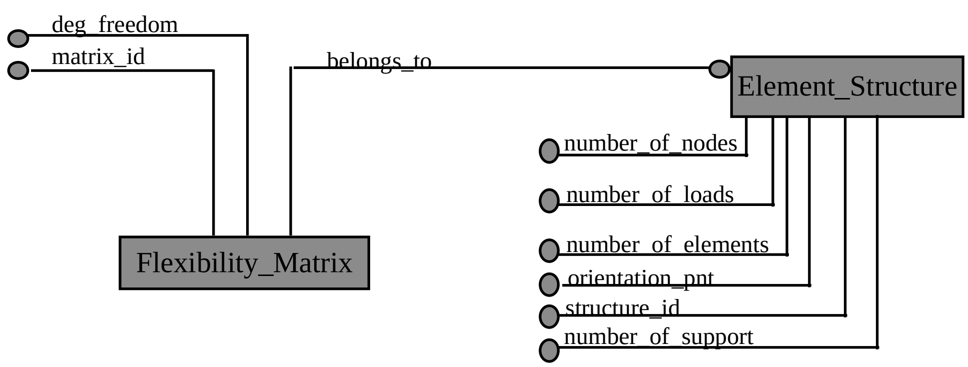


Figure 6.6 Example EXPRESS Relation

Flexibility_Matrix **Element_Structue**	number_deg_of_freedom	matrix_id
number_of_nodes	H/H	L/L
number_of_loads	M/M	L/L
number_elements	H/H	L/L
number_of_supports	M/M	L/L
orientation_pnt	L/L	L/L

structure_id	L/L	H/H

Table 6.1 Flexibility_Matrix vs. Element_Structue C-FAR Matrix

Flexibility_Matrix **Flexibility_Matrix**	number_deg_of_freedom	matrix_id
number_deg_of_freedom	I	L/L
matrix_id	-	I

Table 6.2 Flexibility_Matrix vs. Flexibility_Matrix C-FAR Orthogonality Matrix

Element_Structue **Element_Structue**	number nodes	number loads	number elements	number supports	orientation pnt	structure id
number_of_nodes	I	M/M	H/H	M/M	L/L	L/L
number_of_loads	-	I	M/M	M/M	L/L	L/L
number_elements	-	-	I	M/M	L/L	L/L
number_of_supports	-	-	-	I	L/L	L/L
orientation_pnt	-	-	-	-	I	L/L
structure_id	-	-	-	-	-	I

Table 6.3 Element_Structue vs. Element_Structue C-FAR Orthogonality Matrix

6.2 C-FAR Usage

C-FAR construction is the initial stage of the implementation. The C-FAR usage articulates the capabilities and the scope of the methodology. Figure 6.7 illustrates the main parts of the C-FAR usage. The first two boxes represent pre-processing stages where the engineer interacts with the C-FAR schema to choose the relevant changeable objects according to desired engineering changes he or she wants to deploy on the current design that is reflected in the EXPRESS schema. The following two boxes in Figure 6.7 Find “Simple Paths” and “Calculate Linkage Value” represent a user transparent algorithmic part of the C-FAR usage. The last box, “Interpret Results”, answers the user with an estimation on how a change in a given object may influence another object.

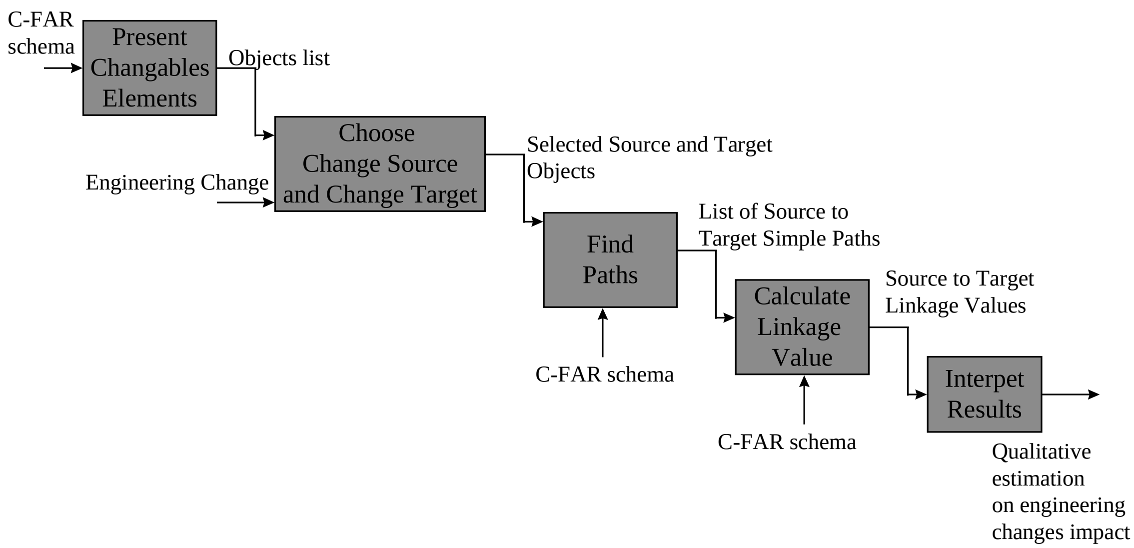


Figure 6.7 C-FAR Usage Components

6.2.1 Present Changeable Elements and Choose Change Source and Change Target

One of the key issues in using C-FAR is to be aware of what is changeable and what is not changeable. The C-FAR user inputs are elements within the C-FAR schema. However, engineering changes are not necessarily explicitly represented via the C-FAR vocabulary. Therefore, it is important to choose and map engineering changes to entities within the C-FAR schema. The engineer does not have to learn the secrets of data modeling in general or EXPRESS or C-FAR in particular. The essential information that the user should have is a list of the entities and their corresponding attributes. The user may choose any attribute from any entity that is subjected to a change. Next, the user can choose attributes or entities that are of interest. Then the following question can be raised: What is the correlation between the design change scenarios and the C-FAR schema ? The answer is that the C-FAR schema is built on top of an EXPRESS domain schema, and therefore it is expected that engineering change scenarios taken from the same EXPRESS covered domain will use the similar vocabulary in describing the modeled paradigm. To achieve representation of the changeable elements within the C-FAR schema, the EXPRESS schema is stripped of all its components except the attributes. For example, the following is an EXPRESS schema accompanied by a list of entities and their attributes, which represents the changeable elements within the C-FAR schema.

```
SCHEMA circle;

ENTITY point_3D;
    x1:    REAL;
    x2:    REAL;
```

```
  x3:    REAL;
END_ENTITY;

ENTITY circle;
  center_point:   point_3D;
  radius:         REAL;
END_ENTITY

END_SCHEMA;
```

Entity	Changeable Attributes
point_3D	x1 x2 x3
circle	center_point radius

Table 6.4 Example Changeable Attributes Table

Engineering changes as well as the EXPRESS schema coverage may vary in field or level of abstraction. In case the redesign activity is highly related to the C-FAR schema, it is likely that the user will find a set of a attributes that directly reflect the engineering change scenario. For example, if the user wants to see how a change in the circle size influences other element in the schema, it is clear that the attribute to be changed is the circle radius. For explicit mapping between the redesign scenarios and the C-FAR schema, the domain and the abstraction level of both should be closely related.

6.2.2 C-FAR Paths

The first step in finding out whether a source entity has a any linkage to the target is to find out if they are connected via the schema network and if they are indeed connected, which entities the paths go through. An example to this problem is given in Figure 6.8
The problem input will be a set of tuples of three items. First in the set is the graph, the second is the node from which change is initiated (the source), and the last input will be the node that the propagated change is being measured against (the target). Therefore, a graph will have the following characteristic form:

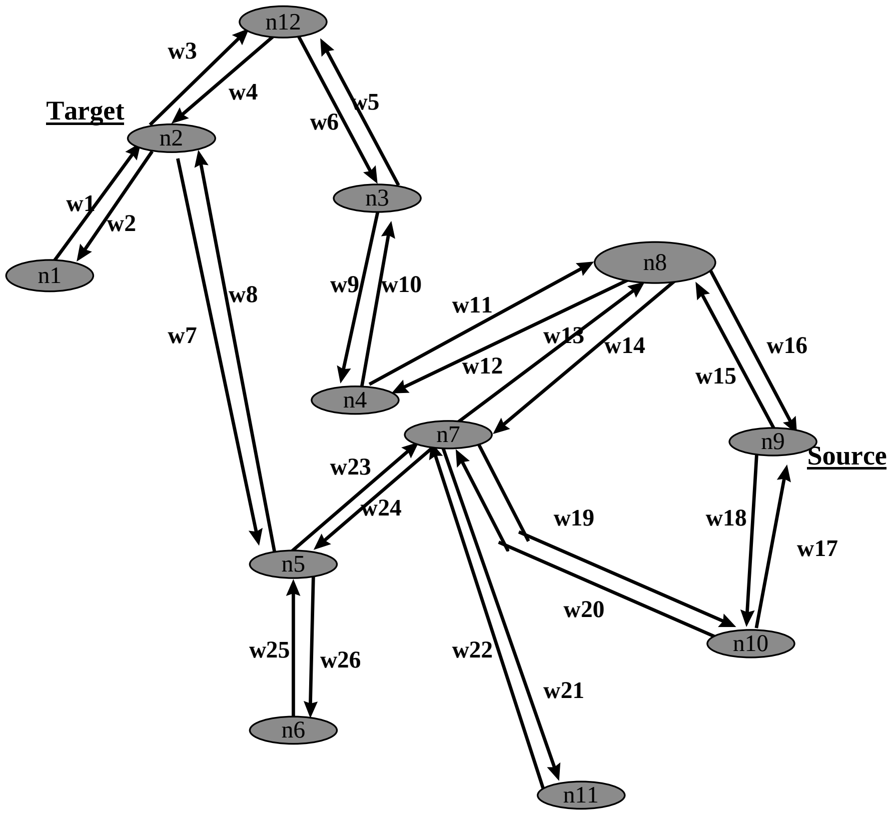


Figure 6.8 Example C-FAR Paths

Each edge has an assigned weight representing the linkage from the tail of the arrow to the head of it. The algorithmic solution will deal with the case of finding all the simple paths from the source to the target. It is desirable to specify the paths since it may provide insights on exactly how and by whom the linkage is influenced. Finding simple paths in a graph is not a trivial task in terms of computational resources. The computational cost is order of V!, where V is number of edges in the graph. In this research the most complex graph had ~20 edges. For larger implementation abstraction mechanisms are needed to cluster related elements.

6.2.3 Linkage Values Calculation

After finding the set of simple paths that leads from the source entity to the target entity, The C-FAR matrices linkage values are utilized to calculate the linkage value interval. The calculation of linkage values has several important stages. The first is the change vector and matrix multiplication. For each two entities that are within a relevant simple path, the multiplication takes place. Consequently, orthogonality factorization is being done for any change vector and C-FAR matrix multiplication. The computing cost for these two parts is of polynomial order. Therefore, the dominant computing cost is still finding the simple path stage. Finally, an interval linkage value result is achieved by summing the linkage values from all the source-to-target simple paths. The upper bound for the total linkage value interval is a result of the summation, and the lower bound of the interval is achieved by choosing the maximum value among the linkage values from the relevant simple paths.

6.2.4 Result Interpretation

C-FAR's range of results provided to the user is from 0 to 0.9, where 0 means that a change in the source attribute does not influence the target attribute, and the value 0.9 means that a change in the source strongly influences the target attribute. A value of 0.3 means that a change in the source somewhat influences the target attribute. These three numeric values provides the user with a measurement for any numeric results he may get between 0 and 0.9. The user should also expect to get an interval result, such as 0.77-0.85. The intervals are results of a multi-simple path solutions. C-FAR provides the user with more than a number or a number interval. C-FAR selects the simple path set that leads from the source attribute to the target attribute. Therefore, it can provide the user with specific path and intermediate linkage values that can provide additional insight on the influence. Namely, the user can have an idea on how exactly the change had propagated and what elements in the domain are involved in this connection. The larger the numeric value of the linkage values may mean a higher degree of correlation between the source and the target. This issue is examined in chapter 16. A small linkage value interval indicates a single dominant simple path. For example, in case "path1", the linkage value is 0.65 and there are three more paths with linkage values of 0.05. Therefore, the linkage value interval is 0.8-0.65. The dominant path contribution is 0.65 and the rest of the paths contribute 0.8-0.65=0.15. However, a large linkage value interval indicates several paths without one dominant path. For example, the path1 linkage value is 0.4 as well as path2. The interval for this example is 0.8-0.4.

6.2.5 C-FAR Usage Algorithmic Procedure

The following section provides a short description of the algorithmic procedure that C-FAR uses to estimate linkage values.

C-FAR input (C-FAR Schema, Source entity and attribute, Target entity and attribute)

1. Find all simple path that leads from
2. Calculate linkage value for each path
3. Create interval of calculated linkage value

A more detailed pseudo algorithm is provided in Appendix G.

6.3 Summary

In this chapter, C-FAR implementation was described. The implementation was two main stages: C-FAR construction and C-FAR usage. C-FAR construction is an activity which enriches the EXPRESS schema with knowledge from an expert domain. This knowledge is translated to a C-FAR matrix, which provides a qualitative linkage measure to relations in the EXPRESS schema. The second main stage of the C-FAR approach is usage. After the C-FAR schema is built, a user can query the schema and ask what the consequences are of a given change. The main parts of the C-FAR construction are the express schema scoping and matrix construction. The C-FAR usage explains the importance of presenting and choosing the source and target attributes. The C-FAR usage stage is also compounded of the “Find Path” stage as well as calculating linkage value stage. C-FAR represents entities, attributes, and linkages between entities. For each linkage there is a C-FAR matrix and for each entity there is an orthogonal C-FAR matrix. The basic entity attribute data structure is a two-dimensional array. The first dimension describes the entity and the second describes the attribute. A second two-dimensional array is used to describe the entities and their relations. The first array dimension represents an entity and the second describes the entities that are connected to it. Each element in the entities array represents a C-FAR matrix.

PART III

VALIDATION

Chapter 7

Evaluation Introduction

The evaluation part of the thesis has two parts: validation and verification. In the validation part, four C-FAR analysis case studies will be presented. A case study structure has a short domain introduction followed by an EXPRESS information model schema, description C-FAR schema, and a set of scenarios. The role of the validation stage will first be used to examine the capability of C-FAR to model various realistic engineering domain problems with different degrees of information complexity. Secondly, the ability of C-FAR to represent change and change propagation will be examined. The capability of the C-FAR methodology to model engineering domains is examined by the actual model construction, while the ability of C-FAR to represent change and propagate it is measured by materialization of the scenarios.

The role of the verification stage role is to examine the quality and reliability of the results that are presented in the validation stage. The verification stage uses three measures to examine C-FAR. The first measurement tests the reliability of the C-FAR methodology for the matrix construction phase. The question that this measure attempts to answer is how reliable the C-FAR matrix is in representing linkage values between the attributes of two entities.

The second measurement is a qualitative discussion about the scenarios results. The C-FAR schema builder (a domain expert by C-FAR definition) evaluates the C-FAR results and asks whether the linkage value achieved by C-FAR corresponds to the knowledge domain he or she obtains. This second measure examines overall C-FAR performance, namely, C-FAR construction, change representation, propagation and results interpretation. The third verification measure also examines C-FAR's change representation and tracking mechanism. A source entity's attributes and a target entity's attributes have been processed by the C-FAR methodology and have been presented to an independent non C-FAR literate expert domain. The expert is asked to estimate the linkage value between the given attributes. The answer is compared with calculated linkage values achieved with C-FAR.

7.1 Case Study Choice

The first case study is a simple 2D truss model. This is the simplest case study among the four. Its roll is to examine the basic change representation and change propagation mechanisms. The C-FAR methodology was developed together with this baseline model. The second case study deals with the bumper components and its connectivity to bumper tests. This case study is more complex, with more attributes. C-FAR's assumption mechanisms were checked against this model. The first two models were developed specifically for the sake of this research and by the thesis author. Since C-FAR is based on a generic EXPRESS model, it is useful to examine the methodology applicability, reliability and correctness against an existing information model that describes various engineering domains. Therefore, the third and forth case study are based on C-FAR schemas that were not developed by the thesis author but by graduate research assistants who are experts in the case study domain. The third case study is in Printed Wiring Board domain. The fourth case study is in the injection molding domain. Both case study are complex, deal with complex information diagrams, and were based on existing EXPRESS information schemas. Since these two case studies were based on already existing EXPRESS schemas, so they are good measures of how C-FAR works in real engineering domain problems. The matrix in Figure 7.1 describes how the research objectives are addressed by the case studies. Relevancy of coverage, change representation and change propagation are covered by all the case studies. However the PWB and injection molding case study were constructed and verified by different domain experts.

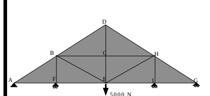
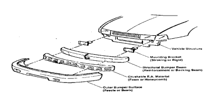
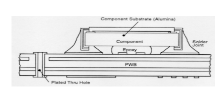
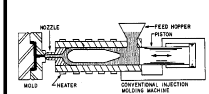
Case Study / Objective	**Truss-2D** 	**Bumper** 	**PWB** 	**Injection Molding** 
Relevancy of Coverage	✓	✓	✓	✓
Enable Engineering Change Representation	✓	✓	✓	✓
Enable Change Propagation	✓	✓	✓	✓
Correctness scenarios / expert	✓ /	✓ /	✓ / ✓	✓ / ✓

Figure 7.1 Research Objectives vs. Case Studies

Chapter 8

2D Truss Structural Analysis Model Case Study

8.1 Introduction

The following_information model describes a partial analysis and finite element approach for 2D truss problem. The main entities in this domain are the structure, elements and nodes. Those parts are the main building blocks for a characteristics 2D truss. An example for a 2D truss is illustrated in Figure 8.1

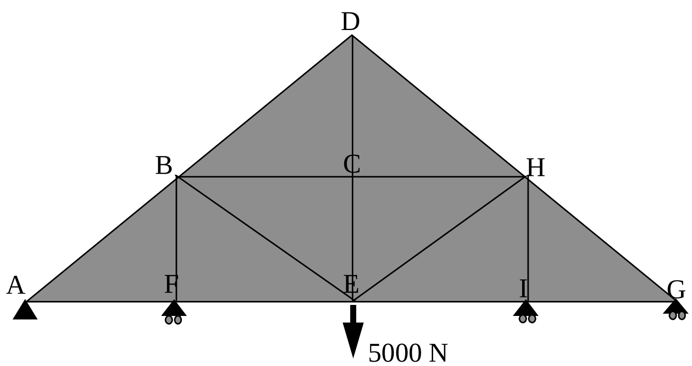


Figure 8.1 2D Truss Model

8.2 Information model

The schema captures the main structure-2D elements. In the core of the schema is the element structure representation. The structure is compounded of elements that are bounded by nodes. Loads are applied on the nodes while flexibility matrix is a structural characteristic of the construct. The force vector described is a vector list of the loads applied within the construct framework. As explained in chapter 2, the corresponding EXPRESS-G information model for the 2D truss is presented in Figure 8.2

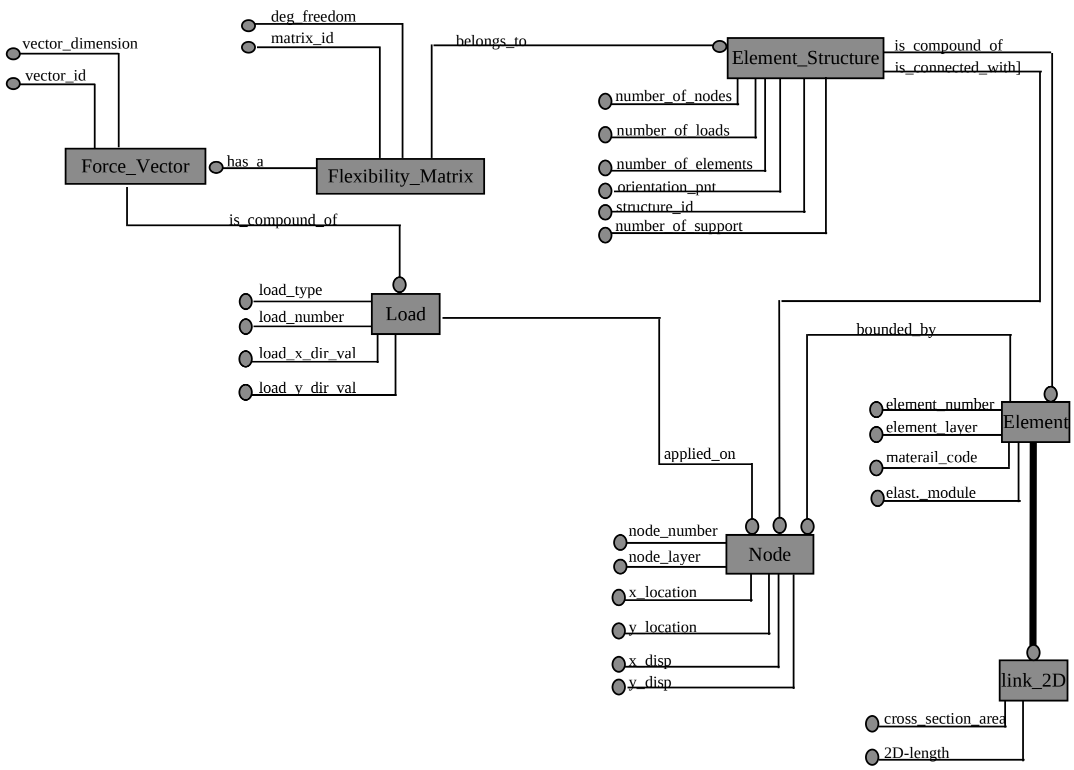


Figure 8.2 2D Truss Structure Analysis Model

The entity element link_2D is a type of elements and as such, inherits the attributes from the entity element. The flexibility matrix describes physical characteristics of the structure. As this schema touches the main aspects of the analysis of 2D problem domain, it is a relatively simple schema and therefore is adequate to illustrate the C-FAR methodology initially.

8.3 C-FAR Analysis

8.3.1 Changeable Attribute List

Entity	**Changeable Attributes**
Element_Structure	structure_id number_of_nodes number_of_loads number_of_elements number_of_supports orientation_point
Node	node_ number node_ layer x_location y_location x_disp y_dsip

link_2D	element_number element_layer material_code elastic_module cross_section_area 2D-length
load	load_number load_type load_x_dir_val load_y_dir_val
Force_Vector	vector_id vector_dimension
Flexibility_Matrix	matrix_id deg_freedom

Table 8.1 Changeable Attribute List

8.3.2 C-FAR Matrices

The following is a representative set of C-FAR matrices that are used in the scenarios. The complete set of C-FAR matrices is provided in appendix B.

Force_Vector **Flexibility_Matrix**	vector_dimension	vector_id
number_deg_of_freedom	H/H	L/L
matrix_id	L/L	H/H

Table 8.2 Force_Vector vs. Flexibility_Matrix

Flexibility_Matrix **Element_Structue**	number_deg_of_freedom	matrix_id
number_of_nodes	H/H	L/L
number_of_loads	M/M	L/L
number_elements	H/H	L/L
number_of_supports	M/M	L/L
orientation_pnt	L/L	L/L
structure_id	L/L	H/H

Table 8.3 Flexibility_Matrix vs. Element_Structue

Node **Element_Structue**	node number	node layer	x location	y location	x disp	y disp
number_of_nodes	L/L	L/L	L/L	L/L	H/L	H/L
number_of_loads	L/L	L/L	L/L	L/L	H/L	H/L
number_elements	L/L	L/L	L/L	L/L	H/L	H/L

number_of_supports	L/L	L/L	L/L	L/L	H/L	H/L
orientation_pnt	L/L	L/L	M/L	M/L	L/L	L/L
structure_id	H/M	L/L	L/L	L/L	L/L	L/L

Table 8.4 Node vs. Element_Structue

link_2D **Element_Structue**	element number	element layer	material code	elastic module	cros_sec _area	2D-length
number_of_nodes	L/L	L/L	L/L	L/L	L/L	L/L
number_of_loads	L/L	L/L	L/L	L/L	L/L	L/L
number_elements	L/L	L/L	L/L	L/L	L/L	L/L
number_of_supports	L/L	L/L	L/L	L/L	L/L	L/L
orientation_pnt	L/L	L/L	L/L	L/L	L/L	L/L
structure_id	H/H	L/L	L/L	L/L	L/L	L/L

Table 8.5 link_2D vs. Element_Structue

Node **link_2d**	node number	node layer	x location	y location	x disp	y disp
element_number	H/H	L/L	L/L	L/L	L/L	L/L
element_layer	L/L	H/H	L/L	L/L	L/L	L/L
material_code	L/L	L/L	L/L	L/L	H/L	H/L
elatic_module	L/L	L/L	L/L	L/L	H/L	H/L
cross_sec_area	L/L	L/L	L/L	L/L	H/L	H/L
2D_length	L/L	L/L	M/M	M/M	M/H	M/H

Table 8.6 Node vs. link_2d

Load **Force_Vector**	load_type	load_number	load_x_dir_ val	load_y_dir_ val
vector_dimension	L/L	L/L	L/L	L/L
vector_id	L/L	H/H	L/L	L/L

Table 8.7 Load vs. Force_Vector

Node Load	node number	node layer	x location	y location	x disp	y disp
load_type	L/L	L/L	L/L	L/L	L/L	L/L
load_number	H/H	L/L	L/L	L/L	L/L	L/L
load_x_dir_val	L/L	L/L	L/L	L/L	H/L	H/L
load_y_dir_val	L/L	L/L	L/L	L/L	H/L	H/L

Table 8.8 Load vs. Node

In this section, several engineering change scenarios are provided. The first scenario is checking the consequences of changing the force vector dimension value on the node attributes. Table 8.1 provides the changeable components in the C-FAR schema. The second stage is choosing the entities and attributes that will be the source and target entities.

8.3.3 Evaluation 2D Truss Model Scenario 1

The first scenario is checking the consequences of changing the force vector dimension value on the node attributes. Therefore, the source attribute that is chosen is "Force_Vector.vector_dimension" and the target attributes will be all six attributes of the Node entity: "node_number", "node_layer", "x_location", "y_location", "x_disp", and "y_disp". First, the simple path algorithm provides three possible paths that lead from "Force_Vector" to the "Node" entity. Path1 = "Force_Vector" - "Flexibility_Matrix" - "Element_Structure" - "Node"

Path2 = "Force_Vector" - "Flexibility_Matrix" - "Element_Structure" - "Element" - "Node"

Path3 = "Force_Vector" - "Load" - "Node"

Path1:

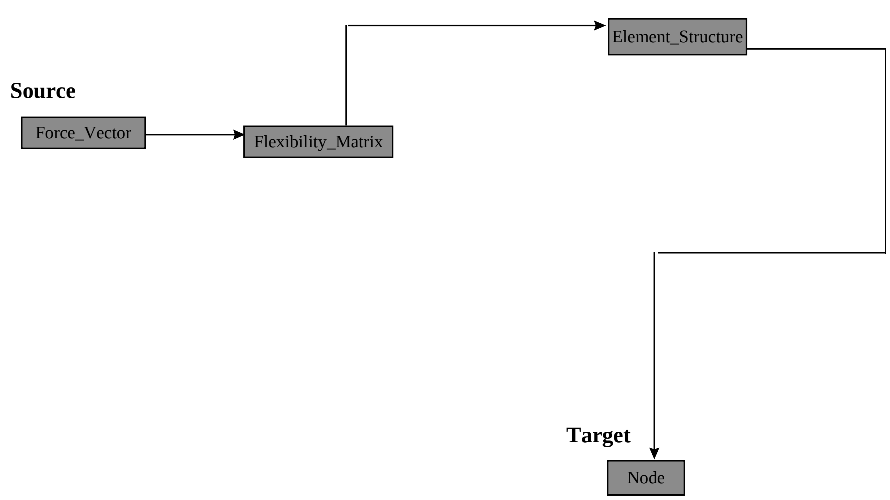


Figure 8.3 Scenario 1 Path1

Path1:
The “Force_Vector” entity has two dimensions, and the “Flexibility_Matrix” entity has two dimensions.

$$Force\_Vector = \begin{bmatrix} vector\_\dim ension \\ vector\_id \end{bmatrix}$$

$$\Delta path1\_Force\_Vector = \begin{bmatrix} \Delta 1 \\ \Delta 2 \end{bmatrix}$$

Given a change vector is $\begin{bmatrix} \Delta 1 \\ \Delta 2 \end{bmatrix} = \begin{bmatrix} \Delta \\ 0 \end{bmatrix}$

The first element is non-zero and the second element is zero. Therefore, we are examining how change in the “vector_dimension” is propagated.
From Table 8.2 the C-FAR matrix that describes the linkage from “Force_Vector” to “Flexibility_Marix” is:

$$C(Force\_Vector, Flexibility\_Matrix) = \begin{bmatrix} H & L \\ L & H \end{bmatrix}$$

$$\Delta Force\_Vector * C(Force\_Vector, Flexibility\_Matrix) =$$

$$\Delta path1\_Flexibility\_Marix = \begin{bmatrix} \Delta * H \\ 0 \end{bmatrix}$$

The above result is the first order propagation in Path1.
The second order propagation in Path1 occurs between “Flexibility_Matrix” and “Element_Structure”.
From Table 8.3 the C-FAR matrix that describes the linkage from “Force_Vector” to “Flexibility_Marix” is:

$$C(Flexibility\_Matrix, Element\_structure) = \begin{bmatrix} H & M & H & M & L & L \\ L & L & L & L & L & H \end{bmatrix}$$

$$\Delta Flexibility\_Marix * C(Flexibility\_Matrix, Element\_structure) = \begin{bmatrix} \Delta * H * H \\ \Delta * H * M \\ \Delta * H * H \\ \Delta * H * M \\ \Delta * H * L \\ \Delta * H * L \end{bmatrix} =$$

$= \Delta path1\_Element\_Structure$

The above result is the second order propagation in Path1.

The third order propagation in Path1 occurs between “Element_Structue” and “Node”. $C(Element\_Structure, Node)$ is extracted from Table 8.4.

$$C(Element\_structure, Node) = \begin{bmatrix} L\ L\ L\ L\ H\ H \\ L\ L\ L\ L\ H\ H \\ L\ L\ L\ L\ H\ H \\ L\ L\ L\ L\ H\ H \\ L\ L\ M\ M\ L\ L \\ H\ L\ L\ L\ L\ L \end{bmatrix}$$

$$\Delta path1\_Element\_Structure\ *\ C(Element\_Structure, Node) =$$

$$= \begin{bmatrix} \Delta * H * H \\ \Delta * H * M \\ \Delta * H * H \\ \Delta * H * M \\ \Delta * H * L \\ \Delta * H * L \end{bmatrix} * \begin{bmatrix} L\ L\ L\ L\ H\ H \\ L\ L\ L\ L\ H\ H \\ L\ L\ L\ L\ M\ M \\ L\ L\ L\ L\ H\ H \\ L\ L\ M\ M\ L\ L \\ H\ L\ L\ L\ L\ L \end{bmatrix} = \Delta path1\_Node$$

$$\Delta path1\_Node =$$

$$\Delta * \begin{bmatrix} (H*H*L)+(H*M*L)+(H*M*L)+(H*M*L)+(H*L*L)+(H*L*H) \\ (H*H*L)+(H*M*L)+(H*M*L)+(H*M*L)+(H*L*L)+(H*L*L) \\ (H*H*L)+(H*M*L)+(H*M*L)+(H*M*L)+(H*L*M)+(H*L*L) \\ (H*H*L)+(H*M*L)+(H*M*L)+(H*M*L)+(H*L*M)+(H*L*L) \\ (H*H*H)+(H*M*H)+(H*H*H)+(H*M*H)+(H*L*L)+(H*L*L) \\ (H*H*H)+(H*M*H)+(H*H*H)+(H*M*H)+(H*L*L)+(H*L*L) \end{bmatrix}$$

The only non “L” linkage value in the $\Delta path1\_Node$ are the last two elements. After substituting 0.9 for H, 0.3 for M and 0 for L. The $\Delta path1\_Node$ has the following form

$$\Delta path1\_Node = \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ 1.944 \\ 1.944 \end{bmatrix}$$

$$\text{Orth}(\Delta path1\_Node) = \overline{\Delta path1\_Node} = \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ H \\ H \end{bmatrix}$$

$\Delta path1\_Node$ symbolized the effect a change Δ in the attribute "vector_dimension" of "Vector_Force" entity has on the entity "Node" by the specified path1.
since $\Delta path1\_Node$ is at the target node.
$\overline{\Delta path1\_Node} \equiv \Delta Path(1)$

Path2:

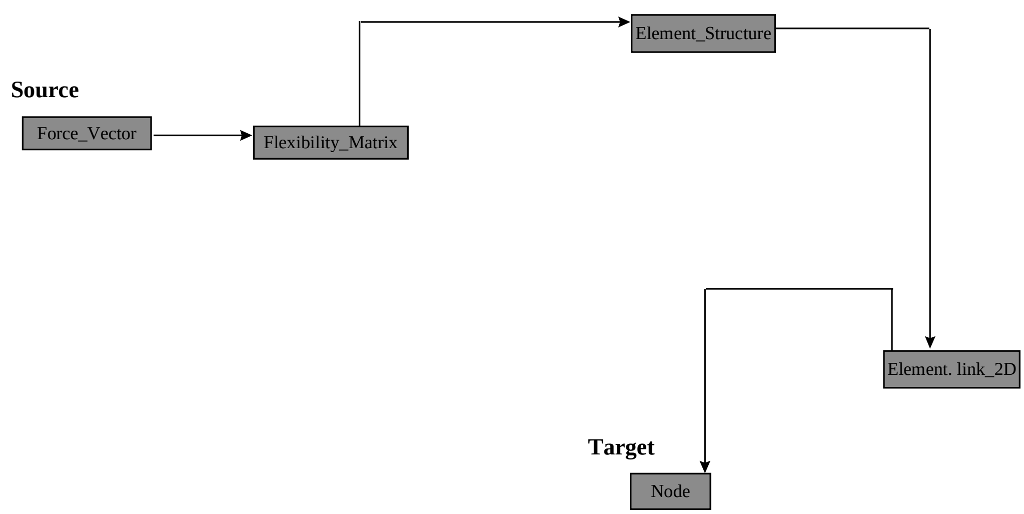


Figure 8.4 Scenario 1 Path2

Path2 = "Force_Vector" - "Flexibility_Matrix" - "Element_Structure" - "Element" - "Node"
The first part of Path2 is identical to Path1. Namely, "Force_Vector" - "Flexibility_Matrix" - "Element_Structure". Therefore the $\Delta path1\_Element\_Structure$ that was initiated in $\Delta path1\_Force\_Vector$ is the same as $\Delta path2\_Element\_Structure$.

$$\Delta path1\_Element\_Structure = \Delta path2\_Element\_Structure = \begin{bmatrix} \Delta * H * H \\ \Delta * H * M \\ \Delta * H * M \\ \Delta * H * M \\ \Delta * H * L \\ \Delta * H * L \end{bmatrix}$$

Third order propagation in Path2 occurs between "Element_Structue" and "Element_link_2D". $C(Element\_Structure, Element\_link2D$ is taken from Table 8.5.

$$C(Element\_structure, Element\_link\_2D) = \begin{bmatrix} L & L & L & L & L & L \\ L & L & L & L & L & L \\ L & L & L & L & L & L \\ L & L & L & L & L & L \\ L & L & L & L & L & L \\ H & L & L & L & L & L \end{bmatrix}$$

$$C(Element\_Structure, Element\_link2D = \begin{bmatrix} \Delta * H * H \\ \Delta * H * M \\ \Delta * H * M \\ \Delta * H * M \\ \Delta * H * L \\ \Delta * H * L \end{bmatrix}^T * \begin{bmatrix} L & L & L & L & L & L \\ L & L & L & L & L & L \\ L & L & L & L & L & L \\ L & L & L & L & L & L \\ L & L & L & L & L & L \\ H & L & L & L & L & L \end{bmatrix} =$$

$$\Delta path2\_Element\_link\_2D =$$

$$\Delta * \begin{bmatrix} (H*H*L)+(H*M*L)+(H*M*L)+(H*M*L)+(H*L*L)+(H*L*H) \\ (H*H*L)+(H*M*L)+(H*M*L)+(H*M*L)+(H*L*L)+(H*L*L) \\ (H*H*L)+(H*M*L)+(H*M*L)+(H*M*L)+(H*L*L)+(H*L*L) \\ (H*H*L)+(H*M*L)+(H*M*L)+(H*M*L)+(H*L*L)+(H*L*L) \\ (H*H*L)+(H*M*L)+(H*M*L)+(H*M*L)+(H*L*L)+(H*L*L) \\ (H*H*L)+(H*M*L)+(H*M*L)+(H*M*L)+(H*L*L)+(H*L*L) \end{bmatrix}$$

Orth($\Delta path2\_Element\_link\_2D$) = $\overline{\Delta path2\_Element\_link\_2D}$ = $\Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ L \end{bmatrix}$

$\Delta path2\_Element\_link\_2D$ symbolized the effect a change "Δ "in the attribute "vector_dimension" of "Vector_Force" entity has on the entity "Element_link_2D" by the specified path2.
Fourth order propagation in Path2 occurs between "Element_link_2D" and "Node". $C(Element\_link\_2D, Node)$ is taken from Table 8.6.

$$C(Element\_link\_2D, Node) = \begin{bmatrix} H & L & L & L & L & L \\ L & H & L & L & L & L \\ L & L & L & L & H & H \\ L & L & L & L & H & H \\ L & L & L & L & H & H \\ L & L & M & M & M & M \end{bmatrix}$$

$$\overline{\Delta path2\_Element\_link\_2D} * C(Element\_link\_2D, Node) = \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ L \end{bmatrix} * \begin{bmatrix} H & L & L & L & L & L \\ L & H & L & L & L & L \\ L & L & L & L & H & H \\ L & L & L & L & H & H \\ L & L & L & L & H & H \\ L & L & M & M & M & M \end{bmatrix} =$$

$\Delta path2\_Node$

$$\text{Orth}(\Delta path2\_Node) = \overline{\Delta path2\_Node} = \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ L \end{bmatrix}$$

$\Delta path2\_Node$ symbolized the effect a change "Δ " in the attribute "vector_dimension" of "Vector_Force" entity has on the entity "Node" by the specified path2.
since $\Delta path2\_Node$ is at the target node.

$\overline{\Delta path2\_Node} \equiv \Delta Path(2)$

The last simple path is Path3:
Path3 = "Force_Vector" - "Load" - "Node"

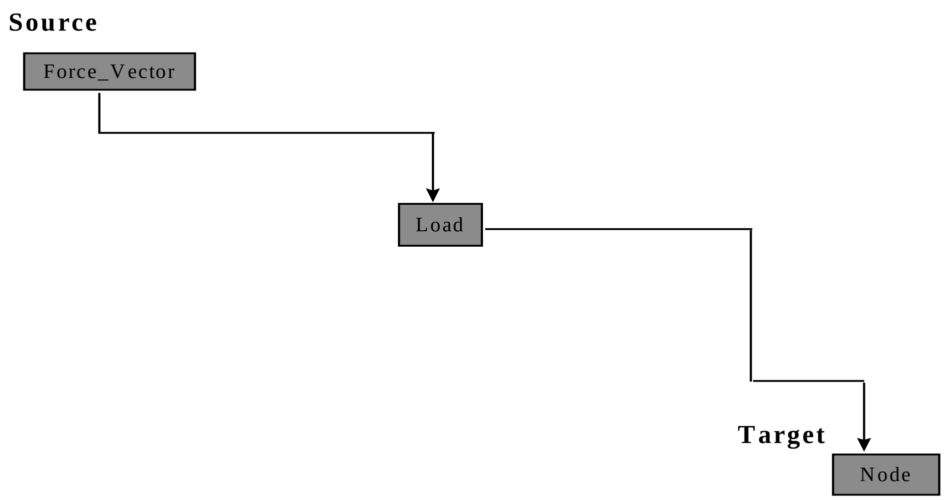


Figure 8.5 Scenario 1 Path3

Force_Vector entitle has two dimension and Load has four dimensions.

$$Force\_Vector = \begin{bmatrix} vector\_\dim ension \\ vector\_id \end{bmatrix}$$

$$\Delta path1\_Force\_Vector = \begin{bmatrix} \Delta 1 \\ \Delta 2 \end{bmatrix}$$

Given a change vector is $\begin{bmatrix} \Delta 1 \\ \Delta 2 \end{bmatrix} = \begin{bmatrix} \Delta \\ 0 \end{bmatrix}$

The first element is non-zero and the second element is zero. Therefore, we are examining how change in the "vector_dimension" is propagated. The semi C-FAR matrix that describes the linkage from "Force_Vector" to "Load" is $C(Force\_Vector, Load)$. It is taken from Table 8.7.

$$C(Force\_Vector, Load) = \begin{bmatrix} L\,L\,L\,L \\ L\,H\,L\,L \end{bmatrix}$$

$$\Delta Force\_Vector * C(Force\_Vector, Load) = \Delta path3\_Load = \begin{bmatrix} \Delta * L \\ \Delta * L \\ \Delta * L \\ \Delta * L \end{bmatrix}$$

The above result is the first order propagation in Path3.

Second order propagation in Path3 occurs between "Load" and "Node".

The $C(Load, Node)$ is extracted from Table 8.8.

$$C(Load, Node) = \begin{bmatrix} L\,L\;\;L\,L\,L\,L \\ H\,L\,L\,L\,L\,L \\ L\,L\,L\,L\,H\,H \\ L\,L\,L\,L\,H\,H \end{bmatrix}$$

$\Delta path3\_\ Load *\ C(Load, Node)\ =$

$$\begin{bmatrix} \Delta * L \\ \Delta * L \\ \Delta * L \\ \Delta * L \end{bmatrix}^T * \begin{bmatrix} L\,L\;\;L\,L\,L\,L \\ H\,L\,L\,L\,L\,L \\ L\,L\,L\,L\,H\,H \\ L\,L\,L\,L\,H\,H \end{bmatrix} = \Delta * \begin{bmatrix} (L*L)+(L*H)+(L*L)+(L*L) \\ (L*L)+(L*L)+(L*L)+(L*L) \\ (L*L)+(L*H)+(L*L)+(L*L) \\ (L*L)+(L*H)+(L*L)+(L*L) \\ (L*L)+(L*H)+(L*H)+(L*H) \\ (L*L)+(L*H)+(L*H)+(L*H) \end{bmatrix} = \Delta path3\_\ Node$$

$$\text{Orth}(\ \Delta path3\_\ Node\ ) = \overline{\Delta path3\_\ Node}\ =\ \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ L \end{bmatrix}$$

since $\Delta path3\_\ Node$ is at the target node.

$\overline{\Delta path3\_\ Node} \equiv \Delta Path(3)$

After the influence of the three simple paths that leads from entity “Force_Vector” to entity “Node” was identified, the total influence is computed in the following manner:

$$\Delta Path(1)\ =\ \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ H \\ H \end{bmatrix},\ \Delta Path(2)\ =\ \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ L \end{bmatrix},\ \Delta Path(3)\ =\ \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ L \end{bmatrix}$$

Therefore the maximum linkage value is:

Total influence = $\sum_{i=1}^{n} \Delta Path(i) = \Delta Path(1) + \Delta Path(2) + \Delta Path(3) =$

$$\Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ H \\ H \end{bmatrix} + \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ L \end{bmatrix} + \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ L \end{bmatrix} = \Delta * \begin{bmatrix} L+L+L \\ L+L+L \\ L+L+L \\ L+L+L \\ H+L+L \\ H+L+L \end{bmatrix} =$$

$$\Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ H \\ H \end{bmatrix} = \text{ Total influence from attribute “vector\_dimension” in entity “Force\_Vector”}$$

and the “Node” entity. The Table 8.9 illustrates the results:
Since this is also the influence of path1, the maximum linkage value is also the minimum linkage value.

Node **Force_Vector(partial)**	node number	node layer	x location	y location	x disp	y disp
vector_dimension	L	L	L	L	H	H

Table 8.9 Scenario 1 Results

8.3.4 Results Analysis

These results represent the calculated linkage value from “vector_dimension” (adding or deleting loads) to the attributes of the entity “Node”. The “node_number”, “node_layer” and the “x_location” and “y_location” all have low linkage value. That gives a hint that a change in a “vector_dimension” of the “Force_Vector” will probably not influence those attributes. However, the high linkage value between the “vector_dimension” and the “x_disp” and “y_disp” indicate that a change in the “vector_dimension” will likely influence the Node “x” and “y” displacements.

8.3.5 Evaluation 2D Truss Model Scenario 2

For this scenario, the user is interested in learning how a change in the magnitude of a load influences the elements in the structure. Therefore, the source attribute is chosen to be “load_y_dir_val” and consecutively “load_x_dir_val” and the target attributes will be

all six attributes of the element entity: “element_number”, “element_layer”, “material_code”, “elastic_module”, “cross_section_area” and “2D-length”.
First, the simple paths algorithm provides three possible paths that lead from “Load” to the “Element” Entity.
Path1 = “Load” - “Force_Vector” - “Flexibility_Matrix” - “Node” - “Element.link_2D”
Path2 = “Load” - “Force_Vector” - “Flexibility_Matrix” - “Element.link_2D”
Path3 = “Load” - “Node” - “Element.link_2D”
Path1:

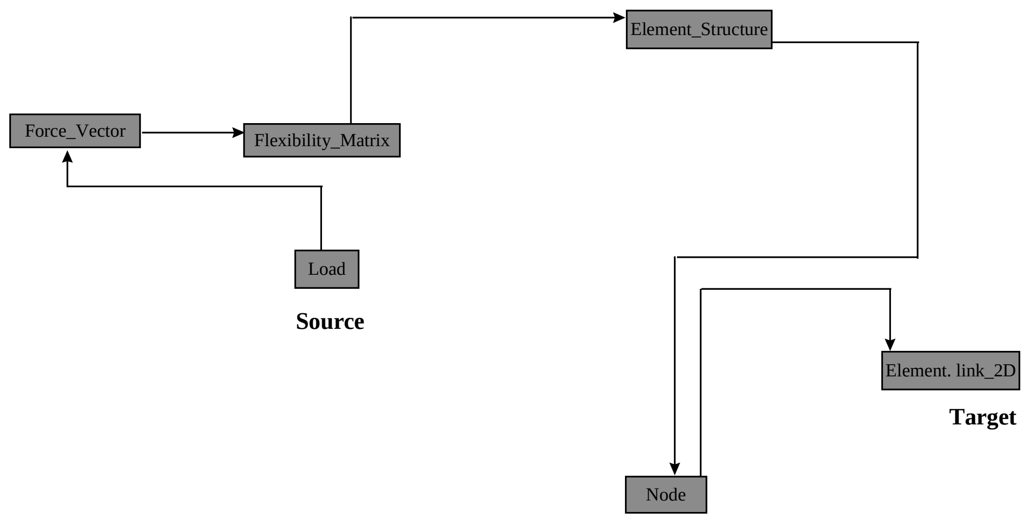


Figure 8.6 Scenario 2 Path1

Path1:
The “Force_Vector” entity has two dimension and “Load” has four attributes.

Given a change vector is $= \begin{bmatrix} 0 \\ 0 \\ \Delta \\ 0 \end{bmatrix}$

The first change vector that is examined is one which includes only a change in the “load_x_dir_val” attribute.
Therefore, we are examining how a change in the “load_x_dir_val” attribute is propagated. $C(Load, Force\_Vector)$ is extracted from Table 8.7.

$$C(Load, Force\_Vector) = \begin{bmatrix} L & L \\ L & H \\ L & L \\ L & L \end{bmatrix}$$

$$\Delta Load * C(Load, Force\_Vector) = \Delta path1\_Force\_Vector = \begin{bmatrix} \Delta * L \\ \Delta * L \end{bmatrix}$$

The initial change vector linkage values are both “L”. Since the change propagation is defined by the multiplication operator and any term which is multiplied by “L” is still “L”, the final change vector on the entity element will therefore be:

$$\Delta Path(1) = \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ L \end{bmatrix}$$

Path2:

Path2 = “Load” - “Force_Vector” - “Flexibility_Matrix” - “Element.link_2D”

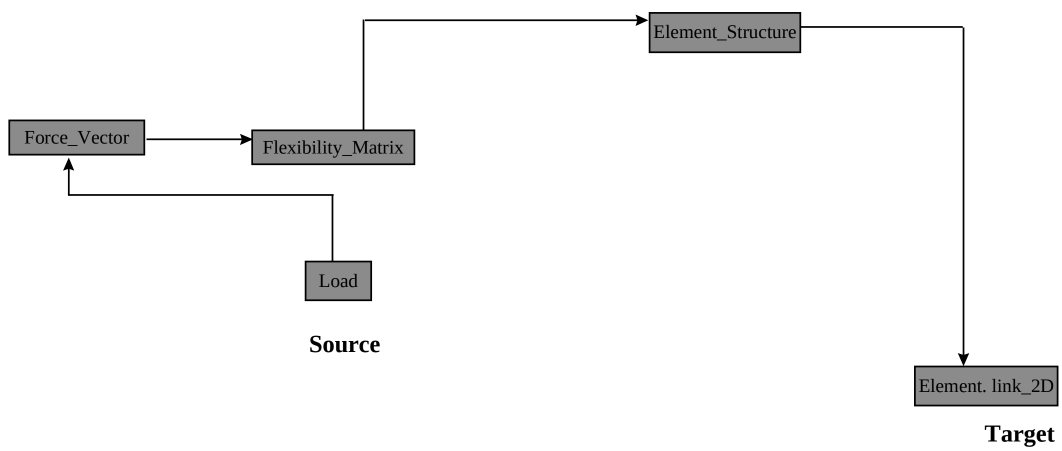


Figure 8.7 Scenario 2 Path2

Path2 has the same first four stages in its propagation as path1. However after the first propagation step it was shown that path1 calculated linkage value is:

$$\Delta Path(2) = \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ L \end{bmatrix}$$

Path3:

Path3 = “Load” - “Node” - “Element.link_2D”

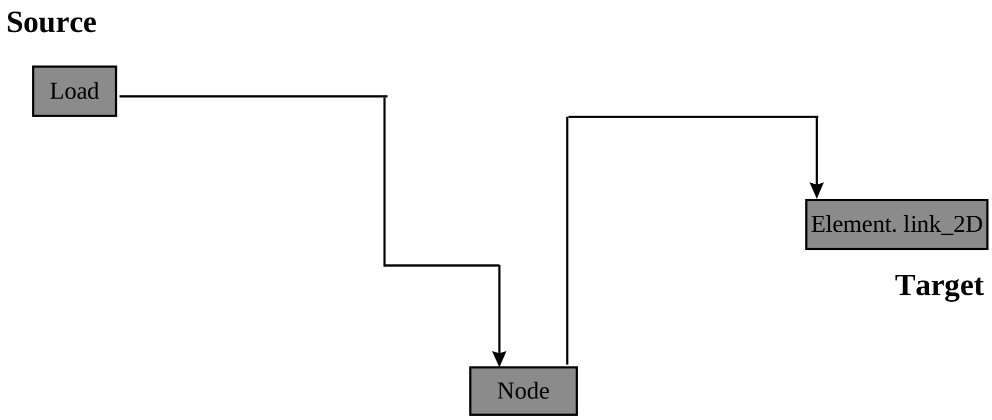


Figure 8.8 Scenario 2 Path3

The “node” entity has six dimensions and the “Load” entity has four attributes.

Given a Load change vector $= \begin{bmatrix} 0 \\ 0 \\ \Delta \\ 0 \end{bmatrix}$

Therefore, we are examining how a change in the “load_x_dir_val” attribute is propagated. $C(Load, Node)$ is extracted from Table 8.8.

$$C(Load, Node) = \begin{bmatrix} L & L & L & L & L & L \\ H & L & L & L & L & L \\ L & L & L & L & H & H \\ L & L & L & L & H & H \end{bmatrix}$$

$$\Delta Load * C(Load, Node) = \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ H \\ H \end{bmatrix} = \Delta path3\_Node$$

The next entity is the target entity, namely “Element.link_2D”.
$C(Node, Element.link\_2D)$ is extracted from Table 8.6.

$$C(Node, Element.link\_2D) = \begin{bmatrix} H & L & L & L & L & L \\ L & H & L & L & L & L \\ L & L & L & L & L & M \\ L & L & L & L & L & M \\ L & L & L & L & L & H \\ L & L & L & L & L & H \end{bmatrix}$$

$$\Delta path3\_Node \;*C(Node, Element.link\_2D) = \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ H \\ H \end{bmatrix}^T * \begin{bmatrix} H & L & L & L & L & L \\ L & H & L & L & L & L \\ L & L & L & L & L & M \\ L & L & L & L & L & M \\ L & L & L & L & L & H \\ L & L & L & L & L & H \end{bmatrix} =$$

$$\Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ H*H+H*H \end{bmatrix} = \Delta path3\_Element.link\_2D$$

Orth($\Delta path3\_Element.link\_2D$) = $\overline{\Delta path3\_Element.link\_2D}$ = $\Delta Path(3)$

$$\Delta Path(3) = \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ H \end{bmatrix}$$

Max($\Delta Path(1)$, $\Delta Path(2)$, $\Delta Path(3)$) = $\Delta Path(3)$

Therefore, the minimum value for the calculated linkage value between the source entity attribute to the target entity attributes is exactly $\Delta Path(3)$. The Maximum value of the result interval is the summation of the contribution from all the paths.

$$\Delta Path(1) = \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ L \end{bmatrix}, \Delta Path(2) = \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ L \end{bmatrix}, \Delta Path(3) = \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ H \end{bmatrix}$$

Therefore the maximum linkage value is

Total influence = $\sum_{i=1}^{n} \Delta Path(i) = \Delta Path(1) + \Delta Path(2) + \Delta Path(3) =$

$$\Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ H \end{bmatrix} + \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ L \end{bmatrix} + \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ L \end{bmatrix} = \Delta * \begin{bmatrix} L+L+L \\ L+L+L \\ L+L+L \\ L+L+L \\ L+L+L \\ H+L+L \end{bmatrix}$$

$\Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ H \end{bmatrix}$ = Total influence from attribute load_x_dir_val in entity Load and the Element.link_2D entity. The following Table illustrates the results.

Since this is also the influence of path3, the maximum linkage value is also the minimum linkage value.

Element.link_2D **Load(partial)**	element number	element layer	material code	elastic module	cross section_area	2D length
load_x_dir_val	L	L	L	L	L	H

Table 8.10 Scenario 2 Results

8.3.6 Result Analysis

These results represent the calculated linkage value from the Load “load_x_dir_val” attribute to the attributes of the entity “Element.link_2D”. All but one of the

“Element.link_2D” attributes have an “L” linkage value for a change from the source entity; the 2D_length attribute has a “H” for its linkage value. The high linkage value between the “load_x_dir_val” and the “2D_length” indicates that a change in the “load_x_dir_val” will likely influence the “Element.link_2D”. The C-FAR analysis will be the same for the “load_y_dir_val” attribute un the Load entity. Therefore, the C-FAR schema suggests that a change in a Load magnitude will very likely change the “2D_length” of an element. It will most likely not change the element number, layer or material code.

The inverse linkage value between “2D_length” and “load_x_dir_val” is not necessarily the same value, namely “H”. A change in the “2D_length” does not mean that there is a change in the “load_x_dir_val”. The C-FAR schema captures this notion, and a change vector that has as its source entity the “Element.link_2D” will have the following form:

$$\text{A change vector in Element.link\_2D entity for a change in the 2D\_length attribute} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \Delta \end{bmatrix}$$

The target is the Load entity. The result of the C-FAR analysis is given in Table 8.11

Element.link_2D **Load(partial)**	load type	load number	load_x dir_val	load_y dir_val
2D_length	L	L	L	L

Table 8.11 Element.link_2D vs. Load(partial)

This example illustrate the asymmetrical characteristics of change within the C-FAR schema. Namely, a change in “load_x_dir_val” may hint a likely change in “2D_length”. However, a change in “2D_length” does not imply a likelihood of change in the “load_x_dir_val” attribute of the Load element.

Chapter 9

Bumper Model Case Study

9.1 Introduction

This bumper case study concentrates on the bumper components and their relation to the bumper requirements. Before 1973, the bumper role was mainly decorative, fancy and shiny. It did not provide much in terms of damage protection to the vehicle. The onset of federal regulations for the automotive bumper in 1973 triggered a conceptual change in the role of the bumper. The bumper was made to withstand substantial impact loads. As a result, the bumper design as well as its location on the car and its material selection have changed. According to the regulations written in the 1980's, a bumper must pass a series of tests. The first test is a pendulum test, which involves using a pendulum that weighs the same amount as the vehicle itself. The pendulum hits the vehicle at a required test velocity. The second test is a barrier test, where the vehicle is pulled into a fixed barrier at a required speed. The tests are pass/fail based and the success criteria are that the bumper should maintain its structural integrity and also have no observable cosmetic damage. The pendulum test was initially the first test suggested, but insurance companies claimed that this test alone was not sufficient. Therefore, the car manufactures started to use the barrier test in addition.

Several factors are important in designing bumpers. Some of these factors are styling, weight reduction, corrosion resistance, reparability, engine cooling and cost. The bumper core is a beam, which can be steel or plastic laminates or reinforced thermoplastic beams with long glass fibers. Attached to the beam is an energy absorbent element. Its role is to take most of the energy from the impact. Energy absorbent material can be a foamed plastic or plastic honeycomb. The mounting brackets also take some of the impact load energy. Finally, the decorative bumper requirements are fulfilled by the bumper covers, or facia. The material must be able to flex without breaking or cracking during impact. The facia material can be thermoplastic olefin (TPO) or a material from the thermoplastic polyester elastomer family, or reaction injection molding.

More details about the bumper components can be found in [K. C. Rusch. "An Overview of Automotive Plastic Bumpers" ,1990]

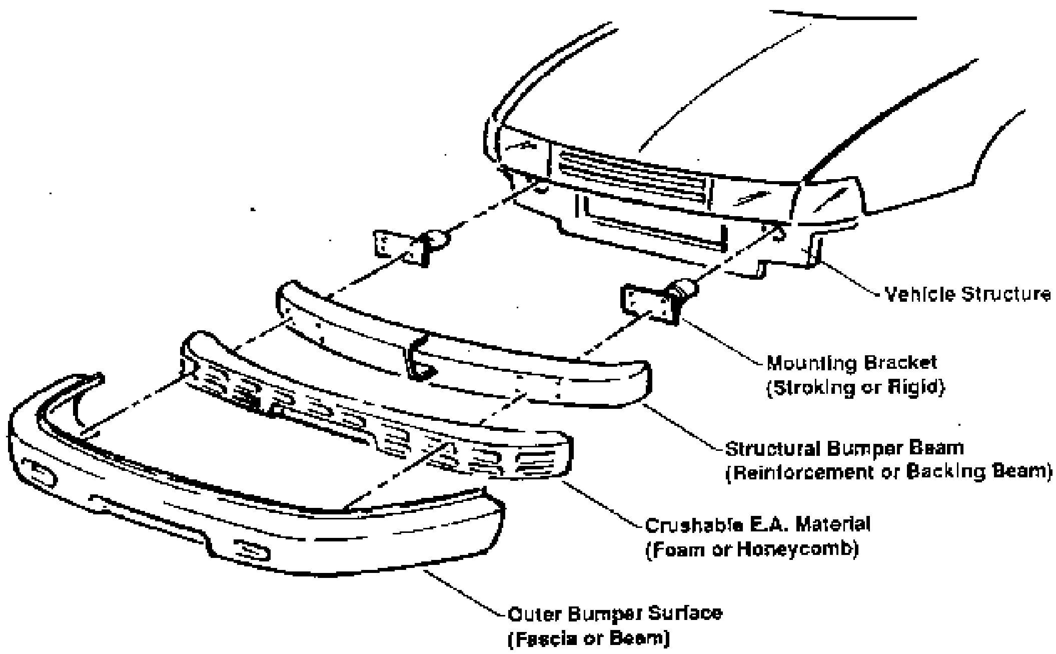


Figure 9.1 Bumber Components
(Credit K. C. Rusch. “An Overview of Automotive Plastic Bumpers” ,1990)

9.2 Information model

In this case study, a short description of the model is given first, followed by a schematic information model. The EXPRESS model is then translated to a flat EXPRESS model. Its role is to capture the relations, entities and their attributes. Next, an explicit layout of the C-FAR schema is given, including C-FAR matrices and change scenarios. Finally, two examples of change scenarios are provided, followed by a case study summary.

In this case study, the EXPRESS model captures the main components of the bumper on the one hand and the bumper tests on the other hand. The bumper entity has a “is_compound_of” relationship to the “Bumper_Component” entity. The “Bumper_Component” entity is a supertype entity for the four main bumper components: “Energy_Absorbent”, “Bumper_Beam”, “Bumper_Facia” and “Bumper_Brackets”. Also described in the schema are the two test type that are deployed on the bumper. Figure 9.2 is an EXPRESS-G diagram of the entities.A complete data and case study description is given in appendix C.   The EXPRESS schema is shown here:

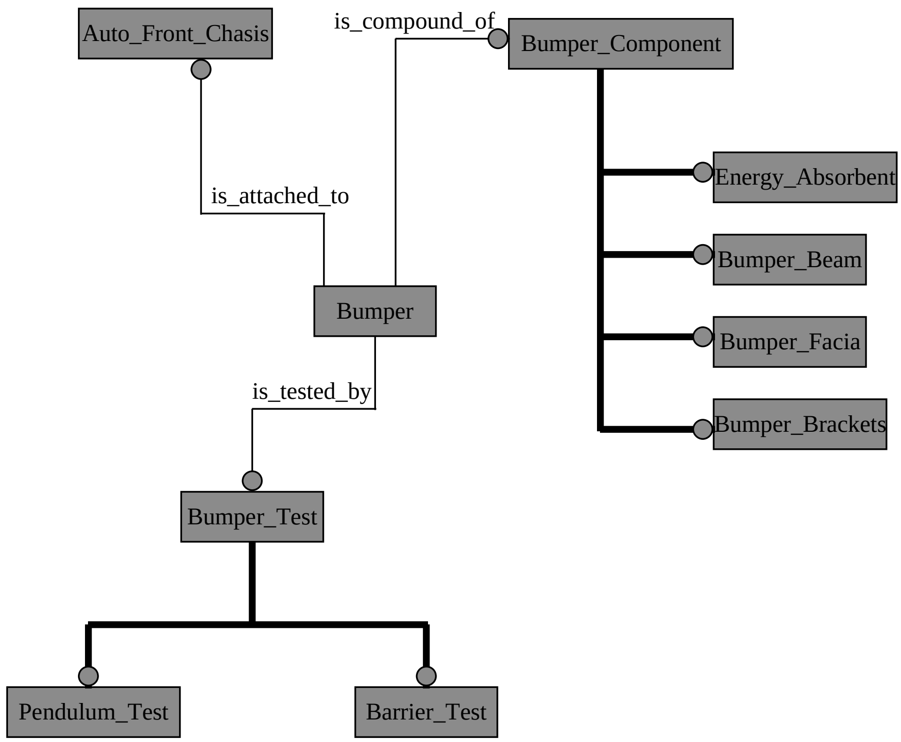


Figure 9.2 Bumper EXPRESS Model

9.3 C-FAR Analysis

9.3.1 Changeable Attribute List

Entity	Changeable Attributes
Bumper	weight length width depth height color offset styling_req corrosion_resistance_req weight _reduction_req damage_protection engine_cooling_req cost
Energy_Absorbent	part_ number weight length width

	depth cost material_code absorber_density absorber_pattern
Bumper_Beam	part_ number weight length width depth material_code beam_profile wall_thickness elas_module beam_type

Table 9.1 Changeable Attribute List

Entity	Changeable Attributes
Bumper_Facia	part_ number weight length width depth material_code facia_color facia_rigidity facia_process
Bumper_Brackets	part_ number weight length width depth bracket_mechanism max_deflection max_energy
Auto_Front_Chasis	base_high max_rail_load
Pendulum_Test	test_location pendulum_weight pendulum_speed
Barrier_Test	test_location test_velocity

Table 9.1 Changeable Attribute List (Cont.)

9.3.2 C-FAR Matrices

The following is a representative set of C-FAR matrices that are used in the scenarios. The complete set of C-FAR matrices is provided in appendix C.

Energy_Absorbent Bumper	weight	length	width	depth	absorber density	absorber pattern
part_assembly number	L/L	L/L	L/L	L/L	L/L	L/L
weight	H/H	M/M	M/M	M/M	L/H	L/M
length	M/M	H/H	L/L	L/L	M/L	L/L
width	M/M	L/L	H/H	L/L	M/L	L/L
depth	M/M	L/L	L/L	H/H	M/L	L/L
height	L/L	L/L	M/M	L/L	L/L	L/L
color	L/L	L/L	L/L	L/L	L/L	L/L
offset	L/L	L/L	L/L	H/H	L/L	L/L
styling_req.	L/L	M/L	H/L	H/L	L/L	M/L
corrosion. resistance_req.	L/L	L/L	L/L	L/L	L/L	L/L
weight_reduction req.	H/L	M/L	M/L	M/L	H/L	M/L
damage_protection req.	H/L	M/L	H/L	H/L	H/L	H/L
engine_cooling req.	L/L	L/L	M/L	M/L	M/L	H/L
cost	L/H	L/H	L/H	L/H	L/H	L/H

Table 9.2 Energy_Absorbent vs. Bumper

Bumper_Beam **Bumper**	part number	weight	length	width	depth	material code	beam profile
part_assembly number	H/H	L/L	L/L	L/L	L/L	L/L	L/L
weight	L/L	H/H	M/H	M/H	M/H	L/L	M/H
length	L/L	H/M	H/H	L/L	L/L	L/L	M/M
width	L/L	M/M	L/L	H/H	L/L	L/L	H/H
depth	L/L	M/M	L/L	L/L	H/H	L/L	H/H
height	L/L	L/L	L/L	M/M	L/L	L/L	L/H
color	L/L	L/L	L/L	L/L	L/L	L/L	L/L
offset	L/L	L/L	L/L	L/L	H/H	L/L	L/L
styling_req.	L/L	L/L	M/L	H/L	H/L	L/L	M/L
corrosion. resistance_req.	L/L	L/L	L/L	L/L	L/L	L/L	L/L
weight_reduction req.	L/L	H/L	H/L	H/L	H/L	L/L	H/L
damage_protection req.	L/L	H/L	H/L	H/L	H/L	L/L	H/L
engine_cooling req.	L/L	L/L	L/L	M/L	H/L	L/L	M/L
cost	L/L	L/H	L/H	L/H	L/H	L/L	L/H

Table 9.3 Bumper vs. Bumper_Beam

Bumper_Beam(cont) **Bumper**	wall thickness	elas module	beam type
part_assembly number	L/L	L/L	L/L
weight	M/H	M/H	M/H
length	M/M	M/M	M/M
width	M/H	M/M	M/M
depth	M/H	M/M	M/M

height	L/L	L/L	L/L
color	L/L	L/L	L/L
offset	L/L	L/L	L/L
styling_req.	L/L	L/L	M/L
corrosion. resistance_req.	M/L	M/L	H/L
weight_reduction req.	H/L	H/L	H/L
damage_protection req.	H/L	H/L	H/L
engine_cooling req.	M/L	M/L	H/L
cost	L/M	L/H	L/H

Table 9.3 Bumper vs. Bumper_Beam (cont)

Auto_Front_Chasis Bumper	base height	max_rail load
part_assembly number	L/L	L/L
weight	L/L	L/L
length	L/L	L/L
width	L/L	L/L
depth	L/L	L/L
height	H/H	L/L
color	L/L	L/L
offset	L/L	L/L
styling_req.	L/L	L/L
corrosion. resistance_req.	L/L	L/L
weight_reduction req.	L/L	L/L
damage_protection req.	H/L	H/L

engine_cooling req.	L/L	L/L
cost	L/M	L/H

Table 9.4 Auto_Front_Chasis vs. Bumper

Bumper_Brackets Bumper	weight	length	width	depth	bracket mech	max deflec.	max energy
part_assembly number	L/L	L/L	L/L	L/L	L/L	L/L	L/L
weight	M/H	L/M	L/M	L/M	L/L	L/L	L/L
length	L/L	L/L	L/L	L/L	L/L	L/L	L/L
width	L/L	L/L	H/H	L/L	L/L	L/L	L/L
depth	L/L	L/L	L/L	H/H	L/L	L/L	L/L
height	L/L	L/L	L/L	L/L	M/L	L/L	L/L
color	L/L	L/L	L/L	L/L	L/L	L/L	L/L
offset	L/L	L/L	L/L	H/H	L/L	H/H	M/M
styling_req.	L/L	H/L	H/L	H/L	M/L	M/L	M/L
corrosion. resistance_req.	L/L	L/L	L/L	L/L	L/L	L/L	L/L
weight_reduction req.	H/L	L/L	L/L	L/L	L/L	L/L	L/L
damage_protection req.	L/L	L/L	L/L	L/L	H/L	H/L	H/L
engine_cooling req.	L/L	L/L	L/L	L/L	L/L	L/L	L/L
cost	L/M	L/L	L/L	L/L	L/H	L/M	L/M

Table 9.5 Bumper_Brackets vs. Bumper

Pendulum_Test Bumper	test location	pendulum weight	pendulum speed
part_assembly number	L/L	L/L	L/L
weight	L/L	H/L	L/L
length	H/L	L/L	L/L
width	H/L	L/L	L/L
depth	L/L	L/L	L/L
height	L/L	L/L	L/L
color	L/L	L/L	L/L
offset	L/L	L/L	L/L
styling_req.	L/L	L/L	L/L
corrosion. resistance_req.	L/L	L/L	L/L
weight_reduction req.	L/L	L/L	L/L
damage_protection req.	H/L	H/L	H/L
engine_cooling req.	L/L	L/L	L/L
cost	L/L	L/H	L/M

Table 9.6 Pendulum_Test vs. Bumper

In this section, several engineering change scenarios are provided. Table 9.1 provides the changeable components in the C-FAR schema. This table serves as a knowledge pool from which elements will be chosen according the given scenarios.

9.3.3 Evaluation Bumper Model Scenario 1

How would a change in the energy absorbent length influences the bumper beam attributes? In this case, there is only one simple path, and this path passes from the "Energy_Absorbent" entity through the "bumper" entity to the "bumper beam" entity.
The change vector is: Δ Energy_Absorbent change vector = [0 0 Δ 0 0 0 0 0]
The path: Energy_Absorbent - Bumper - Bumper_beam.
$C(Energy\_Absorbent, Bumper)$ is extracted from Table 9.2.
Δ Energy_Absorbent change vector * $C(Energy\_Absorbent, Bumper)$ =

It propagate to be: $\Delta * \begin{bmatrix} L \\ M \\ H \\ L \\ L \\ L \\ L \\ L \\ L \\ L \\ L \\ L \\ H \end{bmatrix}$

Next, this vector is multiplied with $C(Bumper, Bumper\_Beam)$.
$C(Bumper, Bumper\_Beam)$ is extracted from Table 9.3

$$\Delta * \begin{bmatrix} L \\ M \\ H \\ L \\ L \\ L \\ L \\ L \\ L \\ L \\ L \\ L \\ H \end{bmatrix} * C(Bumper, Bumper\_Beam) = \Delta path1\_Bumper\_Beam$$

$$\text{Orth}(\Delta path1\_Bumper\_Beam) = \Delta Path(1) = \Delta * \begin{bmatrix} L \\ H \\ H \\ 0.09 \\ 0.09 \\ L \\ 0.09 \\ 0.09 \\ 0.09 \\ 0.09 \end{bmatrix}$$

9.3.4 Results Analysis

The results repress the influence of a change on the length attribute of the energy absorbent entity on the attributes of the bumper beam entity. Three classes of influence can be observed. The first class is the attributes that are strongly influenced by a change in the energy absorbent length. It is expected that as the bumper beam length will change, so will its weight .The second group of attributes have calculated linkage of 0.09 and the third attribute group have a linkage value of L. It is interesting to point out that the attributes that belong to the second group are describing physical characteristics of the bumper beam that are not directly related to the given change in the energy absorbence. The 0.09 linkage value hints that those attributes, like the bumper beam width or depth, are not as closely linked to the given change as the bumper beam length. However those attributes are more linked to the given change than to the part number attribute.

9.3.5 Evaluation Bumper Model Scenario 2

How would a change to the automobile chassis height influence the bumper beam ?

The change vector for the Auto Front Chassis is: $[\Delta \;\; 0]$

This entity has two attributes, the base height, which is a dimension representing the elevation of the automobile chassis from the ground. The maximum rail load is the second attribute of the "Auto Front Chassis". In this scenario, the examined change is originated in the first attribute. The first target entity is the bumper entity. The only simple path from the source entity to the target entity passes through the bumper entity. $C(Auto\_Front\_Chassis, Bumper)$ is extracted from Table 9.4.

$$[\Delta \;\; 0] * C(Auto\_Front\_Chassis, Bumper) = [\Delta \;\; 0] * \begin{bmatrix} L\,L \\ L\,L \\ L\,L \\ L\,L \\ L\,L \\ H\,L \\ L\,L \\ L\,L \\ L\,L \\ L\,L \\ L\,L \\ L\,L \\ L\,L \\ M\,H \end{bmatrix}^T =$$

$$= \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ H \\ L \\ L \\ L \\ L \\ L \\ L \\ L \\ M \end{bmatrix} = \Delta \text{ bumper}$$

The height change to the "Auto Front Chassis" is highly linked to a the height of the bumper and has a linkage value of "M" with the bumper cost. However, it is less likely to influence other parameters of the bumper. The influence on the energy bumper beam is given by multiplying Δ bumper and $C(Bumper, Bumper\_Beam)$

$$\Delta \text{ bumper} * C(Bumper, Bumper\_Beam) = \begin{bmatrix} L \\ L \\ L \\ 0.27 \\ L \\ L \\ L \\ L \\ L \\ L \end{bmatrix}$$

where
$C(Bumper, Bumper\_Beam)$ is given in 9.3

9.3.6 Results Analysis

The only attribute of the bumper beam that does not have an "L" linkage value is the width. The value 0.27 is close to the value 0.3 that represents "M" linkage value.

This linkage value hints that a change in the chassis height somewhat influences the width of the bumper beam, but its not likely to influence any other attributes of the bumper beam.

9.3.7 Evaluation Bumper Scenario 3

How would a change in the automobile chassis height influence the bumper brackets? The change vector for the Auto Front Chassis is: [Δ 0]. The simple path from the source entity to the target entity passes through the bumper entity. Therefore the propagation path includes C-FAR matrices 9.4.

$$[\Delta \;\; 0] * C(Auto\_Front\_Chassis, Bumper) = [\Delta \;\; 0] * \begin{bmatrix} L & L \\ L & L \\ L & L \\ L & L \\ L & L \\ H & L \\ L & L \\ L & L \\ L & L \\ L & L \\ L & L \\ L & L \\ L & L \\ M & H \end{bmatrix}^T =$$

$$= \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ H \\ L \\ L \\ L \\ L \\ L \\ L \\ L \\ M \end{bmatrix} = \Delta \text{ bumper}$$

The influence on the bumper brackets is given by multiplying Δ bumper and $C(Bumper, Bumper\_Brackets)$, given in Table 9.5.

$$\Delta \text{ bumper} * C(Bumper, Bumper\_Brackets) = \begin{bmatrix} L \\ L \\ L \\ L \\ 0.27 \\ L \\ L \\ L \end{bmatrix}$$

9.3.8 Results Analysis

The only attribute of the bumper bracket that does not have an "L" linkage value is the bracket mechanism. The value 0.27 is close to the value 0.3 that represents the "M" linkage value. This linkage value hints that a change in the chassis height may influence the choice of the bumper brackets mechanism. However, it is not likely to influence any other attributes of the bumper brackets.

9.3.9 Evaluation Bumper Scenario 4

How would a change to the automobile chassis height relate to the pendulum test attributes? There is one simple path that leads from the Auto_Front_Chassis entity to the Pendulum Test entity: “Auto_Front_Chassis” - “Bumper” - “Pendulum_Test”.
The change vector for the Auto Front Chassis is: [Δ 0]. The simple path from the source entity to the target entity passes through the bumper entity. Therefore the propagation path includes C-FAR matrices 9.4.

$$[\Delta \;\; 0] * C(Auto\_Front\_Chassis, Bumper) = [\Delta \;\; 0] * \begin{bmatrix} L\,L \\ L\,L \\ L\,L \\ L\,L \\ L\,L \\ H\,L \\ L\,L \\ L\,L \\ L\,L \\ L\,L \\ L\,L \\ L\,L \\ L\,L \\ M\,H \end{bmatrix}^T =$$

$$= \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ H \\ L \\ L \\ L \\ L \\ L \\ L \\ L \\ M \end{bmatrix} = \Delta \text{ bumper}$$

The influence on the pendulum test entity is given by multiplying Δ bumper and $C(Bumper, Pendulum\_Test)$, given in Table 9.6.

$$\Delta \text{ bumper} * C(Bumper, Pendulum\_Test) = \begin{bmatrix} L \\ L \\ L \end{bmatrix}$$

9.3.10 Results Analysis

The vector $\begin{bmatrix} L \\ L \\ L \end{bmatrix}$ indicates that the change to the automobile chassis elevation does not influences any of the pendulum test attributes.

Chapter 10

Printed Wiring Board Model Case Study

10.1 Introduction

Printed Wiring Boards (PWBs) are made up of one or more layers of circuitry bonded onto insulate substrates. PWBs are used in almost all electrical integrated circuits. PWBs provide mechanical support to the electronic components as well as electrical connectivity between layers. PWBs are better than conventional wiring because they provides superior packaging density as well as highly reliable and predictable electrical performance. More informatiom about this domain is given in [Lynch, 1989]

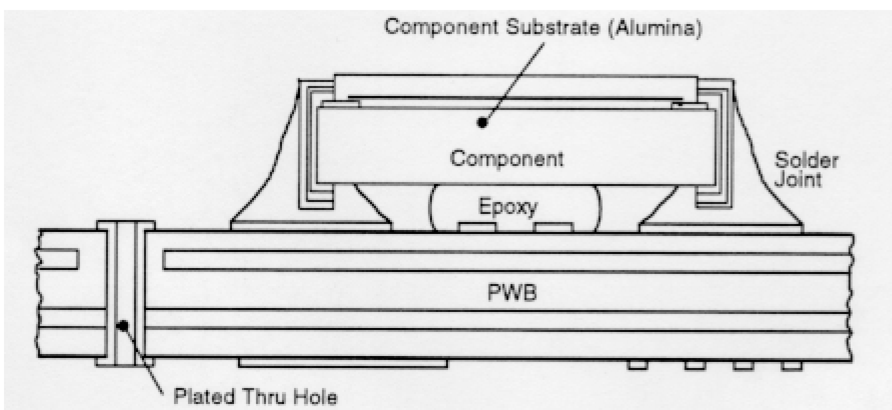


Figure 10.1 Example PWB
(Credit R.S.Peak 93)

PWBs withstand temperature loading that can cause warpage. Figure 10.2 illustrates a PWB warpage.

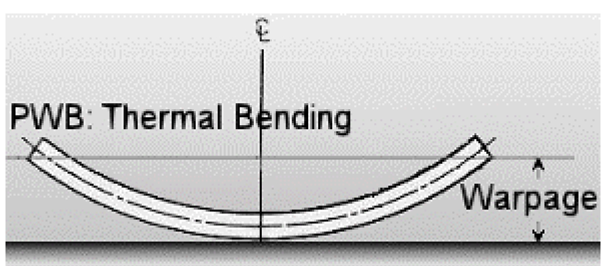


Figure 10.2 PWB Thermal Bending Warpage Model
(Credit R.S.Peak 93)

10.2 Information Model

This case study examines PWBs and their relations to PWB thermal models. Some of the main components in this schema are the PWB, PWB thermal model, and the Printed Wiring Assembly, which is associated with the Printed Wiring Board. Three types of possible layers are described in the schema: PWB Copper layer, Prepreg set, and PWB copper-cladded laminate. The PWA entity describes the component construction in the PWB. The PWB is the bare board and its thermal bending behavior is described by the entity PWB thermal bending model. Each electrical component has an electrical package and a components occurrences entity which is described by its surface and location. More detailed discussion on PWB technology and thermal bending model is given in [Engelmaier, 89]. A complete C-FAR model for the PWB case study is give in D.

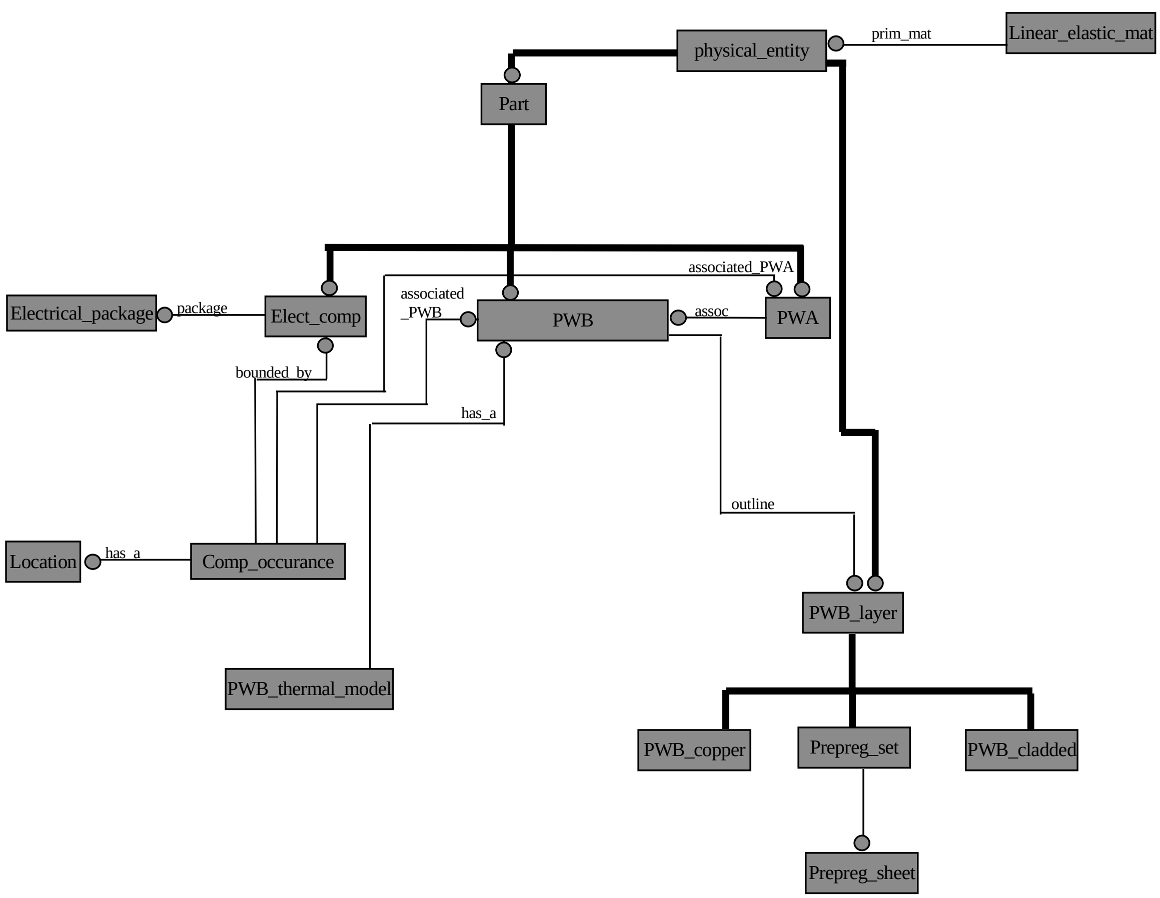


Figure 10.3 PWB EXPRESS Model

10.3 C-FAR Analysis

10.3.1 Changeable Attribute List

Entity	Changeable Attributes
Location	rot0, x0 y0 z0
linear_elastic_material.PWB_Copper	manufacturer name youngs_modulus shear_modulus cte poissons_ratio
linear_elastic_material.Elect_copm	manufacturer name youngs_modulus shear_modulus cte poissons_ratio
linear_elastic_material.PWB	manufacturer name youngs_modulus shear_modulus cte poissons_ratio
linear_elastic_material.PWA	manufacturer name youngs_modulus shear_modulus cte poissons_ratio
linear_elastic_material.Prepreg_set	manufacturer name youngs_modulus shear_modulus cte poissons_ratio

Table 10.1 Changeable Attributes

Entity	Changeable Attributes
pwb_thermal_bending_model	length thickness CTB

	reference_temperature associated_temperature temperature_change warpage
electrical_component	description total_length total_width total_height primary_structural_material part_number cost magnitude tolerance power_rating
pwb	description total_length total_width total_height primary_structural_material part_number cost min_required_finished_thickness nominal_required_finished_thickness maximum_required_finished_thickness miminum_required_laminated_thickness nominal_required_laminated_thicknessm aximum_required_laminated_thickness coefficient_of_thermal_bending total_diagonal

Table 10.1 Changeable Attributes(Cont.)

Entity	**Changeable Attributes**
pwb_copper	description total_length total_width total_height primary_structural_material

	weight_per_unit_area layer_function min_thickness nominal_thickness max_thickness percent_etched
pwb_prepreg_set	description total_length, total_width total_height primary_structural_material
pwb_prepreg_sheet	prepreg_id min_thickness nominal_thickness max_thickness ho
pwb_copper_cladded_laminate	description total_length total_width total_height primary_structural_material laminate_id top_copper_layer bottom_copper_layer
pwa	description total_length total_width total_height primary_structural_material part_number cost
component_occurrence	reference_designator associated_location surface

Table 10.1 Changeable Attributes (Cont.)

10.3.2 C-FAR Matrices

The following is a representative set of C-FAR matrices that are used in the scenarios. The complete set of C-FAR matrices is provided in appendix D.

PWB **PWB Copper**	Description	Total length	Total width	Total height	Cost	Part number	Total diagonal

Description	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Total length	L/L	H/H	M/M	L/L	H/M	L/L	H/M
Total width	L/L	M/M	H/H	L/L	H/M	L/L	H/M
Total height	L/L	M/M	M/M	H/H	H/M	L/L	L/L
Nom. Thick	L/L	M/M	M/M	H/H	H/M	L/L	L/L
Max. Thick	L/L	M/M	M/M	H/H	H/M	L/L	L/L
Min thick	L/L	M/M	M/M	H/H	H/M	L/L	L/L
Layer function	L/L	L/L	L/L	H/L	H/L	L/L	L/L
Weight	L/L	M/M	M/M	H/H	H/M	L/L	L/L

Table 10.2: PWB vs. Pwb_copper

PWB **PWB Copper**	CTB	Nominal req L thickness	Max. L req thickness	Min. L req thickness
Description	L/L	L/L	L/L	L/L
Total length	L/L	L/L	L/L	L/L
Total width	L/L	L/L	L/L	L/L
Total height	H/M	L/H	L/H	L/H
Nom. Thick	H/M	L/H	L/H	L/H
Max. Thick	H/M	L/H	L/H	L/H
Min thick	H/M	L/H	L/H	L/H
Layer function	H/L	L/M	L/M	L/M
Weight	H/M	L/H	L/H	L/H

Table 10.2 PWB vs. Pwb_copper (Comt.)

PWB **PWB Copper**	Nominal req F thickness	Max. F req thickness	Min. F req thickness	Size_of_layup
Description	L/L	L/L	L/L	L/L
Total length	L/L	L/L	L/L	L/L
Total width	L/L	L/L	L/L	L/L
Total height	L/H	L/H	L/H	L/M
Nom. Thick	L/H	L/H	L/H	L/M
Max. Thick	L/H	L/H	L/H	L/M

Min thick	L/H	L/H	L/H	L/M
Layer function	L/M	L/M	L/M	M/M
Weight	L/H	L/H	L/H	L/M

Table 10.2: PWB vs. Pwb copper (Cont.)

Thermal Model **PWB**	Length	Thickness	CTB	Reference Temp	Associated Temp	Temp Change	Warpage
Description	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Total length	H/H	L/L	M/L	L/L	L/L	L/L	H/M
Total width	L/L	L/L	M/L	L/L	L/L	L/L	H/M
Total height	L/L	H/H	M/L	L/L	L/L	L/L	H/M
Cost	L/L	L/L	L/M	L/L	L/L	L/L	M/M
Part Number	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Total Diagonal	M/H	L/L	M/L	L/L	L/L	L/L	H/M
CTB	L/L	L/L	H/H	L/L	L/L	L/L	H/M
Nominal req L thickness	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Max. L req thickness	L/L	L/L	L/L	L/L	L/L	L/L	L/L

Min. L req thickness	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Nominal req F thickness	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Max. F req thickness	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Min. F req thickness	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Size_of_layup	L/L	H/M	H/M	L/L	M/L	M/L	H/L

Table 10.3 PWB vs. PWB Thermal Model

Component occur. **PWB**	Reference Designator	Surface
Description	L/L	L/L
Total length	L/L	M/L
Total width	L/L	M/L
Total height	L/L	M/L
Cost	L/L	L/L
Part Number	L/L	L/L
Total Diagonal	L/L	M/L
CTB	L/L	M/L
Nominal req L thickness	L/L	M/L
Max. L req thickness	L/L	M/L
Min. L req thickness	L/L	M/L
Nominal req F thickness	L/L	M/L
Max. F req thickness	L/L	M/L
Min. F req thickness	L/L	M/L

Size_of_layup	L/L	L/L

Table 10.4 PWB vs. Component Occurrence

Elect Package **Component**	Body style id	Inter solder joint distance
Description	L/L	L/L
Total length	H/H	H/H
Total width	H/H	H/H
Total height	H/H	L/L
Cost	M/H	L/M
Part Number	L/L	L/L
Magnitude	L/L	L/L
Tolerance	L/L	L/L
Power rating	M/M	L/L

Table 10.5 Electrical Component vs. Electrical Package

Component Occurrence **Electrical Component**	Reference Designator	Surface
Description	L/L	L/L
Total length	L/L	L/L
Total width	L/L	L/L
Total height	L/L	M/M
Cost	L/L	L/L
Part Number	L/L	L/L
Magnitude	L/L	L/L
Tolerance	L/L	L/L
Power rating	L/L	M/M

Table 10.6 Electrical Component vs. Component Occurrence

Component occurrence **PWA**	Reference Designator	Surface
Total Length	L/L	M/M
Total Width	L/L	M/L
Total Height	L/L	M/L
Cost	L/L	L/L
Part Number	L/L	L/L
# of components	L/L	M/L
Assembly order	M/M	L/H
Number of Sides	L/L	H/H

Table 10.7 PWA vs. Component Occurrence

10.3.3 Evaluation PWB Case Study Scenario 1

In this section, several engineering change scenarios are provided. Table 10.1 provide the changeable components in the C-FAR schema. This table serves as a knowledge pool from which elements will be chosen according the given scenarios. How would a change to the PWB Copper layer function changes the PWB thermal model? PWB Copper layer(description, total_length, total_width, total_height, nom_thickness, max_thickness, min_thickness, layer_function, weight). PWB Copper layer change vector has the following form: [0, 0, 0, 0, 0, 0, 0, Δ, 0] The target entity is PWB_Thermal_Model. There is one simple path, PWB Copper layer - PWB - PWB_Thermal_Model. The change vector is multiplied by the C-FAR matrix that relates PWB Copper layer to PWB. $C(PWB\_Copper\_Layer, PWB)$ is given in Table 10.2.

$\Delta path1\_PWB$ = [0, 0, 0, 0, 0, 0, 0, Δ, 0] * $C(PWB\_Copper\_Layer, PWB)$ =

= Δ * [L L L H H L L H L L L L L L M]^T

The PWB attributes that have linkage value of "H" are the height, cost and Coefficient of Thermal Bending (CTB). Most of the rest of the PWB attributes linkage values indicate indifference to a change in the PWB Copper layer function. $C(PWB, PWB\_Thermal\_Model)$ is extracted from Table 10.3.

$$\Delta path1\_PWB\_Thermal\_Model = \Delta * \Delta path1\_PWB *$$

$$* C(PWB, PWB\_Thermal\_Model) = \Delta * \begin{bmatrix} L \\ HH + MH \\ MH + HH + HM \\ L \\ MM \\ MM \\ HH + MH + HM \end{bmatrix}$$

$$\text{Orth}(\Delta path2\_PWB\_Thermal\_Model) = \Delta * \begin{bmatrix} L \\ H \\ H \\ L \\ 0.09 \\ 0.09 \\ H \end{bmatrix} = \Delta Path(1)$$

10.3.4 Results analysis

The results indicate that a change in the layer function of the "PWB_Copper" will strongly influence the thickness, CTB and warpage attributes of the PWB Thermal Model. The associated temperated and the temperature change attributes are both somewhat influenced by a the change in the layer function of the "PWB_Copper".

10.3.5 Evaluation PWB Case Study Scenario 2

How would a change to the Electrical Package body style influence the PWA entity ? There are two simple paths that start at the electrical package entity and end at the PWA. The first is Electrical_Package - Electrical_Componenet - Component_Occurance - PWB - PWA. $C(Component\_Occurance, PWB)$ is extracted from Table 10.4.

However, $C(Component\_Occurance, PWB)$ is compound of all low linkage values .

Therefore path1 contribution is $\Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ L \\ L \\ L \end{bmatrix} = \Delta Path(1)$

The second simple path that leads from the component electrical package entity to the PWA passes through the entities "electrical component" and "component occurrence". The path is: Electrical_Package - Electrical_Componenet - Component_Occurence-PWA. The change vector for the electrical package is:

$\Delta path1\_Electrical\_Package = [\Delta\ \ 0]$

$C(Electrical\_Package, Electrical\_Component)$ is extracted from Table 10.5.

$\Delta path1\_Electrical\_Component = \Delta path1\_Electrical\_Package *$

$C(Electrical\_Package, Electrical\_Component) =$

$$= \Delta * \begin{bmatrix} L \\ H \\ H \\ H \\ H \\ L \\ L \\ L \\ M \end{bmatrix}$$

Where $C(Electrical\_Package, Electrical\_Component)$ 10.5. is the semi C-FAR matrix that relates Electrical_Package entity to the Electrical_Component entity. Next, in the path is the entity Component_Occurrence.

$C(Component\_Occurrence, Electrical\_Component)$ is extracted from Table 10.6.

$\Delta path1\_Component\_Occurrence = \Delta path1\_Electrical\_Component *$

$C(Component\_Occurrence, Electrical\_Component) = \Delta * \begin{bmatrix} L \\ MH + MM \end{bmatrix}$

$$\text{Orth}(\Delta path1\_Component\_Occurrence) = \Delta * \begin{bmatrix} L \\ 0.29 \end{bmatrix}$$

Where $C(Component\_Occurrence, Electrical\_Component)$ 10.6 is the semi C-FAR matrix that relates the "Electrical_Component" entity to the "component occurrence" entity. The "component occurrence" entity has two attributes. The first one, "reference designator" is indifferent to a change to the electrical package body style. However, the attribute "surface", which is interrelated to the component height, is somewhat influenced by the original change. The next entity in the path is the PWA.
$C(PWA, Component\_Occurrence)$ is extracted from Table 10.7.

$$\Delta path1\_PWA = \Delta * \begin{bmatrix} L \\ 0.29 \end{bmatrix} * C(PWA, Component\_Occurrence) == \Delta * \begin{bmatrix} 0.08 \\ L \\ L \\ L \\ L \\ L \\ 0.26 \\ 0.26 \end{bmatrix} =$$

$$= \Delta Path(2)$$

$$\text{Total influence} = \sum_{i=1}^{n} \Delta Path(i) = \Delta Path(1) + \Delta Path(2) = \Delta * \begin{bmatrix} 0.08 \\ L \\ L \\ L \\ L \\ L \\ 0.26 \\ 0.26 \end{bmatrix}$$

10.3.6 Results Analysis

These results represent the linkage from path2. Therefore, it is the maximum and the minimum value for the result interval. The calculated linkage values between the electrical package body style and the PWA are not high. The PWA length, assembly order, and number of sides are somewhat influenced from the given change.

Chapter 11

Injection Molding Model Case Study

11.1 Introduction

Injection molding is a plastics processing activity. The plastic is raised, pressure is applied, and the plastic is injected into a mold. The first injection molding patent was issued in 1872. However, the complexity of the process was not completely understood until the 1950s. The process is complex because it involves a combination of temperature conditions and mechanical loads. As Figure 11.1 illustrates, the plastic material is heated and then injected to a machine. The machine uses a piston that presses heats and injects the plastic to a mold. The plastic parts geometry and in turn the mold geometry can be very complex. The complexity of the geometry makes the injection molding process even more difficult. The plastic part should not have undesirable holes, should be free of unnecessary molding marks, and have a long list of structural and aesthetic requirements. Both the machine and the mold should maintain a tight control on the physical attributes of the process. Most of the information for this case study was taken from [Rosato, 87].

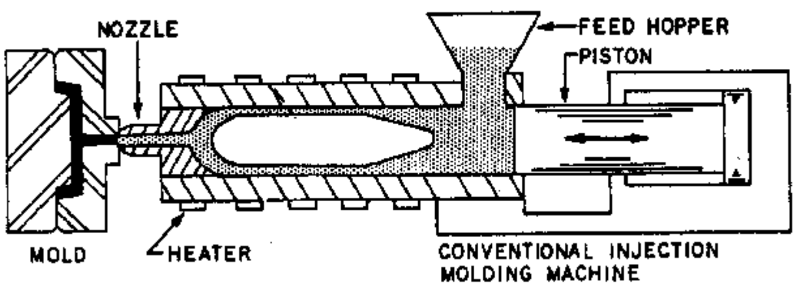


Figure 11.1 Injection Molding Machine
(Credit Picture Rosato, 87)

11.2 Information model

The EXPRESS-G model given in Figure 11.2 illustrates the main components of the injection molding process. At the heart of the EXPRESS schema is the injection molding process. This process uses the entities “machine”, “material”, “part mold coolant” and “cavity core material”. The part entity represents the injection molding product. The material is the plastic material used in the process. The machine is the machine used for a specific molding. The process also uses a mold coolant as well as a cavity core material. The part is molded by a mold and it has a geometry. The part is molded by the molder and the part geometry is described by the entity part geometry. The cavity core geometry is derived from the part geometry. Finally, the mold maker manufactures the mold. Since the injection molding process involves many parameters, this EXPRESS schema includes more than one hundred attributes.

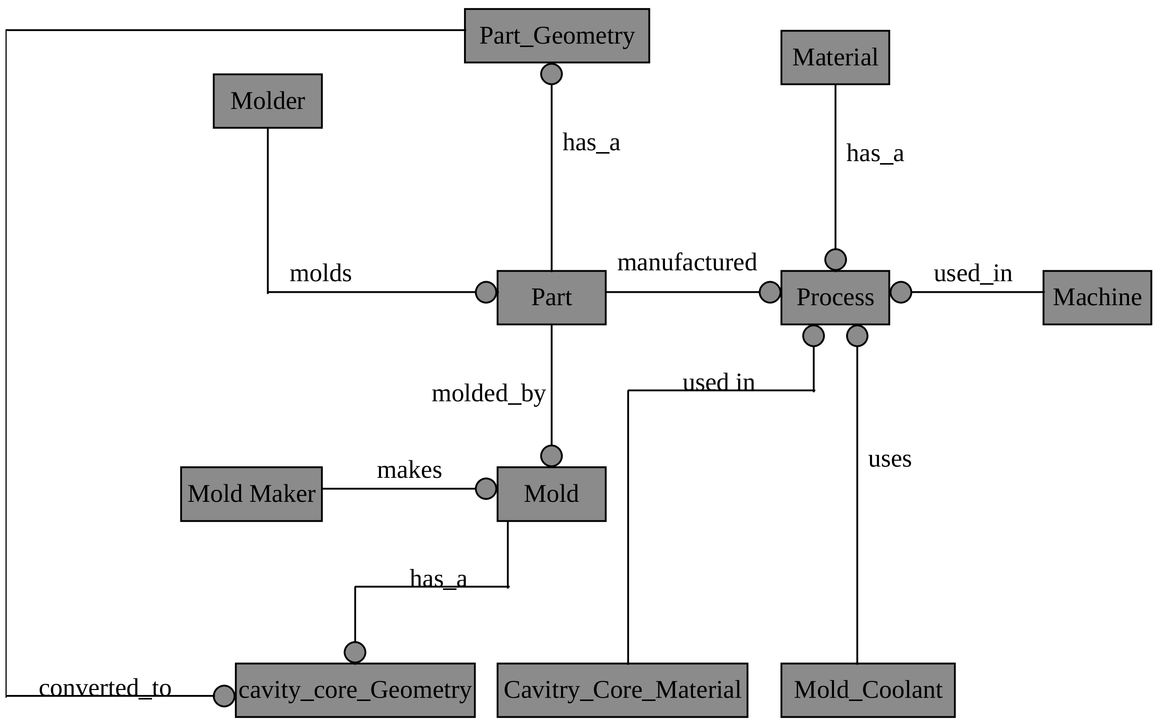


Figure 11.2 An Injection Molding EXPRESS-G Information Model

11.3 C-FAR Analysis

11.3.1 Changeable Attribute List

Entity	Changeable Attributes
Molder	name address equipment condition equipment specs design facilities workforce size simulation facilities track record
Mold Maker	name address equipment condition equipment specs design facilities workforce size sampling facilities simulation facilities track record
Mold	tool number number of cavities mold type production/prototype cost
Cavity-Core-Material	name density specific heat capacity thermal conductivity wear resistance

Table 11.1 Changeable Attribute List

Entity	Changeable Attributes
Part	part number ec-level assembly-level

	description aesthetic req. structural req. quantity req. demand/month enviro-restriction finish-req., cost sink-mark weld-line-location warpage shrinkage
Cavity-Core-Geometry	side-action-mech. ejection-type sprue-specs runner-specs gate-specs delivery-sys-volume water-line-diam. Water-line-pitch
Process	barrel-temp-zone-1 barrel-temp-zone-2 barrel-temp-zone-3 mold-temp injection-pressure packing-pressure holding-pressure-profile clamping-force fill-time pack-time holding-time cooling-time open-time, shot-size coolant-flow-rate

Table 11.1 Changeable Attribute List (Cont.)

Entity	**Changeable Attributes**
Material	name company-name grade-core specific-heat-vs-temp thermal-conductivity-vs-temp

	density transition-temp viscosity-vs-shear-rate izod-strength elastic-modulus shear-strength flextural-strength mold-shrinkage-flow-direction mold-shrinkage-perpendicular-to-flow melt-flow-index(mfi) hardness
Machine	max-shot-size max-injection-rate max-injection-pressure max-screw-speed max-clamping-force daylight-opening min-mold-thickness max-mold-thickness tie-rod-distance max-coolant-flow-rate
Mold-Coolant	name density specific-heat-capacity thermal-conductivity viscosity
Part-Geometry	wall-thickness undercuts tolerances internal-threads blind-holes gate-locations

Table 11.1 Changeable Attribute List (Cont.)

11.3.2 C-FAR Matrices

Follwing is a representative set of C-FAR matrices that are used in the scenarios. The complete set of C-FAR matrices is provided in appendix E.

Part Geometry **Part**	Wall Thickness	Undercuts	Tolerances	Internal Thread	Blind Holes	Gate Locations
Part #	L/L	L/L	L/L	L/L	L/L	L/L
EC level	L/L	L/L	L/L	L/L	L/L	L/L

Assembly level	L/L	L/L	L/L	L/L	L/L	L/L
Description	L/L	L/L	L/L	L/L	L/L	L/L
Aesthetic Req	L/L	M/L	L/L	M/L	M/L	H/L
Structural Req	M/L	L/L	L/L	M/L	L/L	M/L
Quantity reqd/system	L/L	L/L	L/L	L/L	L/L	L/L
Demand/month	L/L	L/L	L/L	L/L	L/L	L/L
Environ. Restrictions	L/L	L/L	L/L	L/L	L/L	L/L
Finish req	L/L	L/L	L/L	L/L	L/L	L/L
Cost	L/M	L/H	L/H	L/H	L/H	L/M
sink marks	L/M	L/L	L/L	L/L	L/L	M/M
weld line location	M/H	L/M	L/L	L/M	L/M	M/H
warpage	M/M	L/M	L/L	L/L	L/L	M/M
shrinkage	L/L	L/L	L/M	L/L	L/L	L/M

Table 11.2 Part Geometry vs. Part

Cavity_Core Geometry **Part Geometry**	Side Action Mechanism	Ejection Type	Sprue Specs	Runner Specs
Wall Thickness	L/L	M/L	M/L	H/L
Undercuts	H/L	M/L	L/L	L/L
Tolerances	L/L	L/L	L/L	L/L
Internal Threads	L/L	M/L	L/L	M/L
Blind Holes	H/L	M/L	L/L	M/L
Gate Locations	M/M	M/L	M/L	H/L

Table 11.3 Part Geometry vs. Cavity Core Geometry

Cavity_Core Geometry **Part Geometry**	Gate Specs	Delivery System Volume	Water Line Diameter	Water Line Pitch
Wall Thickness	H/L	H/L	H/L	H/L
Undercuts	M/L	L/L	M/L	M/L
Tolerances	L/L	L/L	L/L	L/L
Internal Threads	M/L	M/L	M/L	M/L
Blind Holes	M/L	M/L	M/L	M/L
Gate Locations	H/M	H/L	M/L	M/L

Table 11.3 Part Geometry vs. Cavity Core Geometry (Cont.)

Cavity_Core Geometry **Mold**	Side Action Mechanism	Ejection Type	Sprue Specs	Runner Specs
Tool Number	L/L	L/L	L/L	L/L
Number of cavities	M/M	M/L	M/L	H/L
Mold Type	L/L	L/L	M/L	M/L
Production or Prototype	L/L	L/L	L/L	L/L
Cost	L/H	L/M	L/L	L/M
Max number of parts	L/L	L/L	L/L	L/L
Minimum Clamping force	L/L	L/L	L/L	L/M

Table 11.4 Mold vs. Cavity Core Geometry

Cavity_Core Geometry **Mold**	Gate Specs	Delivery System Volume	Water Line Diameter	Water Line Pitch
Tool Number	L/L	L/L	L/L	L/L
Number of cavities	L/L	H/L	M/L	M/L
Mold Type	M/L	M/L	M/L	M/L
Production or Prototype	L/L	L/L	L/L	L/L
Cost	L/L	L/M	L/L	L/M
Max number of parts	L/L	L/L	L/L	L/L
Minimum Clamping force	L/M	L/M	L/L	L/L

Table 11.4 Mold vs. Cavity Core Geometry (Cont.)

Cavity_Core Material **Process**	Name	Density	Specific Heat Capacity	Thermal Conductivity	Wear Resistance
Barrel temp-zone 1	L/L	L/M	M/M	M/M	M/M
Barrel temp-zone 2	L/L	L/M	M/M	M/M	M/M
Barrel temp-zone3	L/L	L/M	M/M	M/M	M/M
Mold temp	L/L	L/L	M/M	M/M	M/M
Injection Pressure	L/L	M/M	M/M	M/M	M/M
Packing Pressure	L/L	L/L	M/M	M/M	M/M
Holding Pressure Profile	L/L	L/L	M/M	M/M	M/M
Clamping force	L/L	L/M	M/M	M/M	M/M
Fill time	L/L	L/M	M/M	M/M	M/M
Pack time	L/L	L/M	M/M	M/M	M/M
Holding time	L/L	L/M	M/M	M/M	M/M
Cooling time	L/L	L/M	M/M	M/M	M/M
Open time	L/L	L/L	L/L	L/L	L/L
Shot size	L/L	L/L	L/L	L/L	L/L

Coolant Flow Rate	L/L	L/M	M/M	M/M	M/M

Table 11.5 Process vs. Cavity Core Material

Mold Coolant **Process**	Name	Density	Specific Heat Capacity	Thermal Conductivity	Viscosity
Barrel temp-zone 1	L/L	L/L	L/L	L/L	L/L
Barrel temp-zone 2	L/L	L/L	L/L	L/L	L/L
Barrel temp-zone3	L/L	L/L	L/L	L/L	L/L
Mold temp	L/L	M/H	M/H	M/H	L/M
Injection Pressure	L/L	L/L	L/L	L/L	L/L
Packing Pressure	L/L	L/L	L/L	L/L	L/L
Holding Pressure Profile	L/L	L/L	L/M	L/M	L/L
Clamping force	L/L	L/L	L/L	L/L	L/L
Fill time	L/L	L/L	L/L	L/L	L/L
Pack time	L/L	L/L	L/L	L/L	L/L
Holding time	L/L	L/L	L/M	L/M	L/L
Cooling time	L/L	M/M	H/H	H/H	M/M
Open time	L/L	L/L	L/L	L/L	L/L
Shot size	L/L	L/L	L/L	L/L	L/L
Coolant Flow Rate	L/L	L/M	L/M	L/M	L/M

Table 11.6 Process vs. Mold Coolant

Mold **Part**	Tool Number	Number of cavities	Mold Type	Production or Prototype
Part #	L/L	L/L	L/L	L/L
EC level	L/L	L/L	L/L	L/L
Assembly level	L/L	L/L	L/L	L/L
Description	L/L	L/L	L/L	L/L
Aesthetic Reqts	L/L	L/L	L/L	L/L
Structural Reqts	L/L	L/L	L/L	L/L
Quantity reqd/system	L/L	L/L	L/L	L/L
Demand/month	L/L	M/L	M/L	L/L
Environ. Restrictions	L/L	L/L	L/L	L/L
Finish reqd	L/L	L/L	L/L	L/L
Cost	L/L	L/M	L/M	L/M
sink marks	L/L	L/L	L/M	L/L
weld line location	L/L	L/L	L/L	L/L
warpage	L/L	L/L	L/M	L/L
shrinkage	L/L	L/L	L/M	L/L

Table 11.7 Part vs. Mold

Mold Part	Cost	Max number of parts	Minimum Clamping force
Part #	L/L	L/L	L/L
EC level	L/L	L/L	L/L
Assembly level	L/L	L/L	L/L
Description	L/L	L/L	L/L
Aesthetic Reqts	M/L	L/L	L/L
Structural Reqts	M/L	L/L	L/L
Quantity reqd/system	L/L	L/L	L/L
Demand/month	M/L	L/L	L/L
Environ. Restrictions	L/L	L/L	L/L
Finish reqd	H/L	M/L	L/L
Cost	L/H	L/H	L/L
sink marks	M/L	L/L	M/M
weld line location	L/L	L/L	L/L
warpage	M/L	L/L	M/M
shrinkage	L/L	L/L	M/M

Table 11.7 Part vs. Mold (Cont.)

Cavity_Core Geometry Mold	Side Action Mechanism	Ejection Type	Sprue Specs	Runner Specs
Tool Number	L/L	L/L	L/L	L/L
Number of cavities	M/M	M/L	M/L	H/L
Mold Type	L/L	L/L	M/L	M/L
Production or Prototype	L/L	L/L	L/L	L/L
Cost	L/H	L/M	L/L	L/M
Max number of parts	L/L	L/L	L/L	L/L
Minimum Clamping force	L/L	L/L	L/L	L/M

Table 11.8 Cavity Core Geometry vs. Mold

Cavity_Core Geometry Mold	Gate Specs	Delivery System Volume	Water Line Dia	Water Line Pitch
Tool Number	L/L	L/L	L/L	L/L

Number of cavities	L/L	H/L	M/L	M/L
Mold Type	M/L	M/L	M/L	M/L
Production or Prototype	L/L	L/L	L/L	L/L
Cost	L/L	L/M	L/L	L/M
Max number of parts	L/L	L/L	L/L	L/L
Minimum Clamping force	L/M	L/M	L/L	L/L

Table 11.8 Cavity Core Geometry vs. Mold (Cont.)

Process **Part**	Barrel temp-zone 1	Barrel temp-zone 2	Barrel temp-zone3	Mold temp	Injection Pressure	Packing Pressure	Holding Pressure Profile	Clamping force
Part #	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
EC level	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Assembly level	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Description	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Aesthetic Req	M/L	M/L	M/L	M/L	M/L	M/L	M/L	L/L
Structural Req	M/L	M/L	M/L	M/L	M/L	M/L	M/L	L/L
Quantity req/system	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Demand/month	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Environ. Restrictions	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Finish req	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Cost	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
sink marks	M/M	M/M	M/M	M/M	M/M	H/M	H/M	M/M
weld line location	M/M	M/M	M/M	M/M	M/M	L/L	L/L	L/L
warpage	M/M	M/M	M/M	M/M	M/M	M/M	M/M	L/L
shrinkage	M/H	M/H	M/H	M/M	M/M	H/H	H/H	M/M

Table 11.9 Process vs. Part

Process **Part**	Clampin g force	Fill time	Pack time	Holding time	Cooling time	Open time	Shot size	Coolant FR
Part #	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
EC level	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Assembly level	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L

Description	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Aesthetic Req	L/L	M/L	M/L	M/L	L/L	L/L	L/L	L/L
Structural Req	L/L	M/L	M/L	M/L	L/L	L/L	L/L	L/L
Quantity req/system	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Demand/month	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Env. Restrictions	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Finish req	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Cost	L/L	L/M	L/M	L/H	L/H	L/M	L/M	L/L
sink marks	M/M	M/M	M/M	M/M	L/L	L/L	M/M	L/L
weld line location	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
warpage	L/L	M/M	M/M	M/M	M/M	L/L	L/L	M/M
shrinkage	M/M	M/M	M/H	M/M	L/L	L/L	M/M	L/L

Table 11.9 Process vs. Part (Cont)

In this section, several engineering changes scenarios have been provided. Table 11.1 provides the changeable components in the C-FAR schema. This table serves as a knowledge pool from which elements will be chosen according the given scenarios.

11.3.3 Evaluation Injection Molding Process Model Scenario 1

How would changing the part geometry wall thickness affect the mold cost ?

First change vector is: [Δ 0 0 0 0 0]. This vector describes a change to the wall thickness of the part geometry. There are two simple paths that lead from the source entity to the target entity. The first is Part_Geometry-Part-Mold and the second one, Part_Geometry-Cavity_Core-Geometry-Mold.

Path1

$[\Delta\ 0\ 0\ 0\ 0\ 0] * C(Part\_Geomety, Part) = \Delta path1Part$

Where $C(Part\_Geomety, Part)$ is taken form Table 11.2

$\Delta path1Part = \Delta * [\text{ L L L L L L L L L L M M H M L}]^T$

$$\Delta path1Part \ * \ C(Part, Mold) = \Delta path1Mold \ = \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ MM + MM \\ L \\ MM + MM \end{bmatrix}$$

Where $C(Part, Mold)$ is taken form Table 11.7

$$\text{Orth}(\Delta path1Mold) = \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ 0.18 \\ L \\ 0.18 \end{bmatrix} = \Delta Path(1)$$

From path1, the linkage value of 0.18 indicates a medium linkage between the part geometry wall thickness and the mold cost.

Path2

$[\,\Delta\ 0\ 0\ 0\ 0\ 0\,] * C(Part\_Geometry, Cavity\_Core\_Geomety) =$
$\Delta path2Cavity\_Core\_Geometry$

Where $C(Part\_Geometry, Cavity\_Core\_Geomety)$ is taken form 11.3

$\Delta path2Cavity\_Core\_Geometry = \Delta * [\text{ L M M H H H H H}]^T$

$$\Delta path2Cavity\_Core\_Geometry \ * \ C(Cavity\_Core\_Geomety, Mold) = \Delta path2\,Mold \ =$$

$$\Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ HM + HM + MM + HM \\ L \\ HM + HM + HM \end{bmatrix}$$

Where $C(Part, Mold)$ is taken form Table 11.7

Orth($\Delta path2\,Mold$) = $\Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ 0.52 \\ L \\ 0.41 \end{bmatrix}$ = $\Delta Path(2)$

From path1, - the linkage value of 0.56 indicates a medium linkage between the part geometry wall thickness and the mold cost. However, it is likely that a change in the part wall thickness will affect the cost through the manner expressed in path2.

Max($\Delta Path(1)$, $\Delta Path(2)$) = $\Delta Path(2)$

Therefore, the minimum value for the calculated linkage value between the source entity attribute to the target entity attributes is exactly $\Delta Path(3)$. The maximum value of the result interval is the summation of the contribution from all the paths.

Therefore the maximum linkage value is

Total influence = $\sum_{i=1}^{n} \Delta Path(i) = \Delta Path(1) + \Delta Path(2) = \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ 0.7 \\ L \\ 0.41 \end{bmatrix}$

and the linkage value for the cost is an interval 0.52-0.7

11.3.4 Results Analysis

This scenario asked how changing the part geometry wall thickness affects the mold cost. The result is an interval with a linkage value of 0.52-0.7. This linkage value is in the high medium linkage value range, which indicates that probably there is a linkage between the part wall thickness mold cost. Moreover, this scenario illustrates that a change to the wall thickness will probably not influence the maximum number of part attributes of the molder. The change to the wall thickness probably will not affect the mold type or the number of cavities. However, a change in the wall thickness will somewhat influence the minimum clamping force of the mold.

11.3.5 Evaluation Injection Molding Process Model Scenario Scenario 2

Will a change to the part gate specification have any affect on the type of coolant that is chosen for the process ? The source entity is the part geometry and the target entity is the mold coolant. There are two simple paths that are relevant to this scenario. The first is “Part_Geometry - Part - Process - Mold_Coolant”. The second is “Part_Geometry - Cavity_Core_Geometry - Mold - Part - Process - Mold_Coolant”.

Path1:

$\Delta path1Part\_Geomtry$ = [0 0 0 0 Δ 0 0 0] ^{T}

$\Delta path1Part\_Geomtry * C(Part\_Geomety\_Part) = \Delta path1Part$

Where $C(Part\_Geomety\_Part)$ is taken form Table 11.3

$\Delta path1Part = \Delta$ * [L L L L L L L L L L M M H M M]^T

$$\Delta path1Part * C(Part, \Pr ocess) = \Delta path1 \Pr ocess = \Delta * \begin{bmatrix} 3*MM+HM \\ 3*MM+HM \\ 3*MM+HM \\ 3*MM+HM \\ 3*MM+HM \\ 2*HM+MM \\ 2*HM+MM \\ 2*MM \\ 2*MM \\ 3*MM \\ 3*MM \\ MM \\ L \\ 2*MM \\ MM \end{bmatrix}$$

$C(Part, \Pr ocess)$ is given in Table 11.9

Orth($\Delta path1 \Pr ocess$) =

= Δ * [0.32 0.32 0.32 0.32 0.32 0.33 0.33 0.11 0.11 0.13 0.13 0.09 L 0.11 0.09]^T

Orth($\Delta path1 \Pr ocess$) * $C(\Pr ocess, Mold\_Coolant)$ =

$$\Delta * \begin{bmatrix} L \\ 0.32M + 0.09M \\ 0.32M + 0.09H \\ 0.32M + 0.09H \\ 0.09M \end{bmatrix}$$

$$\text{Orth}(\Delta path1Mold\_Coolant) = \Delta * \begin{bmatrix} L \\ 0.1 \\ 0.1 \\ 0.1 \\ 0.03 \end{bmatrix} = \Delta Path(1)$$

Path2:

Path2 includes the following entities.
Part_Geometry - Cavity_Core_Geometry - Mold - Part - Process - Mold_Coolant.
$\Delta path2Part\_Geomtry = [0\ 0\ 0\ 0\ \Delta\ 0\ 0\ 0]^{T}$
$\Delta path1Part\_Geomtry * C(Part\_Geomety, Cavity\_Core\_Geometry) = \Delta path1Part$
Where $C(Part\_Geomety, Cavity\_Core\_Geometry)$ is taken form Table 11.3
$\Delta path2Cavity\_Core\_Geometry = \Delta * [\text{ M M M H H H M M }]^{T}$
$\Delta path2Cavity\_Core\_Geometry * C(Part\_Geomety, Cavity\_Core\_Geometry) =$

$$\Delta path1\text{Pr}ocess = \Delta path2Mold = \Delta * \begin{bmatrix} L \\ MM \\ L \\ L \\ 3 * HM + 2 * MM \\ L \\ 3MH \end{bmatrix}$$

$$\text{Orth}(\Delta path2Mold) = \Delta * \begin{bmatrix} L \\ 0.09 \\ L \\ L \\ 0.64 \\ L \\ 0.51 \end{bmatrix}$$

$\text{Orth}(\Delta path2Mold) * C(Mold, Part) = \Delta path2Part$
Where $C(Mold, Part)$ is taken form Table 11.7

$$\Delta path2Part = \Delta * \begin{bmatrix} L \\ L \\ L \\ L \\ L \\ L \\ L \\ L \\ L \\ L \\ 0.09 * M + 0.64 * H \\ 0.51 * M \\ L \\ 0.51 * M \\ 0.51 * M \end{bmatrix}$$

Orth($\Delta path2Part$) = Δ * [L L L L L L L L L L 0.59 0.16 L 0.16 0.16]^T

Orth($\Delta path2Part$) * $C(Part, \Pr ocess)$ =

$$\Delta path2\Pr ocess = \Delta * \begin{bmatrix} 3*0.16M \\ 3*0.16M \\ 3*0.16M \\ 3*0.16M \\ 3*0.16M \\ 2*0.16M + 0.16*H \\ 2*0.16M + 0.16*H \\ 2*0.16M \\ 3*0.16M \\ 3*0.16M \\ 3*0.16M \\ 3*0.16M \\ 0.16*M \\ 2*0.16M \\ 0.16*M \end{bmatrix}$$

Where $C(Part, \Pr ocess)$ is given in Table 11.9

Orth($\Delta path2\Pr ocess$) =
= [0.06 0.06 0.06 0.06 0.06 0.16 0.16 0.06 0.06 0.06 0.06 0.06 0.05 0.06 0.05]

Orth($\Delta path2\Pr ocess$) *

Orth($\Delta path2\Pr ocess$) * $C(\Pr ocess, Mold\_Coolant)$ = $\Delta path2Mold\_Coolant$

Where $C(\Pr ocess, Mold\_Coolant)$ is given in Table 11.6

$$\Delta path2Mold\_Coolant = \Delta * \begin{bmatrix} L \\ 0.06M + 0.06M \\ 0.06M + 0.06H \\ 0.06M + 0.06H \\ 0.06M \end{bmatrix}$$

$$\text{Orth}(\Delta path2\,Mold\_Coolant) = \Delta * \begin{bmatrix} L \\ 0.02 \\ 0.05 \\ 0.05 \\ 0.02 \end{bmatrix}$$

Path1 contribution to the calculated linkage value

$$\Delta Path(1) = \Delta * \begin{bmatrix} L \\ 0.1 \\ 0.1 \\ 0.1 \\ 0.03 \end{bmatrix}, \quad \Delta Path(2) = \Delta * \begin{bmatrix} L \\ 0.02 \\ 0.05 \\ 0.05 \\ 0.02 \end{bmatrix}$$

Path1 influence is stronger than path2. Part1 is partially overlapped by path2, therefore it is not surprising that $\Delta Path(2)$ is made up of more elements then $\Delta Path(1)$.

Max($\Delta Path(1)$, $\Delta Path(2)$) = $\Delta Path(1)$

Therefore, the minimum value for the calculated linkage value between the source entity attribute to the target entity attributes is $\Delta Path(1)$. The Maximum value of the result interval is the summation of the contribution from all paths.

Therefore the maximum linkage value is

$$\text{Total influence} = \sum_{i=1}^{n} \Delta Path(i) = \Delta Path(1) + \Delta Path(2) = \Delta * \begin{bmatrix} L \\ 0.12 \\ 0.15 \\ 0.15 \\ 0.05 \end{bmatrix}$$

11.3.6 Results Analysis

This scenario asked, whether a change in the part gate location will have any affect on the type of coolant chosen for the process ? The answer is that a change to the gate location of the part geometry somewhat influences the mold coolant attributes. The mold coolant attributes that are most highly linked to the suggested change are the mold coolant density, specific heat capacity, and the thermal conductivity. These results mean that a change to the gate location may influence the choice of mold coolant material.

Chapter 12

Validation Summary

The purpose of the validation stage is to demonstrate C-FAR's capability to model in the real engineering domain and to facilitate change representation and propagation mechanisms. The starting point of each case study was an existing EXPRESS model. The model was converted to flat EXPRESS format and was enhanced with C-FAR matrices. The C-FAR matrices were constructed by a person who is an expert domain. The domain expert also suggested a set of scenarios for each case study. The scenario role is to suggest a meaningful engineering change to the case study and test the change representation and propagation mechanism of the C-FAR methodology. For the PWB case study the domain expert put ~10 hours to construct the C-FAR matrcies. However for the injection molding process case studythe domain expert put ~40 hours to consreuct the C-FAR matrices.

Some of the C-FAR matrices represented linkage between attributes that are also connected via mathematical formulation. For example the attributes of the PWB thermal model and the PWB entity in the PWB case study. It is interesting to point out that some of these attribute linkage was high as expected. However some of the linkage values between those elements were low. The reason for this phenomenon is that a change to one element in the mathematical formulation is not relevant from contextual reasons. Namely, C-FAR is able to distinguish that several of the elements are natural inputs or natural outputs. A mathematical formulation can not point out which of the elements is a natural input or output.

12.1 Relevancy of Coverage

The EXPRESS information model was created and is implemented to model engineering fields. As was expected, because C-FAR is based on the EXPRESS main elements, that C-FAR schema was able to model real engineering problems. The four case studies presented in Chapters 8-11 demonstrate the capability of C-FAR to model engineering domains. The truss 2D case study information model covered physical characteristics of the truss as well as truss structural analysis components. The bumper case study was constructed with the aid of General Motors personnel and was compounded of the bumper main components and two bumper tests. The PWB case study and the injection molding EXPRESS models and C-FAR schemes were constructed by experts domain with guidance from the thesis author. The PWB case study was concentrated in the printed wiring board structure, its components, and its thermal bending analysis model. The injection molding case study encompassed over a thousand linkage values that described linkages between connected entities. The focal point of this injection molding schema was the process itself. The schema described the important players and their relations in the injection molding procedure. Each case study described different engineering domains with focus on certain aspects of the domain. The C-FAR case studies were taken from real engineering applications. Therefore, it can be claimed that C-FAR has relevant engineering coverage.

12.2 Change Representation

As illustrated in the case studies, C-FAR provides a generic attribute-based change representation. The change, Δ, represents a different value for a measurable attribute of an entity. As described in Chapter 3, the change in the thesis framework is confined to attributes' values. Therefore, it can be claimed that C-FAR facilitated this change representation. (Change propagation and corretness evaluation are provided in chapter 16)

PART IV

VERIFICATION

Chapter 13

Verification Introduction

The role of the verification stage is to examine the quality and reliability of the results presented in the validation stage. The verification stage uses three measurements to examine C-FAR. The first measurement tests the reliability of the C-FAR methodology for the matrix construction phase. The question that this measurement attempts to answer is how reliable the C-FAR matrix is at representing linkage values between the attributes of two entities. Reliability in this context means that most of the respondents agree on a linkage value or a situation where linkage values are assigned in a fashion that prevent a reasonable estimation. An example of a pathological case is where 10 respondents assign linkage values of “high”, five assign linkage values of “medium” and 12 assign linkage values of “low.”

The second measurement is a pass-fail test. The tested elements in the C-FAR methodology are the case study scenarios. For each scenario in each case study, the C-FAR schema builder (an domain expert by C-FAR definition) evaluates the C-FAR results and asks whether the linkage value achieved by C-FAR corresponds to the knowledge domain he or she has obtained. This second measurements examine overall C-

FAR performance. These measurements are C-FAR construction, change representation, propagation, and results interpretation. The third verification measurement also examines C-FAR's change representation and tracking mechanism. A source entity's attribute and a target entity's attributes are presented to both C-FAR and an independent non-C-FAR literate expert domain. The expert is asked to estimate the linkage value between the given attributes. The answer is compared with calculated linkage value achieved with C-FAR. The correlation between the two linkage values institute the third C-FAR verification measurement. In the C-FAR linkage value estimation, a single value is given to compare with the single value provided by the expert domain. The value is an average of the lower and upper bounds of the C-FAR interval.

Chapter 14

C-FAR Matrix Construction Survey

14.1 Introduction

The purpose of the survey is to evaluate the capability of the High, Medium and Low linkage value mechanism in describing relations in a real engineering problem. Specifically, the survey examines how uniform or non-uniform the assignment of linkage values for each source to target pair is among the respondents. The survey responders all have a technical background and some of them have data modeling experience as well. The survey (appendix A) asks to fill in linkage values between a pinball piston mechanism and a ball as illustrated in Figure 14.1. a term used in the survey is a dominant linkage value. A dominant linkage value is the linkage value which gets the most of the votes on a single source to target pair.

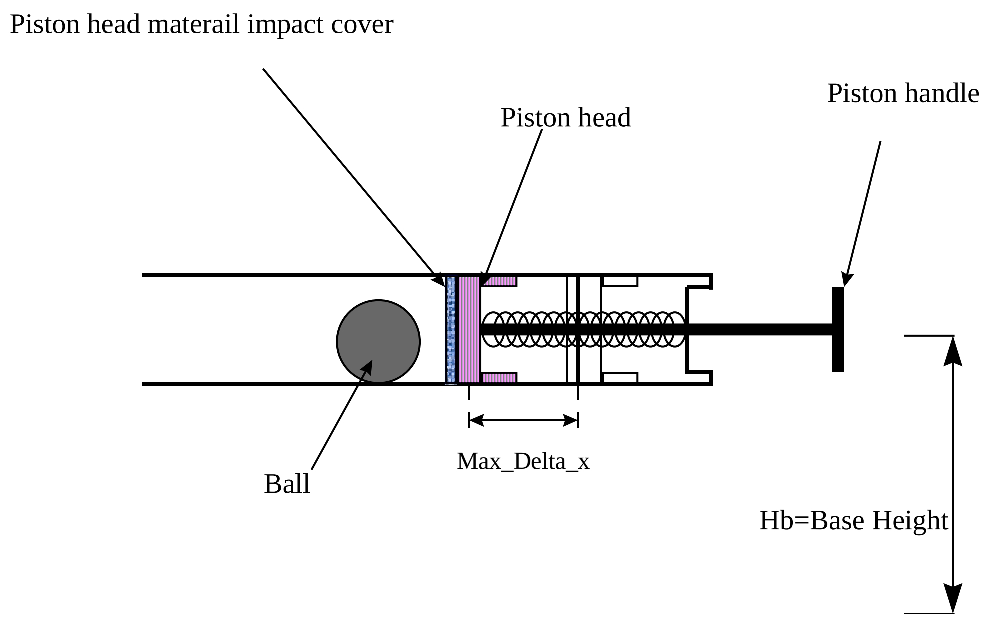


Figure 14.1 Pinball Piston Ball Mechanism

The two entities to be examined are the Ball and the Piston

The Pistons attributes are:

1. Piston cost
2. Max_Delta_x - The max spring compression distance.
3. Hb (Base Height) - Piston height from the pinball machine base.
4. Assembly directions
5. Piston head material impact cover
6. Piston handle diameter
7. Piston head diameter

The Balls attributes are:

1. Ball diameter
2. Ball maximum velocity
3. Ball Manufacturer
4. Ball material

14.2 Survey Results

The main table in the survey describes the linkage value for each source-target pair. A percentage value appears to the right of each number indicating the occurrences of the linkage value. A total of 18 answered surveys were received. In five of the surveys some of the source to target attributes were not completed. The source linkage values that have stars next to their names indicate that less than 18 answers are given

Source Attribute	Target attribute	H occurrences	M occurrences	L occurrences
Max_Delta_x	Ball Diameter	0/0%	14/78%	4/22%
Max_Delta_x	Ball_ Maximum Velocity	18/100%	0/0%	0/0%
Max_Delta_x	Ball_Manufacturer	0/0%	10/55%	8/45%
Max_Delta_x	Ball_Material	15/83%	3/17%	0/0%
Base_Height	Ball Diameter	0/0%	2/11%	16/89%
Base_Height	Ball_Max.Velocity	7/39%	2/11%	9/50%
Base_Height	Ball_Manufacturer	0/0%	0/0%	18/100%
Base_Height	Ball_Material	0/0%	2/11%	16/89%
Assembly Directions *	Ball Diameter	0/0%	4/22%	9/50%
Assembly Directions *	Ball_Maximum Velocity	0/0%	3/17%	10/56%

Table 14.1 Survey Results

Source Attribute	Target attribute	H occurrences	M occurrences	L occurrences
Assembly	Ball_Manufacturer	2/11%	6/33%	5/28%

Directions *				
Assembly Directions *	Ball_Material	0	2/11%	11/61%
Piston Head Material cover	Ball Diameter	0	13/72%	5/28%
Piston Head Material cover	Ball_Maximum Velocity	18/100%	0/0%	0/0%
Piston Head Material cover	Ball_Manufacturer	14/78%	2/11%	2/11%
Piston Head Material cover	Ball_Material	18/100%	0/0%	0/0%
Piston Handle Diameter	Ball Diameter	0/0%	2/11%	16/89%
Piston Handle Diameter	Ball_Maximum Velocity	2/11%	4/22%	12/67%
Piston Handle Diameter	Ball_Manufacturer	0/0%	0/0%	18/100%
Piston Handle Diameter	Ball_Material	0	0	18/100%
Piston head diameter	Ball Diameter	17/94%	1/6%	0/0%
Piston head diameter	Ball_Maximum Velocity	4/22%	13/72%	1/6%
Piston head diameter	Ball_Manufacturer	5/27%	10/56%	3/17%
Piston head d.	Ball_Material	1/6%	10/55%	7/39%
Piston spring Coef-K	Ball Diameter	0/0%	7/39%	11/61%
Piston spring Coef-K	Ball_Maximum Velocity	18/100%	0/0%	0/0%
Piston spring Coef-K	Ball_Manufacturer	0/0%	7/39%	11/61%
Piston spring Coef-K	Ball_Material	15/83%	3/17%	0/0%

Table 14.1 Survey Results (Cont.)

The next table illustrates the overall average of the percentage of the dominant linkage values for each source-to-target pair. Moreover, the average of the percentages is classified for the dominant average for the high, medium, and low linkage values. For eight pairs, the dominant linkage value was high; for seven the dominant was medium; and for thirteen pairs, the dominant linkage value was low.

Overall percentage average of the dominant linkage value	76%
A percentage average of the dominant linkage value - H	92%
A percentage average of the dominant linkage value - M	60%
A percentage average of the dominant linkage value - L	75%

Table 14.2 Survey Results Summary

14.3 Results Analysis

In general, the overall percentage average of the dominant linkage value of 76% indicates that in a reasonable number of cases of the linkage value evaluation, there is an agreement on one of the three linkage values. Table 14.2 indicates that in source-to-target pairs that have a linkage value of high and low there is broader agreement among the answers than the linkage values of medium. High percentage choice of a linkage value appears mostly in pairs where there are clear physical linkages, such as the piston spring coefficient and ball maximum velocity, or piston head material and ball material. However, there are some source-to-target pairs that pose questions. Table 14.3 illustrates source-target pairs where their dominant linkage values are less than 73% or have more than two high and low linkage value mismatches for the same pair.

1.	Max_Delta_x	Ball_Manufacturer	0/0%	10/55%	8/45%
2.	Base_Height	Ball_Maximum Velocity	7/39%	2/11%	9/50%
3.	Assembly Directions *	Ball Diameter	0/0%	4/22%	9/50%
4.	Assembly Directions *	Ball_Maximum Velocity	0/0%	3/17%	10/56%
5.	Assembly Directions *	Ball_Manufacturer	2/11%	6/33%	5/28%
6.	Assembly Directions *	Ball_Material	0	2/11%	11/61%
7.	Piston Head Material cover	Ball_Manufacturer	14/78%	2/11%	2/11%
8.	Piston Handle Diameter	Ball_Maximum Velocity	2/11%	4/22%	12/67%
9.	Piston head diameter	Ball_Manufacturer	5/27%	10/56%	3/17%
10.	Piston head diameter	Ball_Material	1/6%	10/55%	7/39%
11.	Piston spring Coef-K	Ball Diameter	0/0%	7/39%	11/61%
12.	Piston spring Coef-K	Ball_Manufacturer	0/0%	7/39%	11/61%

Table 14.3 Weak Dominant Source to Target Percentage

The target entity in rows 1,5,7,9, and 12 is the ball manufacturer. This ball attribute apparently causes problems for the respondents. The change influence on the ball manufacturer attribute is not clear, and it appears that the respondent speculates and therefore their answers varies. Another problematic attribute that caused even more confusion is the piston’s assembly directions, rows 3,4,5, and 6. Five of the respondents left blank some or even all of the slots for the linkage values. In these two cases, the probable reason for below average results is a lack of knowledge about the domain.

In row two, there are two issues. First, the dominant low linkage value was chosen only by 50% of the respondents, moreover 39% of answers marked this pair with high linkage value. The base height dimension is illustrates in 14.1.

Some of the respondents marked a question mark near the base height dimension. Others put a small drawing indicating that the ball falls further as the height dimension becomes larger. It is probable that some of the respondents assumed a situation where the ball is falling from this height to the pinball board. However, most of them saw this height as being indifferent to the maximum ball velocity. Therefore, the probable reason for this disparity is a lack of sufficient explanation for this dimension with relation to the problem.

14.4 Results Summary

The overall survey results are reasonable. From 28 questions that were listed in the survey, respondents were asked to assign one of three linkage values, the overall average for the overall percentage average of the dominant linkage value was 76%.

The survey takes a technical problem domain and asks technical individuals to assign linkage values between two entities in this problem. The survey illustrates that a uniform evaluation, which measures the amount of success in terms of this survey, is a function of the knowledge domain of the respondents. If it is assumed that the respondents are not qualified to estimate the linkage values for the ball manufacturer and the assembly attributes, the overall percentage average of the dominant linkage value becomes 82%. The survey assumed that each respondent had a certain level of knowledge in the domain. domain. It is likely that most of the respondents knew about the relation between a spring elastic coefficient and ball maximum speed but they may have had some problems figuring out the relation between the piston assembly directions and the ball manufacturer.

Chapter 15

Scenario Verification

The role of the scenario verification in this thesis is to decided whether the C-FAR methodology indeed manages to correctly evaluate the change influence of the source on the target.

15.1 2D Truss Case Study

How would a change to the Force_Vector dimension influence the “Node” attributes ? The node attributes are: node_ number, node_ layer, x_location, y_location, x_disp, and y_disp. A change to the force vector dimension means actually adding or removing loads from the structure. In a non-thermal loading condition, only addition or removal of loads can cause nodal displacement. However, there is no relation between the number of loads and the node location, layer or node number. Therefore, it is expected that the node location, which is expressed in the schema as “x_disp, y_disp” will be strongly affected. The rest of the node attributes will not be affected. The C-FAR change vector assigns high linkage values to the nodal displacement and low linkage values to node_ number, node_ layer, x_location, y_location. Therefore, C-FAR succeeded in describing how a change to the source attribute influences the entity “Node”.

In the second scenario, the following question was posed: How would a change to the magnitude of a load influence the elements structure? The element structure attributes are element_number, element_layer, material_code, elastic_module, cross_section_area, 2D-length. A change to the load magnitude will not likely influence the element number, element layer, material code, elastic module or the area cross section. However, a change in the magnitude of the load is highly linked to 2D element elongation. The C-FAR change vector assigned high linkage value for the 2D length of an element as a result of a change to the load magnitude, and low linkage value for element number, element layer, material code, elastic module and area cross section. Therefore, in the second scenario -- this truss case study -- C-FAR was successful in describing the influence of the load magnitude on the 2D element.

15.2 Bumper Case Ctudy

In this scenario, the following question was posed: How would a change in the energy absorbent length influence the bumper beam? The bumper beam attributes are part_ number, weight, length, width, depth, material_code, beam_profile , wall_thickness, elas_module, beam_type. From compatibility considerations, it is expected that the length of the bumper beam will be highly linked to the energy absorbent length. A change in the energy absorbent length may also influence the other physical attributes of the bumper. The C-FAR change vector assigned a strong linkage value between the energy absorbent length and the bumper beam length and weight. C-FAR also suggests that the other physical attributes of the beam (width, depth, beam_profile , wall_thickness, elas_module, beam_type) were somewhat linked to the change in length of the energy absorbency. However, a change in the bumper length has a low linkage value to the bumper beam part number. Since C-FAR detected the high link between the energy absorbent length and the bumper beam length, and weight, the scenario results are acceptable.

In the second scenario, the influence of a change in the automobile chassis height on the bumper beam was examined. According to the federal regulation, the bumper must be in a certain height range above the road. Therefore, there is a certain correlation between the bumper width dimension and its height above the road. The height is measured from the bumper's lower edge. C-FAR results indicate that most of the bumper beam attributes are not linked to the chassis change in height. However, the bumper beam width is somewhat related to the change. In the following scenario, the change to the chassis height influence to the bumper brackets is examined. Vehicles with a high body are usually equipped with a more rigid bumper bracket mechanism. C-FAR assigns a medium linkage value to the bumper bracket mechanism. However, the other brackets attributes are low. The last aspect examined in the chassis height change scenario, is the linkage to the pendulum test. The pendulum test attributes are test_location, pendulum_weight and pendulum_speed. The pendulum attributes are dictated by the tests requirements. The car weight dictates the pendulum weight, and the speed and location are generic across vehicle frames. C-FAR results indicate that there is no linkage between the chassis height dimension and the pendulum test attributes.

15.3 PWB Case Study

The PWB is compounded of layers of circuits. The layers may have various electrical functionality. The first scenario examined how a change in the PWB copper layer function changes the PWB thermal model. A change in the layer functionality directly influences the PWB height cost and coefficient of thermal bending. These PWB attributes strongly influence the PWB thermal bending model of the PWB. The main PWB thermal bending model attributes are thickness, Ctb and warpage. The C-FAR analysis indeed points out that the thickness, Ctb, and warpage are strongly linked to the change in PWB Copper layer function. However, C-FAR analysis also point out that associate temperature and the temperature change attributes are both somewhat influenced by a change in the layer function of the PWB_Copper.

In the second scenario, the influence of the change in the Electrical Package body style on the PWA entity is examined. The electrical package body style change induces a change in the physical characteristics of the electrical a component. The PWA describes assembly of those components on the PWB. Therefore, it is expected that a change in the components dimension may influence the assembly order and the number of sides that will be utilized in the PWA design. C-FAR analysis indicates that a change in the electrical package body style somewhat influences the number of sides as well as the assembly order. C-FAR results are correlates to the expected change influences.

15.4 Injection Molding Case Study

The first scenario discussed the influence of a change in the part wall thickness on the mold cost. The mold design is an expensive iterative process and the wall thickness is an important part in the mold construction. Therefore, it is expected that the mold will be strongly linked to a wall thickness change. C-FAR assigns a linkage value of 0.7 to the mold cost as a result of a change in the wall thickness. This linkage value represent a solid linkage as defined in chapter 16. Therefore, this estimation is reasonable.

The second scenario asked whether a change in the part gate location has any affect on the type of coolant that is chosen for the process. The gate locations are the places where the material is injected. The linkage between the source and target attribute is not strong. However, a change in the gate location will change the location of the weld lines, which are the lines that describe the part wall intersection. The weld line location are also influenced by the process mold temperature, which is related to the mold coolant attributes. Therefore, it would be inaccurate to declare that the source and target entities are not related. The C-FAR results reflect a linkage value of 0.05-0.15 among the mold coolant physical attributes. This linkage indicates a medium linkage between the part gate location and the mold type that is used in the process.

15.5 Summary

The definition of a successful C-FAR estimation in this framework may be divided into two levels. The first plane is whether the C-FAR calculated linkage value was high when it should have been low or low when it should have been high. From the scenario verification stage described above, C-FAR was successful. The second success measure level asks the question: Are C-FAR results reasonable ? Since the core of C-FAR relies on high, medium, and low estimations, the resultant numeric linkage values present an estimation of the quality of linkage. The second success measure asks whether this estimation is reasonable or unreasonable. In all of the scenarios above, the C-FAR estimation was reasonable.

Chapter 16

C-FAR vs. Independent Expert Domain

16.1 Introduction

This section examines the PWB and the injection molding case studies. For each case study a representative set of source and target entities has been chosen. The criteria for choosing entities is based on levels of change propagation, namely a set of source and target pairs that have one, two , three, etc. degrees of change propagation. An domain expert that was not exposed to the C-FAR schema estimated the linkage value. At the same stage, C-FAR calculated the linkage value between the given entities. The correlation of these linkage value was then compared and evaluated . The independent expert domain for these cases are faculty members of the school of mechanical engineering at Georgia Tech.

16.2 Verification Strategy

For each case study, the source-target pairs were selected to facilitate exploration of the C-FAR methodology. First, the basic change representation between two entities was examined. Next, the change propagation mechanism was tested. The change propagation relied on a chain of C-FAR matrices. As such, the reliability of each chain in a chosen path was examined and in turn, the chain functionality as change propagation facilitator was examined. The source and target pairs were chosen by scenarios that appears in the validation part, Chapter 10. The scenarios were prescribed by the schema constructors for both PWB and the injection molding case studies (In the fifth column, the numeric value to the right of the "/" symbolizes the length of the shortest path that C-FAR calculated).

16.3 PWB Case Study

Source entity attribute	Target entity attribute	Domain Expert estimated Linkage value	C-FAR calculated Linkage value
Electrical Package-body style	Electrical Component-length	H	H/1
Electrical Package-body style	Electrical Component-width	H	H/1
Electrical Package-body style	Electrical Component-pr	M	M/1
Electrical Package-body style	Electrical Component-height	H	H/1
Electrical Package-body style	Electrical Component-cost	M	M/1
Electrical Component-length	Component Occurrence-	M	L/1
Electrical Component-width	Component Occurrence-	M	L/1
Electrical Component-power rating	Component Occurrence-	L	M/1
Electrical Component-height	Component Occurrence-	M	M/1
Electrical Component-cost	Component Occurrence-	L	L/1
Electrical Package-body style	Component Occurrence-	M	0.29/2
Component Occurrence-surface	PWA-assembly order	H	H/1
Component Occurrence-surface	PWA-total length	L	L/1
Component Occurrence-surface	PWA- number of sides	H	H/1

Table 16.1 PWB C-FAR vs. Domain Expert Results

Source entity attribute	**Target entity attribute**	**Domain Expert estimated Linkage value**	**C-FAR calculated Linkage value**
Comp Occurrence-surface	PWB-ctb	L	L/3
Component Occurrence-	PWB-total width	M	0.21/3
Component Occurrence-surface	PWB-nominal req l thickness	L	L/3
Electrical Comp. height	PWB-ctb	L	L/4
Electrical Package-body style	PWB-total width	M	0.15/4
Component Occurrence-surface	PWB-total diagonal	L	L/2
Component Occurrence-surface	PWB_Thermal_ length	L	L/3
Component Occurrence-e	PWB_Thermal_ temp change	L	L/3
Component Occurrence-	PWB_Thermal_ temp assoc	L	L/3
Component Occurrence-surface	PWB_Thermal_ temp reference	L	L/3
PWA-assembly order	PWB_Thermal_ temp change	L	L/3
PWA-total length	PWB_Thermal_ temp assoc	L	L/3
PWA- number of sides	PWB_Thermal_ temp reference	L	L/3
Electrical Component-height	PWB_Thermal_ warpage	L	0.02/4
Electrical Package-body style	PWB_Thermal_ warpage	L	0.02/5
Electrical Component-power rating	PWB_Thermal_ warpage	L	L/4
PWB board length	PWB_Thermal_ warpage	H	H/1
PWB board length	PWB_Th_change	L	L/1
PWB board length	Location x	M	0.07/3

Table 16.1 PWB C-FAR vs. Domain Expert Results (Cont.)

Source entity attribute	**Target entity attribute**	**Domain Expert estimated**	**C-FAR calculated**

		Linkage value	**Linkage value**
PWB board length	Location rotation	M	0.07/3
PWB board length	PWA number of sides	M	L/1
PWB board length	Comp Occ. surface	M	0.27/2
PWB board length	Component Occurrence Reference	L	L/2
PWB size of layup	PWB_Thermal_l temp change	L	M/1
PWB size of layup	PWB_Thermal_ warpage	H	H/1
PWB Copper layer function	PWB total length	L	L/1
PWB Copper layer fun.	PWB total height	H	H/1
PWB Copper layer	PWBctb	H	H/1
PWB Copper layer function	PWBThermal_ length	L	L/2
PWB Copp. layer function	PWB_Therma_ thickness	H	H/2
PWB Copper layer	PWB_Tl_reftemp	L	L/2
Prepreg_Set description	PWB_Thermal_ length	L	L/2
Prepreg_Set description	PWB_Thermal_ total height	L	L/2
Prepreg_Set description	PWB_Thermal_ thickness	L	L/2
Prepreg_Set description	PWB_Thermal_l reference temp	L	L/2
Prepreg_Set total height	PWB_Thm_length	M	0.21/2
Prepreg_Set total height	PWB_T_height	H	H/2
Prepreg_Set total height	PWB_Tl_thick	H	H/2

Table 16.1 PWB C-FAR vs. Domain Expert Results (Cont.)

Source entity attribute	**Target entity attribute**	**Domain Expert estimated Linkage value**	**C-FAR calculated Linkage value**

Prepreg_Set total height	PWB_Thermal_ reference temp	L	L/2
Prepreg_Set total height	PWB_Thermal_ warpage	H	H/2
Prepreg_Set description	PWA number of sides	L	L/2
Prepreg_Set description	PWA cost	L	L/2
Prepreg_Set description	PWA # of components	L	L/2
Prepreg_Set total height	PWA number of sides	L	0.35/2
Prepreg_Set total height	PWA cost	M	0.32/2
Prepreg_Set total height	PWA # of components	L	0.35/2
Prepreg_Set description	Location rotation	L	L/4
Prepreg_Set description	Location Z	L	L/4
Prepreg_Set total height	Location rotation	L	0.02/4
Prepreg_Set total height	Location Z	M	0.08/4
Prepreg_Set description	Linear Elastic Material cte	L	L/1
Prepreg_Set description	Linear Elastic G	L	L/1
Prepreg_Set description	Linear Elastic E	L	L/1
Linear Elastic Material G	Prepreg_Set description	L	L/1
Location Z	Prepreg_Set description	L	L/4
Location rotation	Prepreg_desc.	L	L/4
Linear Elastic Material G	Prepreg_ height	M	L/1
Location Z	Prepreg_ height	L	L/4
Location rotation	Prepreg_ height	L	L/4

Table 16.1 PWB C-FAR vs. Domain Expert Results (Cont.)

16.3.1 Numerical Values For Linkage Values For Verification Purposes

In Chapter 3 the linkage values were assigned numerical values of 0.9 for high linkage value, 0.3 for medium linkage value, and 0 for low linkage value. C-FAR assigns linkage values of H, M, or L to all attributes of entities that are connected. However, the change propagation creates linkage values that are numbers with values between 0 and 0.9.

A legitimate question is what the numerical intervals are for the H, M, L linkage values within the 0-0.9 range. Since a linkage value of H is assigned to a pair where a change in the source attribute strongly influences the target attributes, it is expected the numeric value should be high.

In the same manner, a linkage value of L is assigned to a pair where a change in the source attribute does not influence the target attributes. Therefore, it is expected that numeric value should be low. However, the interval for the medium numeric value is not as clearly defined. Therefore, the verification stage assigns larger intervals of numeric values representing M linkage values compared to H or L linkage values. Since the maximum length of an influence path in this research was five entities, the range for high linkage value is chosen to be $0.9 - 0.9^{\wedge 4}$. $0.9^{\wedge 4} = 0.65$. The upper bound for the medium linkage value was chosen to be 0.66. The overlap of 0.01 symbolize the order of error sensitivity for this work. The lower bound for the medium linkage value is chosen to be $0.3^{\wedge 2} = 0.09$. The notion of medium linkage value is more vague than the high linkage value. Therefore three consecutive medium will be considered low.

16.3.2 Results Analysis

Interval one lower bound for the linkage value of H is given by

$H^{\wedge 4}$ = 0.65, to facilitate 4th order high propagation to be high.

Interval one lower bound for the linkage value of M is given by

$M^{\wedge 2}$ = 0.09, to facilitate 2th order medium propagation to be medium

H: 0.9 >= Linkage Value >= 0. 65

M:0.66 >= Linkage Value >= 0.08, overlap by 0.01 the high and low.

L: 0.09 >= Linkage Value >= 0

The first columns in the following tables represent the number of linkage values assigned to each values by the expert domain. The second column in the following tables indicate the number of matching C-FAR answers that have the same value. The third and forth columns indicate the number of C-FAR linkage values that do not match the experts linkage values. The last column indicates the percentage of matching answers between expert linkage values and calculated C-FAR linkage values.

H linkage value given by expert domain	Corresponding H linkage values given by C-FAR	Correspondi ng M linkage value given by C-FAR	Corresp. L linkage value given by C-FAR	Matching index
13	13	0	0	100%

Table 16.2 PWB Domain Expert High Linkage Value Results

M linkage value given by expert domain	Corresponding M linkage values given by C-FAR	Corresponding H linkage value given by C-FAR	Corresponding L linkage value given by C-FAR	Matching index
18	12	0	6	66%

Table 16.3 PWB Domain Expert Medium Linkage Value Results

L linkage value given by expert domain	Corresponding L linkage values given by C-FAR	Correspondin g H linkage value given by C-FAR	Corresponding M linkage value given by C-FAR	Matching index
45	40	0	5	89%

Table 16.4 PWB Domain Expert Low Linkage Value Results

Total linkage values examined	Matching linkage values	Over all matching index
76	65	85.5%

Table 16.5 PWB Domain Expert Overall Linkage Value Results

From Table 16.2-16.5 it is observed that C-FAR and the domain expert agree on attributes that have high linkage between them. However in the 33% of the cases of medium linkage value assigned by the expert domain, C-FAR considered these values to be low. In about 11% of the linkage values labelled as low by the experts were identified as medium by C-FAR.

Table 16.6 provides a closer look at the 11 mismatched values.

	Source entity attribute	**Target entity attribute**	**Domain Expert estimated Linkage value**	**C-FAR calculated Linkage value**
1	Electrical Component-length	Component Occurrence-surface	M	L/1
2	Electrical Component-width	Component Occurrence-surface	M	L/1
3	Linear Elastic Material G	Prepreg_Set total height	M	L/1
4	PWB board length	Location x	M	0.07/3
5	PWB board length	Location rotation	M	0.07/3
6	PWB board length	PWA num_sides	M	L/1
7	Electrical Component-power rating	Component Occurrence-surface	L	M/1
8	Electrical Component-power rating	PWA- number of sides	L	0.27/2
9	PWB size of layup	PWB_Therm model temp change	L	M/1
10	Prepreg_Set total height	PWA number of sides	L	0.35/2
11	Prepreg_Set total height	PWA # of components	L	0.35/2

Table 16.6 Mismatch Linkage Values

The next table classifies the linkage values by order of change.

Experts Linkage Value	Change propagation Order 1 / mismatch	Change propagation Order 2 / mismatch	Change propagation Order 3 / mismatch	Change propagation Order 4 or 5 / mismatch
H	9/-	3/-	-	-
M	8/2	6/2	3/2	2/-
L	10/2	15/3	9/-	11/-

Table 16.7 Linkage Values Classified By Order Of Change

16.3.3 Mismatching Linkage Value Analysis

Observing tables16.2-16.7 reveals three groups of mismatches. In the first group are rows number 1,2,3,6, and 7. The common element for this group of mismatches is that all of them occurred on the first level propagation, namely a mismatch on the C-FAR matrix construction linkage value. The mismatches are between the medium linkage values and low linkage values. The second group of mismatches includes lines 4 and 5. The calculated linkage value is 0.07, and the experts' linkage value is M. 0.07 is very close to 0.08, which is the lower bound of the medium interval determined in a previous section The third group of mismatches includes rows, 8, 10, and 11. The common denominator to this group is that the C-FAR calculated linkage values are of second order of change. In mismatch number 8, C-FAR calculated linkage value of medium while the experts evaluated this linkage value as low. The path between these attributes is: Electrical Component.power rating - Component Occurance.surface - PWA- number of sides. The first part of this path is row number 7, which has a low - medium mismatch. Therefore, the reason for the mismatch at row 8 is the same as for the first group: a mismatch in the

C-FAR matrix construction linkage value. The cause of the mismatches in rows 10 and 11 has its origins in two first-order propagation mismatches. The domain expert and the C-FAR matrix constructor gave different linkage values to Prepreg_Set.total.height - PWB.width and Prepreg_Set.total.height - PWB.width. Therefore, this case also belongs to the first group.

16.3.4 Numeric Linkage Value Analysis

C-FAR produces numerical linkage values that range between 0-0.9. Clearly, a linkage value of 0.9 indicates a stronger linkage than 0.01. However, does a linkage value of 0.2 indeed indicate a stronger linkage value of 0.02 ? Assuming that a high linkage value is indeed 0.9 and low is 0, the interesting linkage value in this aspect is the medium one. The expert had ranked the 18 occurrences of the medium linkage value in the PWB verification stage (Table 16.7). A rank of 3 is given to the strongest medium and a rank of 1 is given to the one that is closest to low linkage value.

Source entity attribute	**Target entity attribute**	**Domain Expert estimated Linkage value**	**Expert Rank**	**C-FAR**
Electrical Package-body style	Electrical Component-power rating	M	2	0.3
Electrical Package-body style	Electrical Component-cost	M	2	0.3
Electrical Component-length	Component Occurrence-surface	M	1	0
Electrical Component-width	Component Occurrence-surface	M	1	0
Electrical Component-height	Component Occurrence-surface	M	2	0.3
Electrical Package-body style	Component Occurrence-surface	M	3	0.3
Electrical Component-height	PWA-assembly order	M	3	0.3
Electrical Package-body style	PWA-total length	M	2	0.18
Component Occurrence-surface	PWB-total width	M	2	0.21
Electrical Package-body style	PWB-total width	M	2	0.15
PWB board length	Location x	M	2	0.07
PWB board length	Location rotation	M	1	0.07
PWB board length	PWA number of sides	M	1	0
PWB board length	Component Occurrence surface	M	1	0.27
Prepreg_Set total height	PWB_Thermal_Model length	M	1	0.2
Prepreg_Set total height	PWA cost	M	1	0.32
Prepreg_Set total height	Location Z	M	1	0.08
Linear Elastic Material G	Prepreg_Set total height	M	1	0

Table 16.8 Expert Ranked Medium Linkage Value

For each medium ranked linkage value group an average of the C-FAR matching linkage values is calculated. The results are illustrated in Figure 16.1

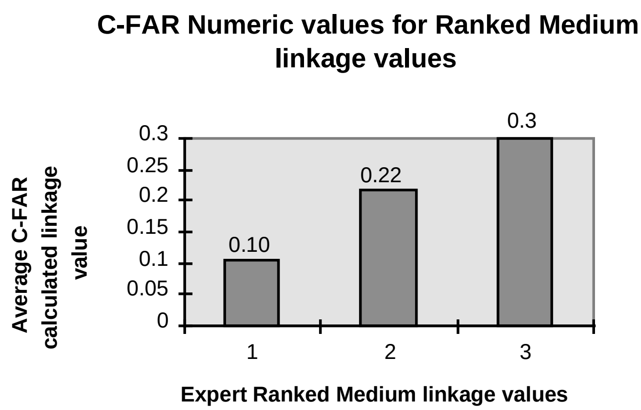


Figure 16.1 PWB C-FAR Numeric Values For Ranked Medium Linkage Values

The results as illustrated in Figure 16.1 indicate that the C-FAR numeric magnitude linkage value is indeed a reasonable estimator for linkage degree between the source to target attributes. The average C-FAR linkage value is ~0.1 for the weakest experts' medium linkage, ~0.2 for the middle group, and ~0.3 for the strong medium linkage value.

16.4 Injection Molding Case Study

Source entity attribute	**Target entity attribute**	**Domain Expert estimated Linkage value**	**C-FAR calculated Linkage value**
Part-Geometry.wall-thickness	Part.part-number	L	L/1
Part-Geometry.wall-thickness	Part.structural.req.	L	L/1
Part-Geometry.wall-thickness	Part.sink-mark	M	M/1
Part-Geometry.wall-thickness	Part.weld-line-location	H	H/1
Part-Geometry.undercuts	Part.cost	H	H/1
Part.weld-line-location	Mold.min-clamp-force	M	L/1
Part.warpage	Mold.number-of-cavities	M	L/1
Part.weld-line-location	Mold.cost	L	L/1
Part.sink-marks	Mold.cost	H	M/1
Part.structural.req.	Mold.cost	M	M/1
Part.finish.req.	Mold.cost	H	H/1
Part-Geometry.undercuts	Cavity-Core-Geometry.side-action-mechanism	H	H/1
Part-Geometry.blind-holes	Cavity-Core-Geometry.side-action-mechanism	M	H/1
Cavity-Core-Geometry.side-action	Mold.cost	H	H/1
Cavity-Core-Geometry.runner-specs	Mold.number-of-cavities	L	L/1
Material.viscosity	Process.mold-temp	M	M/1
Material.mfi	Process.open-time	L	L/1
Material.mfi	Process.injection-pressure	H	H/1
Mold-coolant.thermal-conductivity	Process.mold-temp	M	M/1

Table 16.9 Injection Molding Case Study Results

Source entity attribute	**Target entity**	**Domain**	**C-FAR**

	attribute	Expert estimated Linkage value	calculated Linkage value
Material.viscosity	Process.pack-time	M	H/1
Mold-coolant.thermal-cond.	Machine.max-clamping-force	L	L/2
Mold-coolant.thermal-conductivity	Process.barrel-zone1	L	L/1
Process.barrel-temp-zone1	Part.assembly-level	L	L/1
Process.mold-temp	Part.sink-marks	H	M/1
Process.injection-pressure	Part.warpage	H	M/1
Process.pack-time	Part.sink-marks	M	M/1
Part-Geometry.gate-loc	Part.weld-line-location	H	H/1
Part.weld-line-location	Process.mold-temp	M	M/1
Process.mold-temp	Mold-coolant.thermal-conductivity	H	H/1
Process.cooling-time	Mold-coolant.specific-heat-capacity	H	H/1
Process.barrel-temp-zone1	Mold-coolant.specific-heat-capacity	M	L/1
Part.weld-line-location	Mold-coolant.thermal-conductivity	M	0.09/2
Part-Geometry.gate-location	Mold-coolant.thermal-conductivity	M	0.13/3
Material.mfi	Process.barrel-zone1	H	H/1
Process.coolant-flow-rate	Material.hardness	L	L/1
Process.barrel-zone1	Cavity-Core-Material.wear-resistance	M	M/1
Process.open-time	Cavity-Core-Material.density	L	L/1
Process.fill-time	Cavity-Core-Material.thermal-cond	M	M/1
Material.mfi	Cavity-Core-Material.wear-resistance	M	0.45/2
Mold-Coolant.thermal-conductivity	Process.mold-temp	H	H/1

Table 16.9 Injection Molding Case Study Results (Cont.)

Source entity attribute	Target entity	Domain Expert	C-FAR

	attribute	**estimated Linkage value**	**calculated Linkage value**
Mold-coolant.density	Process.injection-pressure	L	L/1
Mold-Coolant.thermal-conductivity	Part.sink-mark	H	0.31/2
Process.sink-mark	Mold.minimum-clamping-force	H	M/1
Mold-Coolant.thermal-conductivity	Mold.minimum-clamping-force	M	0.22/3
Part.aesthetic-req.	Part-Geometry.gatelocation	H	H/1
Machine.max-clamping-force	Process.fill-time	H	H/1
Part.aesthetic-req.	Cavity-Core-Geometry.runner-specs	H	H/2
Process.barrel-temp-zone1	Mold-Coolant.specific-heat-capacity	M	L/1
Cavity-Core-Geometry.gate-specs	Machine.max-clamping-force	L	L/4

Table 16.9 Injection Molding Case Study Results (Cont.)

Source entity attribute	**Target entity attribute**	**Domain Expert estimated Linkage value**	**C-FAR calculated Linkage value**
Cavity-Core-Geometry.gate-specs	Machine.max-clamping-force	L	L/4
Mold-coolant.thermal-conductivity	Machine.cool-flow-rate	L	L/2
Part-Geometry.gate-location	Cavity-Core-Geometry.runner-specs	H	H/1
Part.aesthetic-req.	Cavity-Core-Geometry.side-action-mech	M	0.63/2
Process.fill-time	Cavity-Core-Material.density	M	M/1
Part.aesthetic-req.	Cavity-Core-Geometry.ejection-type	M	0.45/2
Machine.max-clamping-force	Cavity-Core-Material.thermal-conductivity	M	0.09/2
Part.aesthetic-req.	Cavity-Core-Geometry.sprue-specs	M	0.09/2
Cavity-Core-Geometry.gate-specs	Mold.min-clamping-force	M	M/1
Mold. min-clamp-force	Part.sink-marks	M	M/1
Part.shrinkage	Process.packing-pressure	L	M/1
Cavity-Core-Geometry.gate-specs	Part.sink-marks	M	0.27/2
Part.aesthetic-req.	Machine.max-clamping-force	L	L/2

Table 16.9 Injection Molding Case Study Results (Cont.)

16.4.1 Results Analysis

An explanation for the choice of numeric values for the linkage values is given at section 16.3.1

H: 0.9 >= Linkage Value >= 0. 65

M:0.66 >= Linkage Value >= 0.08

L: 0.09 >= Linkage Value >= 0

The first column in the following tables represent the number of linkage values assigned to each value by the expert domain. The second column in the following tables indicate the number of matching C-FAR answers that have the same value. The third and fourth columns indicate the number of C-FAR linkage values that do not match the expert linkage values. The last column indicates the percentage of matching answers between expert linkage values and calculated C-FAR linkage values.

H linkage value given by expert domain	Corresponding H linkage values given by C-FAR	Corresponding M linkage value given by C-FAR	Corresponding L linkage value given by C-FAR	Matching index
20	15	5	0	75%

Table 16.10 Injection Molding Domain Expert High Linkage Value Results

M linkage value	Corresponding	Corresponding	Corresponding	Matching

given by expert domain	M linkage values given by C-FAR	H linkage value given by C-FAR	L linkage value given by C-FAR	index
26	20	2	4	77%

Table 16.11 Injection Molding Domain Expert Medium Linkage Value Results

L linkage value given by expert domain	Correspondin g L linkage values given by C-FAR	Corresponding H linkage value given by C-FAR	Corresponding M linkage value given by C-FAR	Matching index
15	14	0	1	93%

Table 16.12 Injection Molding Domain Expert Low Linkage Value Results

Total linkage values examined	Matching linkage values	Over all matching index
61	49	80%

Table 16.13 Injection Molding Expert DomainOverall Linkage Value Results

From Tables 16.10-16.13 it is observed that C-FAR and the domain expert had a reasonable matching index of 80%. However, in four cases C-FAR calculated a value as medium while experts said it was high. In this case, the expert medium linkage value had seven mismatched results. Five of them had estimated the medium linkage values as low and two as high. There was one mismatch where C-FAR calculated a linkage value of medium and the expert assigned it a linkage value of low.

Table 16.14 provides a closer look on the 12 mismatched values.

Source entity attribute	**Target entity attribute**	**Domain Expert estimated Linkage value**	**C-FAR calculated Linkage value**
Part.weld-line-location	Mold.min-clamp-force	M	L/1
Part.warpage	Mold.number-of-cavities	M	L/1
Part.sink-marks	Mold.cost	H	M/1
Part-Geometry.blind-holes	Cavity-Core-Geometry.side-action-mechanism	M	H/1
Material.viscosity	Process.pack-time	M	H/1
Process.injection-pressure	Part.warpage	H	M/1
Process.mold-temp	Part.sink-marks	H	M/1
Process.barrel-temp-zone1	Mold-coolant.specific-heat-capacity	M	L/1
Mold-Coolant.thermal-conductivity	Part.sink-mark	H	0.31/2
Process.sink-mark	Mold.minimum-clamping-force	H	M/1
Process.barrel-temp-zone1	Mold-Coolant.specific-heat-capacity	M	L/1
Part.shrinkage	Process.packing-pressure	L	M/1

Table 16.14 Mismatched Linkage Values

The next table classifies the linkage values by order of change

Experts	Change	Change	Change	Change

Linkage Value	propagation Order 1 / mismatch	propagation Order 2 / mismatch	propagation Order 3 / mismatch	propagation Order 4 or 5 / mismatch
H	18/4	2/1	-	-
M	17/7	7/-	2/-	-
L	12/1	3/-	-	1/-

Table 16.15 Linkage Values Classified By Order Of Change

16.4.2 Mismatching Linkage Value Analysis

The mismatches in this case study are primarily caused by a mismatch from the first order. Namely, the reason for the mismatch is imbedded in the C-FAR matrix construction. Therefore, it is a gap between two opinions, namely the schema constructor and the expert domain. There is one mismatch of change propagation order 2. This mismatch, Mold-Coolant.thermal-conductivity vs Part.sink-mark, is illustrated in

Table 16.16

	Source entity attribute	**Target entity attribute**	**Domain Expert estimated Linkage value**	**C-FAR calculated Linkage value**
1.	Mold-Coolant.thermal-conductivity	Process.mold-temp	H	H/1
2.	Process.mold-temp	Part.sink-marks	H	M/1
3.	Mold-Coolant.thermal-conductivity	Part.sink-mark	H	0.31/2

Table 16.16 Example Mismatch Analysis

Row number three is calculated by C-FAR mostly from rows one and two. However, row number two contains a mismatch. Therefore, the mismatch in row three is based on a first order change.

16.4.3 Numeric Linkage Value Analysis

C-FAR produces numeric linkage values that range between 0-0.9. Clearly, a linkage value of 0.9 indicates a stronger linkage than 0.01. However, does a linkage value of 0.2 indeed indicate a stronger linkage value of 0.02 ?

Assuming that a high linkage value is indeed 0.9 and a low linkage value is 0, the interesting linkage value in this aspect is the medium one. The expert had ranked the 26 occurrences of the medium linkage value in the PWB verification stage (Table 16.17) A rank of 3 is given to the strongest medium and a rank of 1 is given to the weakest medium.

Source entity attribute	**Target entity attribute**	**Domain Expert estimated Linkage value**	**Exp Rank**	**C-FAR**
Part-Geometry.wall-thickness	Part.sink-mark	M	3	0.3
Part.weld-line-location	Mold.min-clamp-force	M	2	0
Part.warpage	Mold.number-of-cavities	M	1	0
Part.structural.req.	Mold.cost	M	1	0.3
Part-Geometry.blind-holes	Cavity-Core-Geometry.side-action-mechanism	M	3	0.9
Material.viscosity	Process.mold-temp	M	3	0.3
Mold-coolant.thermal-conductivity	Process.mold-temp	M	1	0.3
Material.viscosity	Process.pack-time	M	2	0.9
Process.pack-time	Part.sink-marks	M	2	0.3
Part.weld-line-location	Process.mold-temp	M	1	0.3
Process.barrel-temp-zone1	Mold-coolant.specific-heat-capacity	M	1	0
Part.weld-line-location	Mold-coolant.thermal-conductivity	M	1	0.09
Part-Geometry.gate-location	Mold-coolant.thermal-conductivity	M	1	0.13
Process.barrel-zone1	Cavity-Core-Material.wear-resistance	M	2	0.3
Process.fill-time	Cavity-Core-Material.thermal-conductivity	M	1	0.3
Material.mfi	Cavity-Core-Material.wear-resis.	M	2	0.45

Table 16.17 Expert Ranked Medium Linkage Value

Source entity attribute	**Target entity attribute**	**Domain Expert estimated Linkage value**	**Expert Rank**	**C-FAR**
Mold-Coolant.thermal-conductivity	Mold.minimum-clamping-force	M	1	0.22
Process.barrel-temp-zone1	Mold-Coolant.specific-heat-capacity	M	2	0.3
Part.aesthetic-req.	Cavity-Core-Geometry.side-action-mech	M	2	0.63
Process.fill-time	Cavity-Core-Material.density	M	1	0.3
Part.aesthetic-req.	Cavity-Core-Geometry.ejection-type	M	3	0.45
Machine.max-clamping-force	Cavity-Core-Material.thermal-conductivity	M	1	0.09
Part.aesthetic-req.	Cavity-Core-Geometry.sprue-specs	M	1	0.09
Cavity-Core-Geometry.gate-specs	Mold.min-clamping-force	M	2	0.3
Mold. min-clamp-force	Part.sink-marks	M	2	0.3
Cavity-Core-Geometry.gate-specs	Part.sink-marks	M	1	0.27

Table 16.17 Expert Ranked Medium Linkage Value (Cont.)

For each medium ranked linkage value group, an average of the C-FAR matching linkage values is calculated. The results are illustrated in Figure 16.2

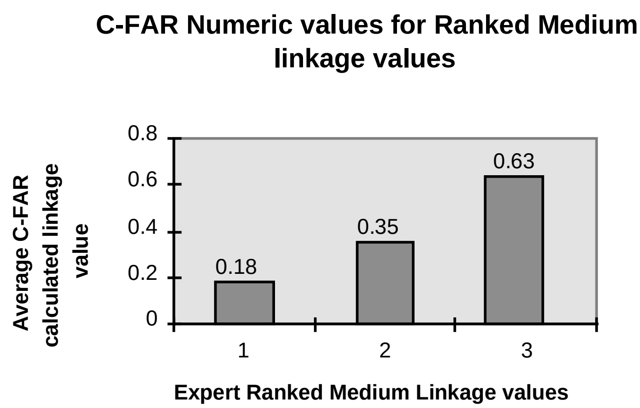


Figure 16.2 Injection Molding Numeric Values For Ranked Medium Linkage Values

The results as illustrated in 16.2 indicate that the C-FAR numeric value magnitude linkage value is indeed a reasonable estimator to linkage degree between the source and target attributes. The average C-FAR linkage value is ~0.18 for the weakest experts medium linkage, ~0.35 for the middle group and ~0.63 for the strong medium linkage value.

16.5 C-FAR vs. Independent Domain Expert Summary

This section tried to estimate the quality of the C-FAR output. A set of over one hundred source and target pairs for PWB and injection molding case studies were assigned linkage values in two ways. For each pair, both C-FAR and an independent domain expert who was not literate in C-FAR assigned linkage values. For both case studies, the correlation between the two set of linkage values was an encouraging ~80%. Moreover, non of the mismatches was high and low or low and high. The mismatches were between medium and low or medium and high. All the mismatches between the domain expert and C-FAR originated at the level of matrix construction. Namely, there was a disagreement between the domain expert and C-FAR schema constructor. Mismatches may occur in two places, the matrices construction and change propagation mechanism. It is likely that the propagation mechanism functioned very well. Another indication of the goodness of the C-FAR calculated linkage values is the correlation between the medium linkage values assigned by the expert and the corresponding calculated C-FAR linkage values. An expert in each domain was asked to divide the medium linkage values into three groups: strong medium, medium medium and low medium. An average of the corresponding C-FAR linkage value groups agreed with the classification done by the expert. These measurement indicate C-FAR estimates the linkage value in a reasonable manner and the results are satisfactory.

Chapter 17

Verification Summary

The verification process measured C-FAR in several dimensions. The first was an isolated test for the C-FAR matrix construction mechanism. The survey dealt with a technical pinball ball and piston mechanism. Eighteen respondents answered the survey and provided important data. In general, the overall survey results were reasonable. From twenty eight linkage values that were listed in the survey, respondents were asked to assign one of three linkage values: high, medium, or low. The overall average for the percentage average of the dominant linkage value was 76%. The second verification measurement was the scenarios verification section. Its role was to decided whether the C-FAR methodology indeed managed to correctly evaluate the change influence of the source on the target. The definition of successful C-FAR estimation in this framework was divided onto two levels. The first level was whether the C-FAR calculated linkage value was high where it should have been low or low were it should have been high. The second success measure level asked whether C-FAR results were reasonable. Since the core of C-FAR relies on high, medium, and low estimations, the resulting numeric linkage values presented an estimation of the quality of linkage. The four case study examples successfully passed both these criteria. The third verification part compared C-FAR calculated linkage values and linkage values assigned by experts domain. This part successfully showed that there is a reasonable correlation between those linkage values. For the PWB case study the ~85% of the linkage values assigned by the expert were matched by C-FAR and ~80% in the injection molding case. Therefore it can be claimed that the C-FAR methodology predicts on a satisfactorily .

17.1 PWB vs. Injection Molding

The PWB and the injection molding verification case studies were both done using the same procedures. First, the thesis author presented the C-'FAR matrix construction theory to the expert domains, and after a guidance stage the experts filled up the matrices independently. The domain expert recommended a set of verifying scenarios on which the verification stage was based.. Different expert domains that were not exposed to the C-FAR model were asked to verify C-FAR output in a detailed fashion. The PWB case study exhibited a better correlation between the domain expert evaluation and C-FAR. There may be several probable reasons. From a subjective aspect, the PWB domain expert evaluator came from the same research group as the C-FAR matrix constructor. Moreover, the PWB domain expert was exposed to the PWB EXPRESS model that the C-FAR diagram was based on. However, the injection molding experts were from separate research group and the evaluator domain expert was not exposed to the any of the matrix constructor work. From objective perspective, the injection molding C-FAR model coverage had more attributes hence more attribute dependencies than the PWB case study. Therefore, it is possible that for more complex problems, C-FAR may have a tougher task estimating linkage values.

17.2 C-FAR Matrix Construction

The survey results emphasized several points. First, the C-FAR matrix linkage value of high, medium, and low provided a reasonable tool for ranking a linkage in a satisfactory manner. Secondly, it was imperative that the C-FAR matrix constructor understand and know the attribute and a change to the attribute meanings. For example, in the survey (Chapter 14) the overall percentage average of the dominant linkage value was 76%. However, most of the linkage values that lowered this average were involved in specific attributes. Ball manufacturer and Assembly direction are two of those attributes. The role of these attributes in the pinball piston mechanism requires more knowledge and understanding in the domain, compared to spring elastic coefficient and ball maximum speed. Without those attributes, the overall percentage average of the dominant linkage value rose to 82%.

In Chapter 16 C-FAR vs. Independent Domain Expert analysis, the results indicated that all of the mismatches between the domain expert and C-FAR were originated since the schema constructor assigned different linkage value than the expert domain. The linkage discrepancies were between medium and low linkage value or high and medium linkage value. It was interesting to observe that there were no discrepancies between high and low linkage values. Nevertheless, the overall correlation between the domain expert and C-FAR for the PWB and the injection molding case studies was ~80% and above.

Inherently, C-FAR matrix construction was subjective. However, the case studies demonstrated a reasonable correlation among experts domain.

17.3 Change Propagation Mechanism

In general, the change propagation was a vector and matrix multiplication operation. The multiplication represented change propagation from one entity to another. The change vector of the source entity was multiplied by the C-FAR matrix that connected it to the next entity.

The C-FAR methodology relied on a subjective part and objective part. The subjective part is the C-FAR matrix construction and the objective part was the change propagation mechanism. The change propagation mechanism included a set of algorithms and assumptions. The results from the scenario analysis where all the scenarios results were considered successful showed that the mechanism adequately facilitated the change to propagate from the source to target entity. Moreover, the results from previous section indicated that all of the mismatches occurring in the PWB and the injection molding stage originated in the schema construction stage, the subjective stage. This finding demonstrated that the change propagation mechanism, the objective part of C-FAR, is functioning very well. Therefore it can be claimed that the C-FAR mechanism facilitated change propagation in a reasonable manner.

17.4 Numeric Linkage Value

An instrumental question in C-FAR analysis concerned the meaning of the numeric linkage value answer. By assigning a linkage value of 0.9 to high linkage value, 0.3 to medium and 0 to low, it was reasonable to assume that a calculated linkage value of 0.3 hints on a stronger linkage than 0.03. However, in a lower degree of confidence it could be claimed that 0.3 hinted at a stronger linkage than 0.25. Nevertheless, the numeric linkage values analysis in section 16.3.5 and 16.4.5 for both the PWB case study and the injection molding case study showed that most likely a larger calculated linkage value hints at stronger linkage.

17.5 C-FAR Correctness

The C-FAR correctness as defined in Chapter 4 depends on one main element: C-FAR methodology of change representation, matrix construction and change propagation. The scenario verification stage as well as the C-FAR vs. Independent Domain Expert part tested both of these elements. This thesis assumes that the EXPRESS model adequately describes the engineering domain it is suppose to cover. However, the scenario analysis and the C-FAR vs. Independent Domain Expert verification stages results may be affected as a result of a mediocre EXPRESS model. Both these verification stages illustrated good results that suggest acceptable EXPRESS model coverage as well as satisfactory C-FAR methodology. Therefore, it can be claimed that the C-FAR methodology has a reasonable level of correctness.

PART V

CLOSING REMARKS

Chapter 18

Future Work

18.1 Expanding Usage of EXPRESS information

C-FAR uses the three main elements of EXPRESS: entities, attributes and relations between the entities. The EXPRESS model provides more information about the problem domain than is used by C-FAR. Constraints, functions and other data types provide insight that is still not used by C-FAR. C-FAR can be further developed so that it makes better use of this information. For example, the usage of mathematical expression among attributes to complement the notion of linkage values. Another possible example is the exploration of cardinality constraints in the C-FAR paradigm Constraints and functions provide relations between parameters. However unlike C-FAR matrices these relations can be implicit and complex. An interesting idea can be creating a relation equivalent C-FAR matrices for constraints.

18.2 C-FAR Schema Integration

An important aspect in large information modeling tasks is schema integration. Several authorities may compose various aspects of an information schema and then integrate it. Therefore, it may be useful to implement C-FAR on a large scale project across different domains to test its methodology for extensibility. The C-FAR schema integration will probably increase the number of relation and entities. Since the finding simple path algorithm cost is of O(V!) it is recommended to explore clustering and abstraction algorithm that will utilize the characteristics of integrated schema.

Tools to construct C-FAR matrices may be beneficial specifically if larger domain are modeled. A tool that explains the attributes meaning in the domain context, will be helpful in describing large C-FAR schemes.

18.3 Fuzzy Theory and Representation For Linkage Values

The calculated linkage value outputted by C-FAR is a numeric value between 0-0.9. A High linkage value is assigned the value 0.9, a medium linkage value is 0.3 and a low linkage value is 0. However, what linkage value is 0.1? Is it consider medium, low, or perhaps medium-low? The same can be asked about 0.45 or 0.65 linkage values -- are they high or medium or medium-high? The answer is not clear. A linkage value of 0.45 is likely to hint at stronger linkage than medium-0.3. However, 0.45 hints at a slightly lower linkage value than high (0.9).

In fuzzy theory, fuzzy numbers [Kaufman, 84] allow terminology definition with a degree of confidence. For example, the value 0 has a low linkagee value with a 100% degree of confidence. An example of fuzzy numbers is illustrated in Figure 18.1

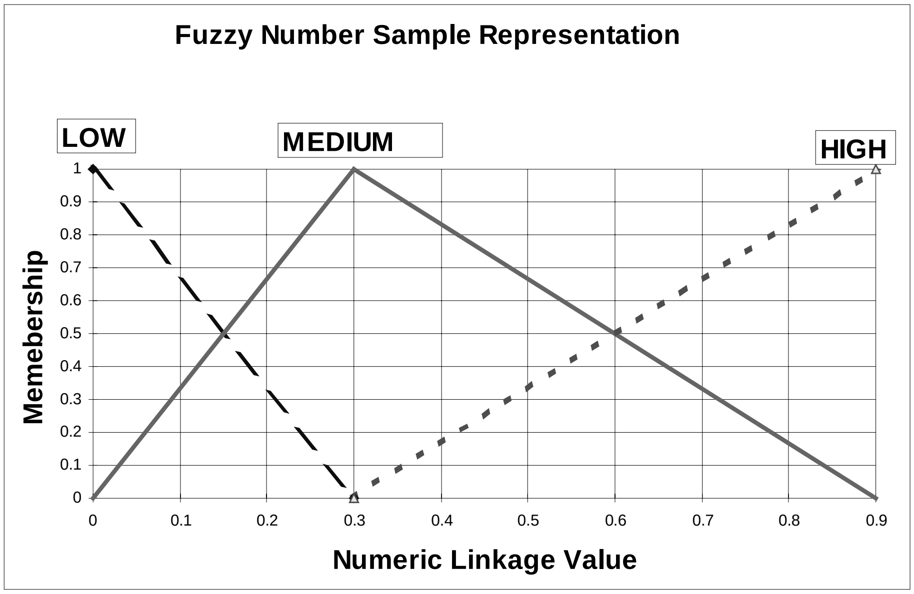


Figure 18.1 Example Fuzzy Number Representation

The left dash line represents the low linkage value. The solid two lines in the middle of 18.1 represent the medium linkage value and the dotted line to the right represents the high linkage value.

The low linkage value according to this example has a membership 0.5 at 0.15. That means that a linkage value of 0.15 according to this schema has 50% membership in the low number. The medium linkage value has membership of 0.5 at 0.15 and 0.6. This diagram indicates that a linkage value of 0.45 means that it has 75% degree of confidence to be medium and 25% degree of confidence to be high and 0% to be low.

This fuzzy number can be used as an input when constructing C-FAR matrices, and consequently the output will be a fuzzy number. C-FAR conducts simple arithmetic manipulations that can be done on fuzzy numbers. For example, the addition of two medium linkage values yields a fuzzy number which is compounded of two lines, one that starts at (0,0) and ends at (0.6,1). The second start at (0.6,1) and ends at (0.9, 0.75). Choosing a function that describes a fuzzy number can be done by experimentally determining the occurrences of its values. The relevancy to C-FAR of the concepts of membership and linkage value function representation should be checked on larger case study than the ones provided in this thesis.

18.4 C-FAR As A Tool For Evaluating Data Modeling

The quality of the EXPRESS model in general is reflected in its ability to truly describe the engineering domain it is suppose to cover. Since C-FAR is built on top of EXPRESS, different EXPRESS models will most likely yield different C-FAR models. An interesting point to examine is how the quality of an EXPRESS information model is reflected in the C-FAR model characteristics. Moreover, if there is a goodness correlation, can any element of C-FAR methodology be an indicator of the quality of the EXPRESS information model? For example, what is the EXPRESS contextual meaning for a C-FAR matrix that has only low linkage values?

18.5 Expanding The Notion of Change

In this research an attribute was subjected to a change. However this change did not have any characteristics, e.g. increase, decrease, large, very large, small, etc. An interesting future research direction is the evolution of C-FAR that will allow more comprehensive notion of change

Chapter 19

Conclusions

This research attempted to aid the redesign process by introducing data driven change representation and a propagation mechanism. The main innovation element in this research was devising, implementing and verifying a methodology to utilize existing information for representing change and its consequences. In increasingly complex engineering domain problems, data modeling has become an important aid to understanding and conveying the domain nature.

Information models are now being developed to support management of key engineering data. The results of this study show that such information models provide a global representation of the linkages among the various engineering components and as such, can be used to assess the propagation of engineering changes.

The thrust of this thesis was to develop a methodology -- C-FAR -- that would utilize this knowledge reservoir to accommodate change representation and change propagation. The information model used in this research was the EXPRESS model.

C-FAR's coverage and change representation is very dependent on the information model scope. There are two important points that may degrade C-FAR performance. First, an inaccurate EXPRESS model will consequently damage C-FAR capability to represent or reflect changes in a reasonably correct manner. Secondly, since C-FAR evaluates change by attribute values, the evaluation will only reach as far as the EXPRESS attributes allow.

The EXPRESS information model is composed of meta data that define data objects and describe the connectivity among them. Meta data attributes define various instances that are defined by attribute values. C-FAR facilitates change representation for the information model data instances. C-FAR uses domain experts to enhance the EXPRESS schema in order to facilitate attribute change representation and propagation. C-FAR deals with engineering domain complex problems. Therefore, change consequences are difficult to quantify. C-FAR's choice for describing change influences are high linkage for strong influence value; medium linkage value for some influence; and low linkage value for no influence. The introduction of domain expert input gives the C-FAR approach a somewhat subjective nature. However, engineering in general, and engineering modeling in particular, contain many subjective issues. This thesis devised a combined subjective expert-structured input together with objective algorithmic methods to facilitate a qualitative evaluation for attribute change consequences. The methodology was developed and evaluated by case study implementation. The case studies were taken from different engineering domains: a truss structure analysis, an automobile bumper schema, a printed wiring board schema and an injection molding process. A set of change scenarios were assigned for each case study. The scenario results were evaluated by a domain expert and were declared successful. Extensive comparative results were obtained for the printed wiring board and injection molding case studies. An independent domain expert who had not been not exposed to the C-FAR model gave linkage value evaluations for a set of changes. The expert results were compared with C-FAR assigned linkage values. The matching index between those assessments were reasonable.

Overall, the C-FAR objectives were relevancy of coverage, facilitation of change representation, and change propagation, and verification of a reasonable level of correctness. In Chapter 15, it was shown that the C-FAR development on top of EXPRESS facilitated fruitful engineering coverage. The case studies illustrated the capability of C-FAR to represent change and change propagation (Chapters 8,9,19,11). In the verification stage it was shown (Chapters 13,14,15,16) that C-FAR linkage value evaluations were on a reasonable level of correctness. Therefore, the conditions of the hypothesis (Chapter 4) were satisfied.

APPENDICES

Appendix A

C-FAR Matrix Construction Survey

In this experiment you are asked to specify a **LINKAGE VALUE** between two elements.

Linkage value may take one of three values. High, Low and Medium

What does **Low** linkage value mean?

A linkage value of **Low** between element A to element B means that if you **change** the value of element A it ***does not influence*** element B

What does **High** linkage value mean?

A linkage value of **High** between element A to element B means that if you **change** the value of element A it ***strongly influences*** element B

What does **Medium** linkage value mean?

A linkage value of **Medium** between element A to element B means that if you **change** the value of element A it ***somewhat influence*** element B

<u>Here is an example to illustrate this terminology</u>:

Given a bottle that contains some liquid. The relation to be examined is between the Bottle itself and the liquid

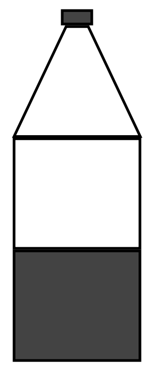


Figure A.1 Survey Example

The bottle attributes are:

1. Bottle Size
2. Bottle Material (Glass, Plastic, etc.)

The liquid attributes are:

1. Liquid type (Wine, Beer, Water, Soft drink, Oil, Milk, etc.)
2. Liquid Quantity

The example illustrate how to determine the **Linkage value** between all the liquid attributes to all the bottle attributes.

How a change in the Liquid type influences the bottle's attributes ?

Linkage Value **Linkage Value**

	Influences Bottle Size	**Influences** Bottle Material (Glass, Plastic, etc.)
How change in Liquid type	**Medium**	**High**

Table A.1 Example Linkage Value

Explanations:

1. Change in the Liquid type somehow related to the bottle size, there are different liquids types that have the same bottle size and there are liquids types with unique bottle sizes. We can not say that there is no linkage at all between Liquid type and Bottle Size. However we can not say there is a strong linkage between them. So we label the linkage value as **Medium.**
2. Change in the Liquid type is strongly related to the choice of bottle material. For milk, plastic for alcoholic beverages - glass etc. we can say there is a strong linkage between them. Therefor we label the linkage value as **High.**

How a change in the Liquid Quantity influences the bottle's attributes ?

Linkage Value **Linkage Value**

	Influences Bottle Size	**Influences** Bottle Material (Glass, Plastic, etc.)
How change in Liquid Quantity	**High**	**Low**

Table A.2 Example Linkage Value

Explanations:

1. Change in the Liquid quantity is strongly related to the bottle size, we can say there is a strong linkage between them. Therefor we label the linkage value as **High.**

2. Change in the Liquid quantity does not related to the choice of bottle material. For example dringing water comes in a plastic container in all sizes. We can say there is no linkage between them. Therefor we label the linkage value as **Low.**

In the following drawing we are examining a Pin Ball piston mechanism.

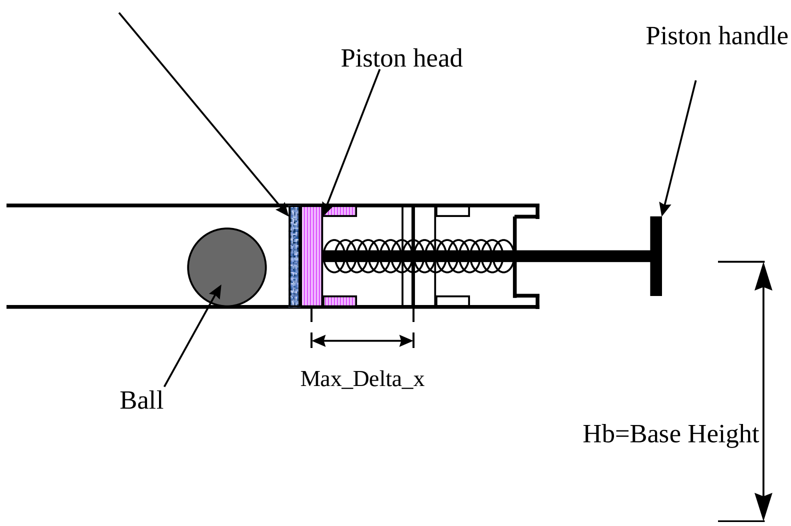


Figure A.2 Ball Piston Mechanism

The two entities to be examined are the Ball and the Piston

THE PISTON'S ATTRIBUTES ARE:	THE BALL'S ATTRIBUTES ARE:
1. Piston cost 2. Max_Delta_x - The max spring compression distance.	1. **Ball diameter** 2. **Ball maximum velocity**
3. Hb (Base Height) - Piston hight from the pinball machine base.	3. **Ball Manufacturer**
4. Assembly directions	**4. Ball material**
5. Piston head material impact cover 6. Piston handle diameter	
7. Piston head diameter	

Table A.3 Survey's Attributes

Directions: Please fill up each of the empty boxes in the table with either, **H, M, L.**

H- means that a change in a Piston attribute ***strongly influences*** the specific Ball attribute

M- means that a change in a Piston attribute ***somehow, may influences*** the specific Ball attribute

L- means that a change in a Piston attribute ***Does not influences*** the specific Ball attribute

------------Ball attributes→ **Piston attributes**	**Influences** Ball diameter	**Influences** Ball maximum velocity	**Influences** Ball Manufacturer	**Influences** Ball material
How change in Piston cost				
How change in Max_Delta_x				
How change in Hb (Base Height)				
How change in Assembly directions				
How change in Piston head material impact cover				
How change in Piston handle diameter				
How change in Piston head diameter				

Table A.4 Survey's Answer Sheet

Thanks

Appendix B

2D Truss Structural Model Case Study

B.1 EXPRESS Model

The EXPRESS information model for the 2D-Truss is given below

```
Schema 2D-Truss;

(* ******************************************************
Developed by: Tal Cohen

        Engineering Information Systems Laboratory
        Georgia Institute of Technology
        Atlanta, GA

June 01, 1997
****************************************************** *)


ENTITY Element_Structure;
      is_compound_of : Element;
      is_connected_with : Node;
      number_of_nodes : INTEGER;
      number_of_loads : INTEGER;
      number_of_elemens : INTEGER;
      number_of_supports : INTEGER;
      orientation_point: 2D_point;
UNIQUE:
      structure_id : INTEGER;
END_ENTITY;

ENTITY Node;
      node_ layer: INTEGER;
      x_location : REAL;
      y_location : REAL;
      x_disp : REAL;
```

```
        y_dsip: REAL;
UNIQUE:
    node_ number : INTEGER;
END_ENTITY;

ENTITY Element;
        ABSTRACT SUPERTYPE OF ( ONEOF( link_2D )  );
        bounded_by : Node;
        element_layer : INTEGER;
        material_code : INTEGER;
        elatic_module: REAL;
UNIQUE:
        element_number : INTEGER;
END_ENTITY

ENTITY link_2D;
        SUBTYPE OF ( Element );
        cross_section_area : REAL;
        2D-length: REAL;
END_ENTITY

ENTITY Lode;
    applied_on : Node;
        load_type : STRING;
        load_x_dir_val : REAL;
        load_y_dir_val : REAL;
UNIQUE:
        load_number: INTEGER;
END_ENTITY;



ENTITY Force_Vector;
    is_compund_of : Load;
        vector_dimension: INTEGER;
UNIQUE:
    vector_id : STRING;
END_ENTITY;

ENTITY Flexibility_Matrix;
    has_a : Load;
        belongs_to : Element_Structure;
        deg_freedom: INTEGER;
```

```
UNIQUE:
        matrix_id : STRING;
END_ENTITY;

END_SCHEMA (*2D-Truss *);
```

B.2 Flat EXPRESS Model

```
Flat EXPRESS Schema 2D-Truss {


/*
Developed by: Tal Cohen

         Engineering Information Systems Laboratory
         Georgia Institute of Technology
         Atlanta, GA

June 01, 1997
*/



Element_Structure{
   entity Flexibility_Matrix;
   entity link_2D;
   entity Node;
   attribute structure_id ;
        attribute number_of_nodes;
        attribute number_of_loads ;
        attribute number_of_elemens ;
        attribute number_of_supports ;
        attribute orientation_point;
};

Node {
        entity Load;
   entity link_2D;
   entity Element_Structure;
        attribute node_ number;
        attribute node_ layer;
```

```
        attribute x_location;
        attribute y_location;
        attribute x_disp;
        attribute y_dsip;
};
link_2D {
        entity Node;
        entity Element_Structure;
        attribute element_number;
        attribute element_layer;
        attribute material_code;
        attribute elatic_module;
        attribute cross_section_area;
        attribute 2D-length;
};
Lode {
    entity  Node;
    entity  Force_Vector;
    attribute load_number;
        attribute load_type;
        attribute load_x_dir_val;
        attribute load_y_dir_val;
};
Force_Vector {
    entity Load;
        entity Flexibility_Matrix;
        attribute vector_id;
        attribute vector_dimension;
}

Flexibility_Matrix{
    entity Load;
        entity Element_Structure;
        attribute matrix_id;
        attribute deg_freedom;
}

END_SCHEMA (*2D-Truss *);
```

B.3 C-FAR Matrices

Force_Vector **Flexibility_Matrix**	vector_dimension	vector_id
number_deg_of_freedom	H/H	L/L
matrix_id	L/L	H/H

Table B.1 Force_Vector vs. Flexibility_Matrix

Flexibility_Matrix **Element_Structue**	number_deg_of_freedom	matrix_id
number_of_nodes	H/H	L/L
number_of_loads	M/M	L/L
number_elements	H/H	L/L
number_of_supports	M/M	L/L
orientation_pnt	L/L	L/L
structure_id	L/L	H/H

Table B.2 Flexibility_Matrix vs. Element_Structure

link_2D **Element_Structue**	element number	element layer	material code	elastic module	cros_sec _area	2D-length
number_of_nodes	L/L	L/L	L/L	L/L	L/L	L/L
number_of_loads	L/L	L/L	L/L	L/L	L/L	L/L
number_elements	L/L	L/L	L/L	L/L	L/L	L/L
number_of_supports	L/L	L/L	L/L	L/L	L/L	L/L
orientation_pnt	L/L	L/L	L/L	L/L	L/L	L/L
structure_id	H/H	L/L	L/L	L/L	L/L	L/L

Table B.3 Element_Structure vs. link_2D

Node **Element_Structue**	node number	node layer	x location	y location	x disp	y disp
number_of_nodes	L/L	L/L	L/L	L/L	H/L	H/L
number_of_loads	L/L	L/L	L/L	L/L	H/L	H/L
number_elements	L/L	L/L	L/L	L/L	H/L	H/L
number_of_supports	L/L	L/L	L/L	L/L	H/L	H/L
orientation_pnt	L/L	L/L	M/L	M/L	L/L	L/L
structure_id	H/M	L/L	L/L	L/L	L/L	L/L

Table B.4 Element_Structure vs. Node

Node **link_2d**	node number	node layer	x location	y location	x disp	y disp
element_number	H/H	L/L	L/L	L/L	L/L	L/L
element_layer	L/L	H/H	L/L	L/L	L/L	L/L
material_code	L/L	L/L	L/L	L/L	H/L	H/L
elatic_module	L/L	L/L	L/L	L/L	H/L	H/L
cross_sec_area	L/L	L/L	L/L	L/L	H/L	H/L
2D_length	L/L	L/L	M/M	M/M	M/H	M/H

Table B.5 link_2d vs. Node

Node **Load**	node number	node layer	x location	y location	x disp	y disp
load_type	L/L	L/L	L/L	L/L	L/L	L/L
load_number	H/H	L/L	L/L	L/L	L/L	L/L
load_x_dir_val	L/L	L/L	L/L	L/L	H/L	H/L
load_y_dir_val	L/L	L/L	L/L	L/L	H/L	H/L

Table B.6 Node vs. Load

Load **Force_Vector**	load_type	load_number	load_x_dir_val	load_y_dir_val
vector_dimension	L/L	L/L	L/L	L/L
vector_id	L/L	H/H	L/L	L/L

Table B.7 Load vs. Force_Vector

Force_Vector **Force_Vector**	vector_id	vector_dimension
vector_id	I	L/L
vector_dimension	-	I

Table B.8 Force_Vector vs. Force_Vector C-FAR Orthogonality Matrix

Load **Load**	load type	load number	load_x dir_val	load_y dir_val
load_type	I	L/L	L/L	L/L
load_number	-	I	L/L	L/L
load_x_dir_val	-	-	I	L/L
load_y_dir_val	-	-	-	I

Table B.9 Load vs. Load C-FAR Orthogonality Matrix

Flexibility_Matrix **Flexibility_Matrix**	number_deg_of_freedom	matrix_id
number_deg_of_freedom	I	L/L
matrix_id	-	I

Table B.10 Flexibility_Matrix vs. Flexibility_Matrix C-FAR Orthogonality Matrix

Element_Structue **Element_Structue**	number nodes	number loads	number elements	number supports	orientation pnt	structure id
number_of_nodes	I	M/M	H/H	M/M	L/L	L/L
number_of_loads	-	I	M/M	M/M	L/L	L/L
number_elements	-	-	I	M/M	L/L	L/L
number_of_supports	-	-	-	I	L/L	L/L
orientation_pnt	-	-	-	-	I	L/L
structure_id	-	-	-	-	-	I

Table B.11 Element_Structue vs. Element_Structue C-FAR Orthogonality Matrix

Node	node	node	x_location	y_location	x_disp	y_disp

Node	number	layer				
node_number	I	L/L	L/L	L/L	L/L	L/L
node_layer	-	I	L/L	L/L	L/L	L/L
x_location	-	-	I	L/L	L/L	L/L
y_location	-	-	-	I	L/L	L/L
x_disp	-	-	-	-	I	M/M
y_disp	-	-	-	-	-	I

Table B.12 Node vs. Node C-FAR Orthogonality Matrix

Element.link_2D **Element.link_2D**	element number	element layer	material code	elastic module	cross section area	2D-length
element_number	I	L/L	L/L	L/L	L/L	L/L
element_layer	-	I	L/L	L/L	L/L	L/L
material_code	-	-	I	L/L	L/L	L/L
elastic_module	-	-	-	I	L/L	L/L
cross_section_area	-	-	-	-	I	L/L
2D-length	-	-	-	-	-	I

Table B.13 Element.link_2D vs. Element.link_2D C-FAR Orthogonality Matrix

Appendix C

Bumper Case Study

C.1 EXPRESS Model

```
Schema Bumper

(* *******************************************************
Developed by: Tal Cohen

        Engineering Information Systems Laboratory
        Georgia Institute of Technology
        Atlanta, GA

Dec 01, 1996
******************************************************* *)

ENTITY Bumper;
      is_compound_of : Bumper_Component;
      is_attached_to : Auto_Front_Chasis;
      is_tested_by : Bumper_Test;
      weight : weight_unit;
      length : length_unit;
      width : length_unit;
      depth : length_unit;
      height : length_unit;
      color : color_type;
      offset : length_unit;
      styling_req : req_type;
      corrosion_resistance_req : req_type;
      weight _reduction_req : req_type;
      damage_protection : req_type;
      engine_cooling_req : req_type;
      cost : cost_unit;
UNIQUE:
      part_assembly_number : STRING;
END_ENTITY;
```

```
ENTITY Bumper_Component;
          ABSTRACT SUPERTYPE OF ( Energy_Absorbent, Bumper_Beam,
          Bumper_Facia, Bumper_Brackets);
          weight : weight_unit;
          length : length_unit;
          width : length_unit;
          depth : length_unit;
          cost : cost_unit;
UNIQUE:
    part_ number : STRING;
END_ENTITY;

ENTITY Energy_Absorbent;
          SUBTYPE OF (Bumper_Component );
          material_code : STRING;
          absorber_density : dens_ratio;
          absorber_pattern : pattern;
END_ENTITY

ENTITY Bumper_Beam;
          SUBTYPE OF (Bumper_Component );
          material_code : STRING;
          beam_profile : profile_type;
          wall_thickness : length_unit;
          elas_module : tens/com_unit;
          beam_type : material_classification;
END_ENTITY


ENTITY Bumper_Facia;
          SUBTYPE OF (Bumper_Component );
          material_code : STRING;
          facia_color : color_type;
          facia_rigidity : facia_type;
          facia_process : process_type;
END_ENTITY

ENTITY Bumper_Brackets;
          SUBTYPE OF (Bumper_Component );
          bracket_mechanism : brack_type;
          max_deflection : length_unit;
          max_energy : energy_unit;
```

```
END_ENTITY

ENTITY Auto_Front_Chasis
    base_height : length_unit;
    max_rail_load : energy_unit;
END_ENTITY

ENTITY Bumper_Test;
          ABSTRACT SUPERTYPE OF (ONEOF (Pendulum_Test, Barrier_Test);
          test_location : point_location;
END_ENTITY;

ENTITY Pendulum_Test;
          SUBTYPE OF (Bumper_Test);
          pendulum_weight : weight_unit;
          pendulum_speed: speed_unit;
END_ENTITY

ENTITY Barrier_Test;
          SUBTYPE OF (Bumper_Test);
          test_velocity : velocity_unit;
END_ENTITY

END_SCHEMA (Bumper);
```

C.2 Flat EXPRESS Model

```
Flat EXPRESS Schema Bumper {

/*
Developed by: Tal Cohen

            Engineering Information Systems Laboratory
            Georgia Institute of Technology
            Atlanta, GA

Dec 01, 1996
*/

Bumper {
          entity Bumper_Component.Energy_Absorbent;
          entity Bumper_Component.Bumper_Beam;
```

```
        entity Bumper_Component.Bumper_Facia;
        entity Bumper_Component.Bumper_Brackets;
        entity Auto_Front_Chasis;
        entity Bumper_Test.Pendulum_Test;
        entity Bumper_Test.Barrier_Test;
        attribute part_assembly_number;
        attribute weight;
        attribute length;
        attribute width;
        attribute depth;
        attribute height;
        attribute color;
        attribute offset;
        attribute styling_req;
        attribute corrosion_resistance_req;
        attribute weight _reduction_req;
        attribute damage_protection;
        attribute engine_cooling_req;
        attribute cost;
};

Bumper_Component.Energy_Absorbent{
    attribute part_ number;
        attribute weight;
        attribute length;
        attribute width;
        attribute depth;
        attribute cost;
        attribute material_code;
        attribute absorber_density;
        attribute absorber_pattern;
};

Bumper_Component.Bumper_Beam {
    attribute part_ number;
        attribute weight;
        attribute length;
        attribute width;
        attribute depth;
        attribute material_code;
        attribute beam_profile
        attribute wall_thickness
        attribute elas_module
```

```
        attribute beam_type
};

Bumper_Component.Bumper_Facia {
        attribute part_ number;
        attribute weight;
        attribute length;
        attribute width;
        attribute depth;
        attribute material_code;
        attribute facia_color;
        attribute facia_rigidity;
        attribute facia_process;
};

Bumper_Component.Bumper_Brackets {
        attribute part_ number;
        attribute weight;
        attribute length;
        attribute width;
        attribute depth;
        attribute bracket_mechanism;
        attribute max_deflection;
        attribute max_energy;
};

Auto_Front_Chasis {
    entity Bumper;
    attribute base_height;
    attribute max_rail_load;
};

Bumper_Test.Pendulum_Test {
    entity Bumper;
        attribute test_location;
        attribute pendulum_weight;
        attribute pendulum_speed;
};

Bumper_Test.Barrier_Test {
    entity Bumper;
        attribute test_location;
        attribute test_velocity;
```

```
};

END_SCHEMA (Bumper);
```

C.3 C-FAR Matrices

Energy_Absorbent Bumper	weight	length	width	depth	abs. density	abs. pattern
part_assembly number	L/L	L/L	L/L	L/L	L/L	L/L
weight	H/H	M/M	M/M	M/M	L/H	L/M
length	M/M	H/H	L/L	L/L	M/L	L/L
width	M/M	L/L	H/H	L/L	M/L	L/L
depth	M/M	L/L	L/L	H/H	M/L	L/L
height	L/L	L/L	M/M	L/L	L/L	L/L
color	L/L	L/L	L/L	L/L	L/L	L/L
offset	L/L	L/L	L/L	H/H	L/L	L/L
styling_req.	L/L	M/L	H/L	H/L	L/L	M/L
corrosion.Resis. req.	L/L	L/L	L/L	L/L	L/L	L/L
weight_reduction req.	H/L	M/L	M/L	M/L	H/L	M/L
damage_protec_req.	H/L	M/L	H/L	H/L	H/L	H/L
engine_cooling req.	L/L	L/L	M/L	M/L	M/L	H/L
cost	L/H	L/H	L/H	L/H	L/H	L/H

Table C.1 Energy_Absorbent vs. Bumper

Bumper_Beam Bumper	part number	weight	length	width	depth	beam profile
part_assembly number	H/H	L/L	L/L	L/L	L/L	L/L
weight	L/L	H/H	M/H	M/H	M/H	M/H
length	L/L	H/M	H/H	L/L	L/L	M/M
width	L/L	M/M	L/L	H/H	L/L	H/H
depth	L/L	M/M	L/L	L/L	H/H	H/H
height	L/L	L/L	L/L	M/M	L/L	L/H
color	L/L	L/L	L/L	L/L	L/L	L/L
offset	L/L	L/L	L/L	L/L	H/H	L/L
styling_req.	L/L	L/L	M/L	H/L	H/L	M/L
corrosion.resistance_req.	L/L	L/L	L/L	L/L	L/L	L/L
weight_reduction req.	L/L	H/L	H/L	H/L	H/L	H/L
damage_protection req.	L/L	H/L	H/L	H/L	H/L	H/L
engine_cooling req.	L/L	L/L	L/L	M/L	H/L	M/L
cost	L/L	L/H	L/H	L/H	L/H	L/H

Table C.2 Bumper vs. Bumper_Beam

Bumper_Beam(cont)	wall	elas	beam

Bumper	thickness	module	type
part_assembly number	L/L	L/L	L/L
weight	M/H	M/H	M/H
length	M/M	M/M	M/M
width	M/H	M/M	M/M
depth	M/H	M/M	M/M
height	L/L	L/L	L/L
color	L/L	L/L	L/L
offset	L/L	L/L	L/L
styling_req.	L/L	L/L	M/L
corrosion. resistance_req.	M/L	M/L	H/L
weight_reduction req.	H/L	H/L	H/L
damage_protection req.	H/L	H/L	H/L
engine_cooling req.	M/L	M/L	H/L
cost	L/M	L/H	L/H

Table C.2 Bumper vs. Bumper_Beam (Cont.)

Auto_Front_Chasis **Auto_Front_Chasis**	base height	max_rail load
base height	I	L/L
max_rail load	-	I

Table C.3 Auto_Front_Chasis vs. Auto_Front_Chasis

Pendulum_Test **Pendulum_Test**	test location	pendulum weight	pendulum speed
test location	I	L/L	H/H
pendulum weight	-	I	L/L
pendulum speed	-	-	I

Table C.4 Pendulum_Test vs. Pendulum_Test

Bumper Facia-- Bumper	part number	weight	length	width	depth	wall thick ness	mat code	facia color
part assembly number	H/H	L/L	L/L	L/L	L/L	L/L	L/L	L/L
weight	L/L	M/H	L/M	L/M	L/M	L/M	L/H	L/L
length	L/L	L/L	H/H	L/L	L/L	L/L	L/L	L/L
width	L/L	L/L	L/L	H/H	L/L	L/L	L/L	L/L
depth	L/L	L/L	L/L	L/L	H/H	L/L	L/L	L/L
height	L/L	L/L	L/L	M/M	L/L	L/L	L/L	L/L
color	L/L	L/L	L/L	L/L	L/L	L/L	L/L	H/H
offset	L/L	L/L	L/L	L/L	L/L	L/M	L/L	L/L
styling_req.	L/L	L/L	M/L	H/L	H/L	H/L	H/L	H/L
corrosion. Resistance req.	L/L	L/L	L/L	L/L	L/L	M/L	L/L	L/L
weight reduction req.	L/L	H/L	L/L	L/L	L/L	L/L	H/L	L/L
damage protection req.	L/L	L/L	L/L	L/L	H/L	H/L	H/L	L/L
engine cooling req.	L/L	L/L	L/L	M/L	M/L	L/L	M/L	L/L
cost	L/L	L/M	L/M	L/M	L/M	L/M	L/H	L/L

Table C.5 Bumper vs. Bumper_Facia

Barrier_Test Barrier_Test	test location	test velocity
test location	I	H/H
test velocity	-	I

Table C.6 Barrier_Test vs. Barrier_Test

Bumper_Brackets	weight	length	width	depth	bracket	max	max

Bumper					mech	deflec.	energy
part_assem_number	L/L	L/L	L/L	L/L	L/L	L/L	L/L
weight	M/H	L/M	L/M	L/M	L/L	L/L	L/L
length	L/L	L/L	L/L	L/L	L/L	L/L	L/L
width	L/L	L/L	H/H	L/L	L/L	L/L	L/L
depth	L/L	L/L	L/L	H/H	L/L	L/L	L/L
height	L/L	L/L	L/L	L/L	M/L	L/L	L/L
color	L/L	L/L	L/L	L/L	L/L	L/L	L/L
offset	L/L	L/L	L/L	H/H	L/L	H/H	M/M
styling_req.	L/L	H/L	H/L	H/L	M/L	M/L	M/L
corrosion.resis._req.	L/L	L/L	L/L	L/L	L/L	L/L	L/L
weight_red req.	H/L	L/L	L/L	L/L	L/L	L/L	L/L
damage_protection req.	L/L	L/L	L/L	L/L	H/L	H/L	H/L
cooling req.	L/L	L/L	L/L	L/L	L/L	L/L	L/L
cost	L/M	L/L	L/L	L/L	L/H	L/M	L/M

Table C.7 Bumper_Brackets vs. Bumper

Auto_Front_Chassis **Bumper**	base height	max_rail load
part_assembly number	L/L	L/L
weight	L/L	L/L
length	L/L	L/L
width	L/L	L/L
depth	L/L	L/L
height	H/H	L/L
color	L/L	L/L
offset	L/L	L/L
styling_req.	L/L	L/L
corrosion.resistance_req.	L/L	L/L
weight_reductionreq.	L/L	L/L
damage_protection req.	H/L	H/L
engine_cooling req.	L/L	L/L
cost	L/M	L/H

Table C.8 Auto_Front_Chasis vs. Bumper

Pendulum_Test **Bumper**	test location	pendulum weight	pendulum speed

part_assem_number	L/L	L/L	L/L
weight	L/L	H/L	L/L
length	H/L	L/L	L/L
width	H/L	L/L	L/L
depth	L/L	L/L	L/L
height	L/L	L/L	L/L
color	L/L	L/L	L/L
offset	L/L	L/L	L/L
styling_req.	L/L	L/L	L/L
corrosion.resis_req.	L/L	L/L	L/L
weight_red.req.	L/L	L/L	L/L
damage_prot req.	H/L	H/L	H/L
engine_cooling req.	L/L	L/L	L/L
cost	L/L	L/H	L/M

Table C.9 Pendulum_Test vs. Bumper

Barrier_Test **Bumper**	test location	test velocity
part_assembly number	L/L	L/L
weight	L/L	L/L
length	H/L	L/L
width	H/L	L/L
depth	L/L	L/L
height	L/L	L/L
color	L/L	L/L
offset	L/L	L/L
styling_req.	L/L	L/L
corrosion. resistance_req.	L/L	L/L
weight_reduction req.	L/L	L/L
damage_protection req.	H/L	H/L
engine_cooling req.	L/L	L/L
cost	L/L	L/M

Table C.10 Bumper vs. Barrier_Test

Bumper **Bumper**	weight	length	width	depth	height	color	offset	styling_ req.
part_assembly	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L

number								
weight	I	L/H	L/H	L/H	L/L	L/L	L/L	L/M
length	-	I	L/L	L/L	L/L	L/L	L/L	L/L
width	-	-	I	M/M	L/L	L/L	L/L	L/M
depth	-	-	-	I	L/L	L/L	H/H	L/M
height	-	-	-	-	I	L/L	L/L	L/H
color	-	-	-	-	-	I	L/L	L/H
offset	-	-	-	-	-	-	I	L/H
styling_req.	-	-	-	-	-	-	-	I

Table C.11 Bumper vs. Bumper

Bumper(cont.) **Bumper**	corrosion resistance _req.	weight reduction req.	damage protection req.	engine cooling req.	cost
part_assembly number	L/L	L/L	L/L	L/L	L/L
weight	L/L	L/H	L/M	L/L	H/L
length	L/L	L/H	L/H	L/L	H/L
width	L/L	L/H	L/H	L/H	H/L
depth	L/L	L/H	L/H	L/H	H/L
height	L/L	L/L	L/H	L/M	M/L
color	L/L	L/L	L/L	L/L	M/L
offset	L/L	L/L	H/H	L/L	L/L
styling_req.	M/M	M/M	M/M	M/M	H/L
corrosion. resistance_req.	I	M/M	M/M	M/M	H/L
weight_reduction req.	-	I	H/H	M/M	H/L
damage_protection req.	-	-	I	H/H	H/L
engine_cooling req.	-	-	-	I	H/L
cost	-	-	-	-	I

Table C.11 Bumper vs. Bumper (Cont.)

Energy_Absorbent **Energy_Absorbent**	weight	length	width	depth	material code	absorber density	absorber pattern
part	L/L	L/L	L/L	L/L	L/L	L/L	L/L

number							
weight	I	L/H	L/H	L/H	L/L	L/H	L/H
length	-	I	L/L	L/L	L/L	L/L	L/L
width	-	-	I	M/M	L/L	L/L	L/L
depth	-	-	-	I	L/L	L/L	L/L
material code	-	-	-	-	I	L/L	L/L
absorber density	-	-	-	-	-	I	L/L
absorber pattern	-	-	-	-	-	-	I

Table C.12 Energy_Absorbent vs. Energy_Absorbent

Bumper_Beam Bumper_Beam	part number	weight	length	width	depth	material code	beam profile
part number	I	L/L	L/L	L/L	L/L	L/L	L/L
weight	-	I	L/H	L/H	L/H	L/L	L/H
length	-	-	I	L/L	L/L	L/L	M/M
width	-	-	-	I	M/M	L/L	H/L
depth	-	-	-	-	I	L/L	H/H
material code	-	-	-	-	-	I	L/L
beam profile	-	-	-	-	-	-	I

Table C.13 Bumper_Beam vs. Bumper_Beam

Bumper_Beam(cont.) Bumper_Beam	wall thickness	elas module	beam type
part number	L/L	L/L	L/L
weight	L/H	L/M	L/H
length	L/M	L/L	L/L
width	L/L	L/L	L/M
depth	L/L	L/L	L/M
material code	L/L	L/L	L/L
beam profile	M/M	M/M	M/M
wall thickness	I	M/M	M/M
elas_module	-	I	M/M
beam type	-	-	I

Table C.13 Bumper_Beam vs. Bumper_Beam (Cont.)

Bumper Facia Bumper Facia	weight	length	width	depth	wall thick ness	mat. code	facia color	facia rigidity	facia process
part number	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
weight	I	L/H	L/H	L/H	L/H	L/H	L/L	L/M	L/M
length	-	I	L/L	L/L	L/L	L/L	L/L	L/L	L/L
width	-	-	I	L/L	L/L	L/L	L/L	L/L	L/L
depth	-	-	-	I	L/L	L/L	L/L	L/L	L/L
wall thickness	-	-	-	-	I	L/L	L/L	H/M	L/H
material code	-	-	-	-	-	I	L/L	L/L	L/L
facia color	-	-	-	-	-	-	I	L/L	L/L
facia rig.	-	-	-	-	-	-	-	I	L/H

Table C.14 Bumper Facia vs. Bumper Facia

Bumper_Brackets Bumper_Brackets	weight	length	width	depth	bracket mech	max deflec.	max energy
part number	L/L	L/L	L/L	L/L	L/L	L/L	L/L
weight	I	L/H	L/H	L/H	L/H	L/M	L/M
length	-	I	M/M	M/M	L/M	M/L	M/L
width	-	-	I	M/M	L/M	M/L	M/L
depth	-	-	-	I	L/M	H/L	H/L
bracket mech	-	-	-	-	I	H/H	H/H
max deflec	-	-	-	-	-	I	H/H
max energy	-	-	-	-	-	-	I

Table C.15 Bumper_Brackets vs. Bumper_Brackets

Appendix D

PWB Case Study

D.1 EXPRESS Model

```
SCHEMA aopm;

(* *******************************************************
Developed by: Diego R. Tamburini (gt1423b@cad.gatech.edu)
            Russell S. Peak (peak@cad.gatech.edu)

            Engineering Information Systems Laboratory
            Georgia Institute of Technology
            Atlanta, GA



Notes:
1. Stripped from original TIGER version for Tal Cohen
2. Eliminated some supertypes and rearranged attributes
   for simplicity.

Stripped on: August 05, 1997
******************************************************* *)



ENTITY location;
      rot0 : OPTIONAL plane_angle_measure;
      x0 : positive_length_measure;
      y0 : positive_length_measure;
      z0 : positive_length_measure;
END_ENTITY;


ENTITY linear_elastic_material;
      manufacturer : STRING;
```

```
        name : STRING;
        youngs_modulus : REAL;
        shear_modulus : REAL;
        cte : REAL;
        poissons_ratio : REAL;
  WHERE
        aat1 : shear_modulus = youngs_modulus/(2*(1-poissons_ratio));
END_ENTITY;


ENTITY pwb_thermal_bending_model;
        associated_pwb : pwb;
        length : positive_length_measure;
        thickness : positive_length_measure;
        coefficient_of_thermal_bending : cte;
        reference_temperature : temperature;
        associated_temperature : temperature;
        temperature_change : temperature;
        warpage : length_measure;
END_ENTITY;


ENTITY physical_entity
  ABSTRACT SUPERTYPE OF (  ONE_OF(part , pwb_layer)  );
        description : STRING;
        total_length : positive_length_measure;
        total_width : positive_length_measure;
        total_height : positive_length_measure;
        primary_structural_material : linear_elastic_material;
END_ENTITY;


ENTITY part
  ABSTRACT SUPERTYPE OF(ONE_OF(electrical_component , pwb , pwa)  )
  SUBTYPE OF ( physical_entity );
        part_number : id;
        cost : money;
END_ENTITY;
ENTITY electrical_component
  SUBTYPE OF( part );
```

```
        package : electrical_package;
        magnitude : positive_real;
        tolerance : positive_real;
        power_rating : positive_real;
END_ENTITY;


ENTITY pwb
  SUBTYPE OF( part );
        min_required_finished_thickness : positive_length_measure;
        nominal_required_finished_thickness : positive_length_measure;
        maximum_required_finished_thickness : positive_length_measure;
        miminum_required_laminated_thickness : positive_length_measure;
        nominal_required_laminated_thickness : positive_length_measure;
        maximum_required_laminated_thickness : positive_length_measure;
        coefficient_of_thermal_bending : REAL;
        total_diagonal : positive_length_measure;
        outline : LIST [1:?] OF xy_coordinates;
        layup : LIST [1:?] OF pwb_layer;
END_ENTITY;


ENTITY pwb_layer
  ABSTRACT SUPERTYPE OF (ONE_OF(pwb_copper_foil , pwb_prepreg_set ,
pwb_copper_cladded_laminate ))
  SUBTYPE OF( physical_entity );
END_ENTITY;


ENTITY pwb_copper_foil
  SUBTYPE OF( pwb_layer );
        weight_per_unit_area : positive_length_measure;
        layer_function : STRING;
        min_thickness : positive_length_measure ;
        nominal_thickness : positive_length_measure ;
        max_thickness : positive_length_measure ;
        percent_etched : positive_real;
END_ENTITY;


ENTITY pwb_prepreg_set
   SUBTYPE OF ( pwb_layer );
        prepregs : LIST[1:?] OF pwb_prepreg_sheet;
```

```
END_ENTITY;


ENTITY pwb_prepreg_sheet;
       prepreg_id : STRING;
       min_thickness : positive_length_measure ;
       nominal_thickness : positive_length_measure ;
       max_thickness : positive_length_measure ;
       ho : positive_length_measure;
END_ENTITY;


ENTITY pwb_copper_cladded_laminate
   SUBTYPE OF ( pwb_layer );
       related_core : pwb_core;
       laminate_id : STRING;
       top_copper_layer : OPTIONAL pwb_copper_foil;
       bottom_copper_layer : OPTIONAL pwb_copper_foil;
END_ENTITY;


ENTITY pwb_core;
       min_thickness : positive_length_measure ;
       nominal_thickness : positive_length_measure ;
       max_thickness : positive_length_measure ;
END_ENTITY;


ENTITY pwa
  SUBTYPE OF( part );
       component_occurences : SET [0:?] OF component_occurrence;
       associated_pwb : pwb;
END_ENTITY;


ENTITY component_occurrence;
       associated_pwa :  pwa;
       component : electrical_component;
       reference_designator : id;
       associated_location : location;
       surface : board_side;
END_ENTITY;
```

END_SCHEMA (* aopm *);

D.2 Flat EXPRESS Model

```
Flat EXPRESS Schema aopm {


/*
Developed by: Tal Cohen

        Engineering Information Systems Laboratory
        Georgia Institute of Technology
        Atlanta, GA

August 17, 1997
*/




 Location {
   entity Comp_Occurance;
        attribute rot0;
        attribute x0;
        attribute y0;
        attribute z0;
};

 linear_elastic_material {
   entity pwb;
   entity pwb_copper;
   entity prepreg_set;
   entity pwb_copper_cladded_laminate
   entity pwa;
   entity Elect_comp;
        attribute manufacturer;
        attribute name;
        attribute youngs_modulus;
        attribute shear_modulus;
        attribute cte;
        attribute poissons_ratio;
```

```
};

pwb_thermal_bending_model {
	entity pwb;
	attribute length;
	attribute thickness;
	attribute ctb;
	attribute reference_temperature;
	attribute associated_temperature;
	attribute temperature_change;
	attribute warpage;
};

electrical_component {
	entity package;
	entity component_occurrence;
	entity linear_elastic_material;
	attribute description;
	attribute total_length;
	attribute total_width;
	attribute total_height;
	attribute primary_structural_material;
	attribute part_number;
	attribute cost;
	attribute magnitude;
	attribute tolerance;
	attribute power_rating;
};

pwb {
	entity pwa;
	entity component_Occurrence;
	entity linear_elastic_material;
	entity pwb_copper;
	entity prepreg_set;
	entity pwb_copper_cladded_laminate;
	entity pwb_thermal_bending_model;
	attribute description;
	attribute total_length;
	attribute total_width;
	attribute total_height;
	attribute primary_structural_material;
	attribute part_number;
```

```
        attribute cost;
        attribute min_required_finished_thickness;
        attribute nominal_required_finished_thickness;
        attribute maximum_required_finished_thickness;
        attribute miminum_required_laminated_thickness;
        attribute nominal_required_laminated_thickness;
        attribute maximum_required_laminated_thickness;
        attribute coefficient_of_thermal_bending;
        attribute total_diagonal;;
};

pwb_copper {
    entity linear_elastic_material;
    entity pwb;
    entity
        attribute description;
        attribute total_length;
        attribute total_width;
        attribute total_height;
        attribute primary_structural_material;
        attribute weight_per_unit_area;
        attribute layer_function;
        attribute min_thickness;
        attribute nominal_thickness;
        attribute max_thickness;
        attribute percent_etched;
};

pwb_prepreg_set {
    entity linear_elastic_material;
    entity pwb;
        entity prepregs;
        attribute description;
        attribute total_length;
        attribute total_width;
        attribute total_height;
        attribute primary_structural_material;
};
pwb_prepreg_sheet {
    entity pwb_prepreg_set;
        attribute prepreg_id;
        attribute min_thickness;
        attribute nominal_thickness;
```

```
        attribute max_thickness;
        attribute ho;
};
pwb_copper_cladded_laminate {
        entity linear_elastic_material;
    entity pwb;
        attribute description;
        attribute total_length;
        attribute total_width;
        attribute total_height;
        attribute primary_structural_material;
        attribute laminate_id ;
        attribute top_copper_layer;
        attribute bottom_copper_layer;
};
pwa {
        entity component_occurences;
        entity pwb;
        attribute description;
        attribute total_length;
        attribute total_width;
        attribute total_height;
        attribute primary_structural_material;
        attribute part_number;
        attribute cost;
};
component_occurrence {
    entity pwa;
    entity pwb;
    entity electrical_component;
        attribute reference_designator;
        attribute associated_location;
        attribute surface : board_side;
};
};
```

D.3 C-FAR Matrices

PWB / **PWB Copper**	Description	Total length	Total width	Total height	Cost	Part number	Total diagonal
Description	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Total length	L/L	H/H	M/M	L/L	H/M	L/L	H/M
Total width	L/L	M/M	H/H	L/L	H/M	L/L	H/M
Total height	L/L	M/M	M/M	H/H	H/M	L/L	L/L
Nom. Thick	L/L	M/M	M/M	H/H	H/M	L/L	L/L
Max. thick	L/L	M/M	M/M	H/H	H/M	L/L	L/L
Min thick	L/L	M/M	M/M	H/H	H/M	L/L	L/L
Layer function	L/L	L/L	L/L	H/L	H/L	L/L	L/L
Weight	L/L	M/M	M/M	H/H	H/M	L/L	L/L

Table D.1 PWB vs. PWB_copper

PWB / **PWB Copper**	CTB	Nominal req L thickness	Max. L req thickness	Min. L req thickness
Description	L/L	L/L	L/L	L/L
Total length	L/L	L/L	L/L	L/L
Total width	L/L	L/L	L/L	L/L
Total height	H/M	L/H	L/H	L/H
Nom. Thick	H/M	L/H	L/H	L/H
Max. thick	H/M	L/H	L/H	L/H
Min thick	H/M	L/H	L/H	L/H
Layer function	H/L	L/M	L/M	L/M
Weight	H/M	L/H	L/H	L/H

Table D.1 PWB vs. PWB_copper (Cont.)

PWB	Nominal req F thickness	Max. F req	Min. F

PWB Copper		thickness	thickness
Description	L/L	L/L	L/L
Total length	L/L	L/L	L/L
Total width	L/L	L/L	L/L
Total height	L/H	L/H	L/H
Nom. Thick	L/H	L/H	L/H
Max. thick	L/H	L/H	L/H
Min thick	L/H	L/H	L/H
Layer function	L/M	L/M	L/M
Weight	L/H	L/H	L/H

Table D.1 PWB vs. PWB_copper (Cont.)

ThermalModel PWB	Length	Thickness	CTB	Ref Temp	Temp Change	Warpage
Description	L/L	L/L	L/L	L/L	L/L	L/L
Total length	H/H	L/L	M/L	L/L	L/L	H/M
Total width	L/L	L/L	M/L	L/L	L/L	H/M
Total height	L/L	H/H	M/L	L/L	L/L	H/M
Cost	L/L	L/L	L/M	L/L	L/L	M/M
Part Number	L/L	L/L	L/L	L/L	L/L	L/L
Total Diagonal	M/H	L/L	M/L	L/L	L/L	H/M
CTB	L/L	L/L	H/H	L/L	L/L	H/M
Nominal req L thickness	L/L	L/L	L/L	L/L	L/L	L/L
Max. L req thickness	L/L	L/L	L/L	L/L	L/L	L/L
Min. L req thickness	L/L	L/L	L/L	L/L	L/L	L/L
Nominal req F thickness	L/L	L/L	L/L	L/L	L/L	L/L
Max. F req thickness	L/L	L/L	L/L	L/L	L/L	L/L
Min. F req thickness	L/L	L/L	L/L	L/L	L/L	L/L
Size_of_layup	L/L	H/M	H/M	L/L	M/L	H/L

Table D.2 PWB vs. PWB Thermal Model

Component occur.	Reference	Surface

PWB	Designator	
Description	L/L	L/L
Total length	L/L	M/L
Total width	L/L	M/L
Total height	L/L	M/L
Cost	L/L	L/L
Part Number	L/L	L/L
Total Diagonal	L/L	M/L
CTB	L/L	M/L
Nominal req L thickness	L/L	M/L
Max. L req thickness	L/L	M/L
Min. L req thickness	L/L	M/L
Nominal req F thickness	L/L	M/L
Max. F req thickness	L/L	M/L
Min. F req thickness	L/L	M/L
Size_of_layup	L/L	L/L

Table D.3 PWB vs. Component Occurrence

Elect Package Component	Body style id	Inter solder joint distance
Description	L/L	L/L
Total length	H/H	H/H
Total width	H/H	H/H
Total height	H/H	L/L
Cost	M/H	L/M
Part Number	L/L	L/L
Magnitude	L/L	L/L
Tolerance	L/L	L/L
Power rating	M/M	L/L

Table D.4 Electrical Component vs. Electrical Package

Component Occurrence **Electrical Component**	Reference Designator	Surface
Description	L/L	L/L
Total length	L/L	L/L
Total width	L/L	L/L
Total height	L/L	M/M
Cost	L/L	L/L
Part Number	L/L	L/L
Magnitude	L/L	L/L
Tolerance	L/L	L/L
Power rating	L/L	M/M

Table D.5 Electrical Component vs. Component Occurrence

Component occurrence **PWA**	Reference Designator	Surface
Total Length	L/L	M/M
Total Width	L/L	M/L
Total Height	L/L	M/L
Cost	L/L	L/L
Part Number	L/L	L/L
# of components	L/L	M/L
Assembly order	M/M	L/H
Number of Sides	L/L	H/H

Table D.6 PWA vs. Component Occurrence

Elect_Comp. **Linear elastic**	Description	Total length	Total width	Total height	Cost	Part number	Magnitude
Manufacturer	L/L	L/L	L/L	L/L	M/M	H/H	L/L
Name	L/L	L/L	L/L	L/L	L/L	L/L	M/M
E	L/L	L/L	L/L	L/L	L/L	L/L	L/L
G	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Cte	L/L	L/L	L/L	L/L	L/L	L/L	M/M
Poissons	L/L	L/L	L/L	L/L	L/L	L/L	M/M

Table D.7 Linear Elastic Material vs. Elect_comp

Electrical Comp. **Linear elastic material**	Tolerance	Power rating
Manufacturer	M/M	L/L
Name	M/M	M/M
E	L/L	L/L
G	L/L	L/L
Cte	M/M	M/M
Poissons	M/M	M/M

Table D.7 Linear Elastic Material vs. Elect_comp (cont.)

PWB **Linear elastic material**	Description	Total length	Total width	Total height	Cost	Part number	Total diagonal
Manufacturer	L/L	L/L	L/L	M/L	M/L	L/L	L/L
Name	L/L	L/L	L/L	M/L	M/L	L/L	L/L
E	L/L	L/L	L/L	M/L	M/L	L/L	L/L
G	L/L	L/L	L/L	M/L	M/L	L/L	L/L
Cte	L/L	L/L	L/L	M/L	M/L	L/L	L/L
Poissons	L/L	L/L	L/L	L/L	L/L	L/L	L/L

Table D.8 Linear elastic material vs. PWB

PWB **Linear elastic material**	CTB	Nominal req L thickness	Max. L req thick	Min. thick	Noml F thick	Max. F req thick	Min. F req thick
Manufacturer	H/M	L/L	L/L	L/L	L/L	L/L	L/L
Name	H/M	L/L	L/L	L/L	L/L	L/L	L/L
E	H/M	L/L	L/L	L/L	L/L	L/L	L/L
G	H/M	L/L	L/L	L/L	L/L	L/L	L/L
Cte	H/M	L/L	L/L	L/L	L/L	L/L	L/L
Poissons	L/L	L/L	L/L	L/L	L/L	L/L	L/L

Table D.8 Linear elastic material vs.. PWB (Cont.)

PWA Linear elastic material	Des.	Total length	Total width	Total height	Cost	Part num.	# of comp.	Assm. order	Num. sides
Manufacturer	L/L	L/L	L/L	M/L	M/L	L/L	L/L	L/L	L/L
Name	L/L	L/L	L/L	M/L	M/L	L/L	L/L	L/L	L/L
E	L/L	L/L	L/L	L/L	M/L	L/L	L/L	L/L	L/L
G	L/L	L/L	L/L	L/L	M/L	L/L	L/L	L/L	L/L
Cte	L/L	L/L	L/L	L/L	M/L	L/L	M/M	M/L	M/L
Poissons	L/L	L/L	L/L	L/L	M/L	L/L	L/L	L/L	L/L

Table D.8 Linear elastic material vs. PWB (Cont.)

Pwb_copper Linear elastic material	Description	Total length	Total width	Total height	Cost	Weight	Layer function
Manufacturer	L/L	L/L	L/L	L/L	M/L	L/L	L/L
Name	L/L	L/L	L/L	L/L	M/L	M/M	L/L
E	L/L	L/L	L/L	L/L	M/L	M/M	M/M
G	L/L	L/L	L/L	L/L	M/L	M/M	M/M
Cte	L/L	L/L	L/L	L/L	M/L	M/M	M/M
Poissons	L/L	L/L	L/L	L/L	M/L	M/M	M/M

Table D.9 Linear elastic material vs. PWB_copper

Pwb_copper Linear elastic material	Min. thickness	Nom. Thickness	Max. thickness	Percent Etched
Manufacturer	L/L	L/L	L/L	L/L
Name	L/L	L/L	L/L	L/L
E	L/L	L/L	L/L	M/M
G	L/L	L/L	L/L	M/M
Cte	L/L	L/L	L/L	M/M
Poissons	L/L	L/L	L/L	M/M

Table D.9 Linear elastic material vs. PWB_copper (Cont.)

Prepreg_set **Linear elastic material**	Description	Total length	Total width	Total Height	Cost
Manufacturer	L/L	L/L	L/L	L/L	M/M
Name	L/L	L/L	L/L	L/L	M/M
E	L/L	L/L	L/L	L/L	M/M
G	L/L	L/L	L/L	L/L	M/M
Cte	L/L	L/L	L/L	L/L	M/M
Poissons	L/L	L/L	L/L	L/L	M/M

Table D.10 Linear elastic material vs. Prepreg_set

Laminate **Linear elastic material**	Description	Total Length	Total width	Total Height	Cost	Laminate Id
Manufacturer	L/L	L/L	L/L	L/L	M/M	M/M
Name	L/L	L/L	L/L	L/L	M/M	M/M
E	L/L	L/L	L/L	L/L	M/M	M/M
G	L/L	L/L	L/L	L/L	M/M	M/M
Cte	L/L	L/L	L/L	L/L	M/M	M/M
Poissons	L/L	L/L	L/L	L/L	M/M	M/M

Table D.11 Linear elastic material vs. pwb_copper_cladded_laminate

PWB **PWA**	Description	Total length	Total width	Total height	Cost	Part Number
Description	M/M	L/L	L/L	L/L	L/L	L/L
Total Length	L/L	H/H	L/L	L/L	M/M	L/L
Total Width	L/L	L/L	H/H	L/L	M/M	L/L
Total Height	L/L	L/L	L/L	H/H	M/M	L/L
Cost	L/L	M/H	M/H	M/H	M/H	L/L
Part Number	L/L	L/L	L/L	L/L	L/L	L/L
Num. comp	L/L	H/H	H/H	M/M	H/M	L/L
Assembly order	L/L	L/M	L/M	L/M	L/L	L/L
Number Sides	L/L	L/L	L/L	M/M	M/L	L/L

Table D.12 PWA vs. PWB

PWB PWA	CTB	Nominal req L thickness	Max. L req thickness	Min. L req thickness
Description	L/L	L/L	L/L	L/L
Total Length	L/L	L/L	L/L	L/L
Total Width	L/L	L/L	L/L	L/L
Total Height	H/H	H/H	H/H	H/H
Cost	L/M	M/H	M/H	M/H
Part Number	L/L	L/L	L/L	L/L
# of components	L/L	M/M	M/M	M/M
Assembly order	L/M	L/L	L/L	L/L
Number of Sides	L/M	L/L	L/L	L/L

Table D.12 PWA vs. PWB (Cont.)

PWB PWA	Max. F req thickness	Min. F req thickness	Size_of_layup
Description	L/L	L/L	L/L
Total Length	L/L	L/L	L/L
Total Width	L/L	L/L	L/L
Total Height	H/H	H/H	M/H
Cost	M/H	M/H	M/H
Part Number	L/L	L/L	L/L
# of components	M/M	M/M	M/L
Assembly order	L/L	L/L	L/L
Number of Sides	L/L	L/L	L/L

Table D.12 PWA vs. PWB (Cont.)

Prepreg set	Description	Total	Total	Total

PWB		length	width	height
Description	L/L	L/L	L/L	L/L
Total length	L/L	H/H	L/L	L/L
Total width	L/L	L/L	H/H	H/H
Total height	L/L	L/L	H/H	H/H
Cost	L/L	L/M	L/M	L/M
Part Number	L/L	L/L	L/L	L/L
Total Diagonal	L/L	M/H	M/H	L/L
CTB	L/L	L/L	L/L	M/M
Nominal req L thickness	L/L	L/L	L/L	L/L
Max. L req thickness	L/L	L/L	L/L	L/L
Min. L req thickness	L/L	L/L	L/L	L/L
Nominal req F thickness	L/L	L/L	L/L	L/L
Max. F req thickness	L/L	L/L	L/L	L/L
Min. F req thickness	L/L	L/L	L/L	L/L
Size_of_layup	L/L	L/L	L/L	M/M

Table D.13 PWB vs. prepreg_set

Laminate **PWB**	Description	Total length	Total width	Total Height	Cost
Description	L/L	L/L	L/L	L/L	L/L
Total length	L/L	H/H	L/L	L/L	M/L
Total width	L/L	L/L	H/H	L/L	M/L
Total height	L/L	L/L	L/L	M/H	M/L
Cost	L/L	L/L	L/L	L/L	L/M
Part Number	L/L	L/L	L/L	L/L	L/L
Total Diagonal	L/L	M/H	M/H	L/L	M/L
CTB	L/L	L/L	L/L	M/H	M/L
Nominal req L thickness	L/L	L/L	L/L	L/L	L/L
Max. L req thickness	L/L	L/L	L/L	L/L	L/L
Min. L req thickness	L/L	L/L	L/L	L/L	L/L
Nominal req F thickness	L/L	L/L	L/L	L/L	L/L
Max. F req thickness	L/L	L/L	L/L	L/L	L/L
Min. F req thickness	L/L	L/L	L/L	L/L	L/L
Size_of_layup	L/L	L/L	L/L	M/M	M/M

Table D.14 PWB vs. pwb_copper_cladded_laminate

Occurrence **Location**	Reference Designator	Surface
Rotation	L/L	L/L
X	L/L	L/L
Y	L/L	L/L
Z	L/L	H/H

Table D.15 Component Occurrence vs. Location

Set **Sheet**	Description	Total length	Total width	Total height	Cost
Prepreg id	L/L	H/H	H/H	H/H	H/H
Min. thick	L/L	L/L	L/L	H/H	M/M
Nom. Thick	L/L	L/L	L/L	H/H	M/M
Max. Thick.	L/L	L/L	L/L	H/H	M/M
Ho	L/L	L/L	L/L	H/H	M/M

Table D.16 prepreg_set vs. prepreg sheet

Linear elastic material **Linear elastic material**	Manufacturer	Name	E	G	Cte	Poissons
Manufacturer	I	M/M	L/L	L/L	L/L	L/L
Name		I	H/M	H/M	H/M	H/M
E			I	H/H	M/M	M/M
G				I	M/M	M/M
Cte					I	M/M
Poissons						I

Table D.17 Linear elastic material vs. Linear elastic material

PWB **PWB**	Description	Total length	Total width	Total height	Cost	Part Number	Total diagonal

Description	I	L/L	L/L	L/L	L/L	L/L	L/L
Total Length		I	M/M	M/M	M/M	L/L	H/M
Total Width			I	M/M	M/M	L/L	H/M
Total height				I	M/M	L/L	L/L
Cost					I	L/L	M/M
Part Number						I	L/L
Total diagonal							I

Table D.18 PWB vs. PWB

PWB **PWB**	CTB	Nominal req L thickness	Max. L req thickness	Min. L req thickness
Description	L/L	L/L	L/L	L/L
Total Length	L/L	M/M	M/M	M/M
Total Width	L/L	M/M	M/M	M/M
Total height	H/M	H/H	H/H	H/H
Cost	M/M	L/M	L/M	L/M
Part Number	L/L	L/L	L/L	L/L
Total diagonal	L/L	L/M	L/M	L/M
CTB	I	L/L	L/L	L/L
Nominal req L thickness		I	H/H	H/H
Max. L req thickness			I	H/H
Min. L req thickness				I

Table D.18 PWB vs. PWB (Cont.)

PWB **PWB**	Nominal req F thickness	Max. F req thickness	Min. F req thickness	Size_of_layup
Description	L/L	L/L	L/L	L/L

Total Length	M/M	M/M	M/M	L/L
Total Width	M/M	M/M	M/M	L/L
Total height	H/H	H/H	H/H	H/M
Cost	L/M	L/M	L/M	H/M
Part Number	L/L	L/L	L/L	L/L
Total diagonal	L/M	L/M	L/M	L/L
CTB	L/L	L/L	L/L	H/L
Nominal req L thickness	H/H	H/H	H/H	H/M
Max. L req thickness	H/H	H/H	H/H	H/M
Min. L req thickness	H/H	H/H	H/H	H/M
Nominal req F thickness	I	H/H	H/H	H/M
Max. F req thickness		I	H/H	H/M
Min. F req thickness			I	H/M
Size_of_layup				I

Table D.18 PWB vs. PWB (Cont.)

PWA PWA	Description	Total length	Total width	Total height	Cost	Part number
Description	I	L/L	L/L	L/L	L/L	L/L
Total length		I	M/M	M/M	M/M	L/L
Total width			I	M/M	M/M	L/L
Total height				I	M/M	L/L
Cost					I	L/L
Part number						I

Table D.19 PWA vs. PWA

PWA PWA	# of components	Assembly order	Number of sides
Description	L/L	L/L	L/L
Total length	M/M	M/L	M/M
Total width	M/M	M/L	M/M
Total height	M/M	L/L	M/M
Cost	M/H	M/M	L/M
Part number	L/L	L/L	L/L
# of components	I	H/L	H/M
Assembly order		I	H/M
Number of sides			I

Table D.19 PWA vs. PWA (Cont.)

Component	Description	Total length	Total width	Total height	Cost

Component					
Description	I	L/L	L/L	L/L	L/L
Total length		I	M/M	M/M	M/L
Total width			I	M/M	M/L
Total height				I	M/L

Table D.20 Electrical Component vs. Electrical Component

Component / **Component**	Part Number	Magnitude	Tolerance	Power rating
Description	L/L	L/L	L/L	L/L
Total length	L/L	L/M	L/M	M/M
Total width	L/L	L/M	L/M	M/M
Total height	L/L	L/M	L/M	M/M
Cost	L/L	M/H	M/H	M/H
Part Number	I	L/L	L/L	L/L
Magnitude		I	M/M	H/H
Tolerance			I	M/M

Table D.20 Electrical Component vs. Electrical Component (Cont.)

Occurrence / **Occurrence**	Reference Designator	Surface
Reference Designator	I	H/H
Surface		I

Table D.21 Component Occurrence vs. Component Occurrence

Package / **Package**	Body style	Inter solder joint distance
Body style	I	H/M
Inter solder joint distance		I

Table D.22 Electrical Package vs. Electrical Package

Set	Description	Total length	Total width	Total height	Cost

Set					
Description	I	L/L	L/L	L/L	L/L
Total length		I	L/L	L/L	M/M
Total width			I	L/L	M/M
Total height				I	M/M
Cost					I

Table D.23 Prepreg Set vs. Prepreg Set

Sheet **Sheet**	Prepreg id	Min. thick	Nom. Thick	Max. Thick.	Ho
Prepreg id	I	H/H	H/H	H/H	H/H
Min. thick		I	H/H	H/H	H/H
Nom. Thick			I	H/H	H/H
Max. Thick.				I	H/H
Ho					I

Table D.24 Prepreg Sheet vs. Prepreg Sheet

PWB Copper **PWB Copper**	Description	Total length	Total width	Total height	Nom. Thick
Description	I	L/L	L/L	L/L	L/L
Total length		I	L/L	L/L	L/L
Total width			I	L/L	L/L
Total height				I	H/H
Nom. Thick					I

Table D.25 PWB_Copper set vs. PWB_Copper

PWB Copper **PWB Copper**	Max. thick	Min thick	Layer function	Weight
Description	L/L	L/L	L/L	L/L
Total length	L/L	L/L	L/L	L/L
Total width	L/L	L/L	L/L	L/L
Total height	H/H	H/H	M/M	H/H
Nom. Thick	H/H	H/H	M/M	H/H
Max. thick	I	H/H	M/M	H/H
Min thick		I	M/M	H/H
Layer function			I	M/M
Weight				I

Table D.25 PWB_Copper set vs. PWB_Copper (Cont.)

Laminate **Laminate**	Description	Total Length	Total width	Total Height	Cost	Laminate Id
Description	I	L/L	L/L	L/L	L/L	L/L
Total Length		I	L/L	L/L	M/M	L/L
Total width			I	L/L	M/M	L/L
Total Height				I	M/M	H/H
Cost					I	H/H
Laminate Id						I

Table D.26 PWB_Copper_Cladded_Laminate vs. PWB_Copper_Cladded_Laminate

Thermal Model **Thermal Model**	thickness	CTB	Ref Temp	Assoc Temp	Temp Change	Warpage
Length	L/L	L/L	L/L	L/L	L/L	H/H
thickness	I	H/H	L/L	L/L	L/L	H/H
CTB		I	L/L	L/L	L/L	H/H
Reference Temp			I	L/L	H/H	H/H
Associated Temp				I	H/H	H/H
Temp Change					I	H/H
Warpage						I

Table D.27 PWB Thermal Model vs. PWB Thermal Model

Location **Location**	Rotation	X	Y	Z
Rotation	I	M/M	M/M	M/M
X		I	M/M	M/M
Y			I	M/M
Z				I

Table D.28 Location vs. Location

Appendix E

Injection Molding Case Study

E.1 EXPRESS Model

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Schema injection_molding;

(* ********************************************************
Developed by: M.C. Ramesh and Tal Cohen

        Engineering Information Systems Laboratory
        Georgia Institute of Technology
        Atlanta, GA

September 29, 1997
******************************************************** *)


ENTITY Molder;
   molds : Part;
        address : STRING;
        equipment condition : STRING;
        equipment specs : STRING;
        design facilities : LIST_STRING;
        workforce size : work_f_unit;
        simulation facilities : LIST_STRING;
        track record : LIST_STRING;:
        name : STRING;
END_ENTITY;

ENTITY Mold_Maker;
        makes : mold;
        address : STRING;
        equipment condition : STRING;
        equipment specs : STRING;
        design facilities : LIST_STRING;
```

```
        workforce size : work_f_unit;
        simulation facilities : LIST_STRING;
        track record : LIST_STRING;
        name : STRING;
END_ENTITY;

ENTITY Mold;
   has_a : cavity_core_geometry;
        tool_number : INTEGER;
        number_of_cavities : INTEGER;
        mold_type : LIST_STRING;
        production/prototype : STRING_TYPE;
        cost : $_UNIT;
        Max_number_parts : INTEGER;
        Min_clamping_force : force_unit;
END_ENTITY;

ENTITY Cavity-Core-Material;
   name : STRING;
        density : density_unit;
        specific_heat_capacity : specific_heat_capacity_unit;
        thermal_conductivity : thermal_conductivity_unit;
        wear_resistance : wear_resistance_unit;
END_ENTITY;

ENTITY Part;
   has_a : Part_Geometry;
   manufactured : Process;
   molded_by : Mold;
   part number : STRING;
        ec-level : ec-level_unit;
        assembly-level : assembly-level_unit;
        description : STRING;
        aesthetic req. : req._unit;
        structural req. : req._unit;
        quantity req. : req._unit;
        demand/month : demand_unit;
        enviro-restriction: req._unit;
        finish-req. : req._unit;
        cost : $_unit;
        sink-mark : sink-mark_unit;
        weld-line-location : weld-line-location_unit;
        warpage : warpage_unit;
```

```
        shrinkage : shrinkage_unit;
END_ENTITY

ENTITY Cavity-Core-Geometry;
        side-action-mech. : side-action-mech_unit;
        ejection-type : ejection-type_unit;
        sprue-specs : specs_unit;
        runner-specs : specs_unit;
        gate-specs : specs_unit;
        delivery-sys-volume : volume_unit;
        water-line-diam. : length_unit;
        Water-line-p  : length_unit;
END_ENTITY;

ENTITY Process;
        barrel-temp-zone-1 : temp_unit;
        barrel-temp-zone-2 : temp_unit;
        barrel-temp-zone-3 : temp_unit;
        mold-temp : temp_unit;
        injection-pressure : pressure_unit;
        packing-pressure : pressure_unit;
        holding-pressure-profile : pressure-profile_unit;
        clamping-force : force_unit;
        fill-time : time_unit;
        pack-time : time_unit;
        holding-time : time_unit;
        cooling-time : time_unit;
        open-time : time_unit;
        shot-size : length_size;
        coolant-flow-rate : flow-rate_size;
END_ENTITY;

ENTITY Material;
   processed_by : Process;
        name : STRING;
        company-name : STRING;
        grade-core : grade-core_unit;
        specific-heat-vs-temp : specific-heat-vs-temp_unit;
        thermal-conductivity-vs-temp : thermal-conductivity-vs-temp_unit;
        density : density_unit;
        transition-temp : temp_unit;
        viscosity-vs-sheer-rate : viscosity-vs-sheer-rate_unit;
        izod-strength : izod-strength_unit;
```

```
          elastic-modulus : pres_unit;
          sheer-strength : pres_unit;
          flextural-strength : pres_unit;
          mold-shrinkage-flow-direction : flow-direction_unit;
          mold-shrinkage-perpendicular-to-flow : flow-direction_unit;
          melt-flow-index(mfi) : flow-index_unit;
          hardness : hardness_unit;
END_ENTITY;

ENTITY Machine;
    used_in : process;
          max-shot-size : length_size;
          max-injection-rate : injection-rate_size_unit;
          max-injection-pressure : injection-rate_size_unit;
          max-screw-speed : speed_unit;
          max-clamping-force : force_unit;
          daylight-opening : length_unit;
          min-mold-thickness: length_unit;
          max-mold-thickness: length_unit;
          tie-rod-distance: length_unit;
          max-coolant-flow-rate : flow-rate;
END_ENTITY;

ENTITY Mold-Coolant;
    used_in : Process;
          name : STRING;
          density : density_unit;
          specific-heat-capacity : specific-heat-capacity;
          thermal-conductivity : thermal-conductivity;
          viscosity : viscosity;
END_ENTITY;

ENTITY Part-Geometry;
          wall-thickness : length_unit;
          undercuts : undercuts_unit;
          tolerances : tolerances_unit;
          internal-threads : internal-threads_unit;
          blind-holes : blind-holes;
          gate-locations : gate-locations_unit;
END_ENTITY;

END_SCHEMA (*injection_molding *);
```

E.2 Flat EXPRESS Model

```
Flat EXPRESS Schema injection_molding {

/*
Developed by: Tal Cohen

        Engineering Information Systems Laboratory
        Georgia Institute of Technology
        Atlanta, GA

October 01, 1997
*/

Molder {
   entity Part;
        attribute name;
        attribute address;
        attribute equipment condition;
        attribute equipment specs;
        attribute design facilities;
        attribute workforce size;
        attribute simulation facilities;
        attribute track record;
};

Mold_Maker {
   entity Mold;
        attribute name;
        attribute address;
        attribute equipment condition;
        attribute equipment specs;
        attribute design facilities;
        attribute workforce size;
        attribute simulation facilities;
        attribute track record;
};

Mold {
   entity Mold_Maker;
   entity Part;
   entity Cavity_Core_Geometry;
        attribute tool number;
```

```
            attribute number of cavities;
            attribute mold type;
            attribute production/prototype;
            attribute cost ;
            Max_number_parts;
            Min_clamping_force;
};

Cavity-Core-Material {
    entity Process;
    attribute name;
            attribute density;
            attribute specific heat capacity;
            attribute thermal conductivity;
            attribute wear resistance;
};

Part {
    entity Process;
    entity Mold;
    entity Molder;
    entity Part_Geometry;
    attribute part number
            attribute ec-level;
            attribute assembly-level;
            attribute description;
            attribute aesthetic req.;
            attribute structural req.;
            attribute quantity req.;
            attribute demand/month;
            attribute enviro-restriction;
            attribute finish-req.;
            attribute cost;
            attribute sink-mark;
            attribute weld-line-location;
            attribute warpage;
            attribute shrinkage;
};

Cavity-Core-Geometry {
    entity Mold;
    entity Cavity_Core_Geometry;
    attribute side-action-mech.;
```

```
        attribute ejection-type;
        attribute sprue-specs;
        attribute runner-specs;
        attribute gate-specs;
        attribute delivery-sys-volume;
        attribute water-line-diam.;
        attribute Water-line-pitch;

};

Process {
   entity Part;
   entity Cavity_Core_Material;
        entity Mold_Coolant ;
        entity Machine;
        entity Material;
        attribute barrel-temp-zone-1;
        attribute barrel-temp-zone-2;
        attribute barrel-temp-zone-3;
        attribute mold-temp;
        attribute injection-pressure;
        attribute packing-pressure;
        attribute holding-pressure-profile;
        attribute clamping-force;
        attribute fill-time;
        attribute pack-time;
        attribute holding-time;
        attribute cooling-time;
        attribute open-time;
        attribute shot-size;
        attribute coolant-flow-rate;
};

Material {
   entity Process;
        attribute name;
        attribute company-name;
        attribute grade-core;
        attribute specific-heat-vs-temp;
        attribute thermal-conductivity-vs-temp;
        attribute density;
        attribute transition-temp;
        attribute viscosity-vs-sheer-rate;
```

```
        attribute izod-strength;
        attribute elastic-modulus;
        attribute sheer-strength;
        attribute flextural-strength;
        attribute mold-shrinkage-flow-direction;
        attribute mold-shrinkage-perpendicular-to-flow;
        attribute melt-flow-index(mfi);
        attribute hardness;
};

Machine {
    entity Process;
        attribute name;
        attribute company-name;
        attribute grade-core;
        attribute specific-heat-vs-temp;
        attribute thermal-conductivity-vs-temp;
        attribute density;
        attribute transition-temp;
        attribute viscosity-vs-sheer-rate;
        attribute izod-strength;
        attribute elastic-modulus;
        attribute sheer-strength;
        attribute flextural-strength;
        attribute mold-shrinkage-flow-direction;
        attribute mold-shrinkage-perpendicular-to-flow;
        attribute melt-flow-index(mfi);
        attribute hardness;
};

Machine {
    entity process;
    attribute max-shot-size;
        attribute max-injection-rate;
        attribute max-injection-pressure;
        attribute max-screw-speed;
        attribute max-clamping-force;
        attribute daylight-opening;
        attribute min-mold-thickness;
        attribute max-mold-thickness;
        attribute tie-rod-distance;
        attribute max-coolant-flow-rate;
};
```

```
Mold-Coolant {
    entity process;
          attribute name;
          attribute density;
          attribute specific-heat-capacity;
          attribute thermal-conductivity;
};

Part-Geometry {
    entity Part;
    entity Cavity_Core_Geometry;
    attribute wall-thickness;
          attribute undercuts;
          attribute tolerances;
          attribute internal-threads;
          attribute blind-holes;
          attribute gate-locations;
};

};
```

E.3 C-FAR Matrices

Part Geometry Part	Wall Thickness	Undercuts	Tolerances	Internal Thread	Blind Holes	Gate Locations
Part #	L/L	L/L	L/L	L/L	L/L	L/L
EC level	L/L	L/L	L/L	L/L	L/L	L/L
Assembly level	L/L	L/L	L/L	L/L	L/L	L/L
Description	L/L	L/L	L/L	L/L	L/L	L/L
Aesthetic Req	L/L	M/L	L/L	M/L	M/L	H/L
Structural Req	M/L	L/L	L/L	M/L	L/L	M/L
Quantity reqd/system	L/L	L/L	L/L	L/L	L/L	L/L
Demand/month	L/L	L/L	L/L	L/L	L/L	L/L
Environ. Restrictions	L/L	L/L	L/L	L/L	L/L	L/L
Finish req	L/L	L/L	L/L	L/L	L/L	L/L
Cost	L/M	L/H	L/H	L/H	L/H	L/M
sink marks	L/M	L/L	L/L	L/L	L/L	M/M
weld line location	M/H	L/M	L/L	L/M	L/M	M/H
warpage	M/M	L/M	L/L	L/L	L/L	M/M
shrinkage	L/L	L/L	L/M	L/L	L/L	L/M

Table E.1 Part Geometry vs. Part

Cavity_Core Geometry Part Geometry	Side Action Mechanism	Ejection Type	Sprue Specs	Runner Specs
Wall Thickness	L/L	M/L	M/L	H/L
Undercuts	H/L	M/L	L/L	L/L
Tolerances	L/L	L/L	L/L	L/L
Internal Threads	L/L	M/L	L/L	M/L
Blind Holes	H/L	M/L	L/L	M/L
Gate Locations	M/M	M/L	M/L	H/L

Table E.2 Part Geometry vs. Cavity Core Geometry

Cavity_Core Geometry **Part Geometry**	Gate Specs	Delivery System Vol	Water Line Diameter	Water Line Pitch
Wall Thickness	H/L	H/L	H/L	H/L
Undercuts	M/L	L/L	M/L	M/L
Tolerances	L/L	L/L	L/L	L/L
Internal Threads	M/L	M/L	M/L	M/L
Blind Holes	M/L	M/L	M/L	M/L
Gate Locations	H/M	H/L	M/L	M/L

Table E.2 Part Geometry vs. Cavity Core Geometry (Cont.)

Cavity_Core Geometry **Mold**	Side Action Mechanism	Ejection Type	Sprue Specs	Runner Specs
Tool Number	L/L	L/L	L/L	L/L
Number of cavities	M/M	M/L	M/L	H/L
Mold Type	L/L	L/L	M/L	M/L
Production or Prototype	L/L	L/L	L/L	L/L
Cost	L/H	L/M	L/L	L/M
Max number of parts	L/L	L/L	L/L	L/L
Minimum Clamping force	L/L	L/L	L/L	L/M

Table E.3 Mold vs. Cavity Core Geometry

Cavity_Core Geometry **Mold**	Gate Specs	Delivery System Volume	Water Line Diameter	Water Line Pitch
Tool Number	L/L	L/L	L/L	L/L
Number of cavities	L/L	H/L	M/L	M/L
Mold Type	M/L	M/L	M/L	M/L
Production or Prototype	L/L	L/L	L/L	L/L
Cost	L/L	L/M	L/L	L/M
Max number of parts	L/L	L/L	L/L	L/L
Minimum Clamping force	L/M	L/M	L/L	L/L

Table E.3 Mold vs. Cavity Core Geometry (Cont.)

Cavity_Core Material Process	Name	Density	Specific Heat Capacity	Thermal Conductivity	Wear Resistance
Barrel temp-zone 1	L/L	L/M	M/M	M/M	M/M
Barrel temp-zone 2	L/L	L/M	M/M	M/M	M/M
Barrel temp-zone3	L/L	L/M	M/M	M/M	M/M
Mold temp	L/L	L/L	M/M	M/M	M/M
Injection Pressure	L/L	M/M	M/M	M/M	M/M
Packing Pressure	L/L	L/L	M/M	M/M	M/M
Holding Pressure Profile	L/L	L/L	M/M	M/M	M/M
Clamping force	L/L	L/M	M/M	M/M	M/M
Fill time	L/L	L/M	M/M	M/M	M/M
Pack time	L/L	L/M	M/M	M/M	M/M
Holding time	L/L	L/M	M/M	M/M	M/M
Cooling time	L/L	L/M	M/M	M/M	M/M
Open time	L/L	L/L	L/L	L/L	L/L
Shot size	L/L	L/L	L/L	L/L	L/L
Coolant Flow Rate	L/L	L/M	M/M	M/M	M/M

Table E.4 Process vs. Cavity Core Material

Mold Coolant **Process**	Name	Density	Specific Heat Capacity	Thermal Conductivity	Viscosity
Barrel temp-zone 1	L/L	L/L	L/L	L/L	L/L
Barrel temp-zone 2	L/L	L/L	L/L	L/L	L/L
Barrel temp-zone3	L/L	L/L	L/L	L/L	L/L
Mold temp	L/L	M/H	M/H	M/H	L/M
Injection Pressure	L/L	L/L	L/L	L/L	L/L
Packing Pressure	L/L	L/L	L/L	L/L	L/L
Holding Pressure Profile	L/L	L/L	L/M	L/M	L/L
Clamping force	L/L	L/L	L/L	L/L	L/L
Fill time	L/L	L/L	L/L	L/L	L/L
Pack time	L/L	L/L	L/L	L/L	L/L
Holding time	L/L	L/L	L/M	L/M	L/L
Cooling time	L/L	M/M	H/H	H/H	M/M
Open time	L/L	L/L	L/L	L/L	L/L
Shot size	L/L	L/L	L/L	L/L	L/L
Coolant Flow Rate	L/L	L/M	L/M	L/M	L/M

Table E.5 Process vs. Mold Coolant

Mold	Tool	Number of	Mold Type	Production or Prototype

Part	Number	cavities		
Part #	L/L	L/L	L/L	L/L
EC level	L/L	L/L	L/L	L/L
Assembly level	L/L	L/L	L/L	L/L
Description	L/L	L/L	L/L	L/L
Aesthetic Reqts	L/L	L/L	L/L	L/L
Structural Reqts	L/L	L/L	L/L	L/L
Quantity reqd/system	L/L	L/L	L/L	L/L
Demand/month	L/L	M/L	M/L	L/L
Environ. Restrictions	L/L	L/L	L/L	L/L
Finish reqd	L/L	L/L	L/L	L/L
Cost	L/L	L/M	L/M	L/M
sink marks	L/L	L/L	L/M	L/L
weld line location	L/L	L/L	L/L	L/L
warpage	L/L	L/L	L/M	L/L
shrinkage	L/L	L/L	L/M	L/L

Table E.6 Part vs. Mold

Mold **Part**	Cost	Max number of parts	Minimum Clamping force
Part #	L/L	L/L	L/L
EC level	L/L	L/L	L/L
Assembly level	L/L	L/L	L/L
Description	L/L	L/L	L/L
Aesthetic Reqts	M/L	L/L	L/L
Structural Reqts	M/L	L/L	L/L
Quantity reqd/system	L/L	L/L	L/L
Demand/month	M/L	L/L	L/L
Environ. Restrictions	L/L	L/L	L/L
Finish reqd	H/L	M/L	L/L
Cost	L/H	L/H	L/L
sink marks	M/L	L/L	M/M
weld line location	L/L	L/L	L/L
warpage	M/L	L/L	M/M
shrinkage	L/L	L/L	M/M

Table E.6 Part vs. Mold (Cont.)

Cavity_Core Geometry	Side Action Mechanism	Ejection Type	Sprue Specs	Runner Specs

Mold				
Tool Number	L/L	L/L	L/L	L/L
Number of cavities	M/M	M/L	M/L	H/L
Mold Type	L/L	L/L	M/L	M/L
Production or Prototype	L/L	L/L	L/L	L/L
Cost	L/H	L/M	L/L	L/M
Max number of parts	L/L	L/L	L/L	L/L
Minimum Clamping force	L/L	L/L	L/L	L/M

Table E.7 Cavity Core Geometry vs. Mold

Cavity_Core Geometry **Mold**	Gate Specs	Delivery System Volume	Water Line Dia	Water Line Pitch
Tool Number	L/L	L/L	L/L	L/L
Number of cavities	L/L	H/L	M/L	M/L
Mold Type	M/L	M/L	M/L	M/L
Production or Prototype	L/L	L/L	L/L	L/L
Cost	L/L	L/M	L/L	L/M
Max number of parts	L/L	L/L	L/L	L/L
Minimum Clamping force	L/M	L/M	L/L	L/L

Table E.7 Cavity Core Geometry vs. Mold (Cont.)

Part / **Process**	Barrel temp- 1	Barrel temp- 2	Barrel temp-3	Mold temp	Inj. Pressure	Packing Pressure	Holding Pressure
Part #	L/L	L/L	L/L	L/L	L/L	L/L	L/L
EC level	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Assembly level	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Description	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Aesthetic Req	M/L	M/L	M/L	M/L	M/L	M/L	M/L
Structural Req	M/L	M/L	M/L	M/L	M/L	M/L	M/L
Quan.req	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Demand/month	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Env.Rests	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Finish req	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Cost	L/L	L/L	L/L	L/L	L/L	L/L	L/L
sink marks	M/M	M/M	M/M	M/M	M/M	H/M	H/M
weld line loc.	M/M	M/M	M/M	M/M	M/M	L/L	L/L
warpage	M/M	M/M	M/M	M/M	M/M	M/M	M/M
shrinkage	M/H	M/H	M/H	M/M	M/M	H/H	H/H

Table E.8 Process vs. Part

Part / **Process**	Clamping force	Fill time	Pack time	Holding time	Cooling time	Open time	Shot size
Part #	L/L	L/L	L/L	L/L	L/L	L/L	L/L
EC level	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Assembly level	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Description	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Aesthetic Req	L/L	M/L	M/L	M/L	L/L	L/L	L/L
Structural Req	L/L	M/L	M/L	M/L	L/L	L/L	L/L
Quantity req	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Demand/month	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Env. Restric.	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Finish req	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Cost	L/L	L/M	L/M	L/H	L/H	L/M	L/M
sink marks	M/M	M/M	M/M	M/M	L/L	L/L	M/M
weld line loc.	L/L	L/L	L/L	L/L	L/L	L/L	L/L
warpage	L/L	M/M	M/M	M/M	M/M	L/L	L/L
shrinkage	M/M	M/M	M/H	M/M	L/L	L/L	M/M

Table E.8 Process vs. Part (Cont.)

Molder / **Part**	Name	Address	Equipment Condition	Equipment Specs
Part #	L/L	L/L	L/L	L/L
EC level	L/L	L/L	L/L	L/L
Assembly level	L/L	L/L	L/L	L/L
Description	L/L	L/L	L/L	L/L
Aesthetic Reqts	L/L	L/L	L/L	L/L
Structural Reqts	L/L	L/L	L/L	L/L
Quantity reqd/system	L/L	L/L	L/L	L/L
Demand/month	L/L	L/L	L/L	L/L
Environ. Restrictions	L/L	L/L	L/L	L/L
Finish reqd	L/L	L/L	L/L	L/L
Cost	L/L	L/L	L/M	L/M
sink marks	L/L	L/L	L/M	L/L
weld line location	L/L	L/L	L/M	L/L
warpage	L/L	L/L	L/M	L/L
shrinkage	L/L	L/L	L/M	L/L

Table E.9 Molder vs. Part

Molder / **Part**	Design Facilities	Workforce Size	Simulation facilities	Track Record
Part #	L/L	L/L	L/L	L/L
EC level	L/L	L/L	L/L	L/L
Assembly level	L/L	L/L	L/L	L/L
Description	L/L	L/L	L/L	L/L
Aesthetic Reqts	L/L	L/L	L/L	L/L
Structural Reqts	L/L	L/L	L/L	L/L
Quantity reqd/system	L/L	L/L	L/L	L/L
Demand/month	L/L	L/L	L/L	L/L
Environ. Restrictions	L/L	L/L	L/L	L/L
Finish reqd	L/L	L/L	L/L	L/L
Cost	L/M	L/L	L/M	L/M
sink marks	L/L	L/L	L/L	L/L
weld line location	L/L	L/L	L/L	L/L
warpage	L/L	L/L	L/L	L/L
shrinkage	L/L	L/L	L/L	L/L

Table E.9 Molder vs. Part (Cont.)

Material	Name	Company	Grade	Specific Heat	Thermal	Density

Process		Name	Code	v/s Temp	Conductivity v/s Temp	
Barrel temp-zone 1	L/L	L/L	L/L	L/H	L/H	L/M
Barrel temp-zone 2	L/L	L/L	L/L	L/H	L/H	L/M
Barrel temp-zone3	L/L	L/L	L/L	L/H	L/H	L/M
Mold temp	L/L	L/L	L/L	L/M	L/M	L/L
Injection Pressure	L/L	L/L	L/L	L/H	L/H	L/M
Packing Pressure	L/L	L/L	L/L	L/M	L/M	L/M
Holding Pressure Profile	L/L	L/L	L/L	L/M	L/M	L/M
Clamping force	L/L	L/L	L/L	L/H	L/H	L/M
Fill time	L/L	L/L	L/L	L/M	L/M	L/M
Pack time	L/L	L/L	L/L	L/M	L/M	L/M
Holding time	L/L	L/L	L/L	L/M	L/M	L/M
Cooling time	L/L	L/L	L/L	L/H	L/H	L/M
Open time	L/L	L/L	L/L	L/L	L/L	L/L
Shot size	L/L	L/L	L/L	L/L	L/L	L/H
Coolant Flow Rate	L/L	L/L	L/L	L/H	L/H	L/M

Table E.10 Material vs. Process

Material Process	Transition Temp	Viscosity vs. Sheer Rat	Izod Strength	Elastic Modulus	Shear Strength
Barrel temp-zone 1	L/H	L/H	L/M	L/M	L/M
Barrel temp-zone 2	L/H	L/H	L/M	L/M	L/M
Barrel temp-zone3	L/H	L/H	L/M	L/M	L/M
Mold temp	L/M	L/M	L/M	L/M	L/M
Injection Pressure	L/L	L/H	L/M	L/M	L/M
Packing Pressure	L/L	L/H	L/M	L/M	L/M
Holding Pressure	L/M	L/H	L/M	L/M	L/M
Clamping force	L/L	L/H	L/M	L/M	L/M
Fill time	L/M	L/H	L/M	L/M	L/M
Pack time	L/M	L/H	L/M	L/M	L/M
Holding time	L/H	L/H	L/M	L/M	L/M
Cooling time	L/H	L/H	L/M	L/M	L/M
Open time	L/L	L/L	L/L	L/L	L/L
Shot size	L/L	L/L	L/L	L/L	L/L
Coolant Flow Rate	L/M	L/L	L/L	L/L	L/L

Table E.10 Material vs. Process (Cont.)

Material Process	Flexural Strength	Mold Shrinkage - flow direction	Mold Shrink.	MFI	Hardness
Barrel temp-zone 1	L/M	L/L	L/L	L/H	L/M
Barrel temp-zone 2	L/M	L/L	L/L	L/H	L/M
Barrel temp-zone3	L/M	L/L	L/L	L/H	L/M
Mold temp	L/M	L/L	L/L	L/M	L/M
Injection Pressure	L/M	L/L	L/L	L/H	L/M
Packing Pressure	L/M	L/H	L/H	L/H	L/M
Holding Pressure Profile	L/M	L/H	L/H	L/H	L/M
Clamping force	L/M	L/L	L/L	L/H	L/M
Fill time	L/M	L/L	L/L	L/H	L/M
Pack time	L/M	L/H	L/H	L/H	L/M
Holding time	L/M	L/H	L/H	L/H	L/M
Cooling time	L/M	L/L	L/L	L/H	L/M
Open time	L/L	L/L	L/L	L/L	L/L
Shot size	L/L	L/L	L/L	L/L	L/L

Table E.10 Material vs. Process (Cont.)

Machine	Max	Max Inject	Max Injection	Max Screw

Process	Shot size	Rate	Pressure	Speed
Barrel temp-zone 1	L/L	L/M	L/M	L/M
Barrel temp-zone 2	L/L	L/M	L/M	L/M
Barrel temp-zone3	L/L	L/M	L/M	L/M
Mold temp	L/L	L/M	L/M	L/M
Injection Pressure	L/L	L/M	L/M	L/M
Packing Pressure	L/L	L/L	L/M	L/L
Holding Pressure Profile	L/L	L/L	L/M	L/L
Clamping force	L/L	L/M	L/M	L/M
Fill time	L/L	L/M	L/M	L/M
Pack time	L/L	L/L	L/L	L/L
Holding time	L/L	L/L	L/L	L/L
Cooling time	L/L	L/L	L/L	L/L
Open time	L/L	L/L	L/L	L/L
Shot size	L/L	L/L	L/L	L/L
Coolant Flow Rate	L/L	L/L	L/L	L/L

Table E.11 Machine vs. Process

Machine / **Process**	Daylight Opening	Min. Mold Thickness	Max Mold Thickness	Tie Rod Distance
Barrel temp-zone 1	L/L	L/L	L/L	L/L
Barrel temp-zone 2	L/L	L/L	L/L	L/L
Barrel temp-zone3	L/L	L/L	L/L	L/L
Mold temp	L/L	L/L	L/L	L/L
Injection Pressure	L/L	L/L	L/L	L/L
Packing Pressure	L/L	L/L	L/L	L/L
Holding Pressure	L/L	L/L	L/L	L/L
Clamping force	L/L	L/L	L/L	L/L
Fill time	L/L	L/L	L/L	L/L
Pack time	L/L	L/L	L/L	L/L
Holding time	L/L	L/L	L/L	L/L
Cooling time	L/L	L/L	L/L	L/L
Open time	L/M	L/L	L/L	L/L
Shot size	L/L	L/L	L/L	L/L
Coolant Flow Rate	L/L	L/L	L/L	L/L

Table E.11 Machine vs. Process (Cont.)

Mold Maker / **Mold**	Name	Address	Equipment Condition	Equipment Specs

Tool Number	L/L	L/L	L/L	L/L
Number of cavities	L/L	L/L	L/L	L/L
Mold Type	L/L	L/L	L/L	L/L
Production or Prototype	L/L	L/L	L/L	L/L
Cost	L/L	L/L	L/M	L/L
Max number of parts	L/L	L/L	L/L	L/L
Minimum Clamping force	L/L	L/L	L/L	L/L

Table E.12 Mold vs. Mold Maker

Mold Maker **Mold**	Design Facilities	Workforce Size	Sampling facilities	Simulation facilities	Track Record
Tool Number	L/L	L/L	L/L	L/L	L/L
Number of cavities	L/L	L/L	L/L	L/L	L/L
Mold Type	L/L	L/L	L/L	L/L	L/L
Production or Prototype	L/L	L/L	L/L	L/L	L/L
Cost	L/M	L/L	L/M	L/M	L/M
Max number of parts	L/L	L/L	L/L	L/L	L/L
Minimum Clamping force	L/L	L/L	L/L	L/L	L/L

Table E.12 Mold vs. Mold Maker (Cont.)

Mold Mold	Tool Number	Number of cavities	Mold Type	Production or Prototype	Cost
Tool Number	I	L/L	L/L	L/L	L/L
Number of cavities		I	M/M	L/L	H/L
Mold Type			I	L/L	M/L
Production or Prototype				I	H/L
Cost					I

Table E.13 Mold vs. Mold

Mold Mold	Max number of parts	Minimum Clamping force
Tool Number	L/L	L/L
Number of cavities	H/L	H/L
Mold Type	M/L	M/L
Production or Prototype	H/L	L/L
Cost	M/M	L/L
Max number of parts	I	L/L
Minimum Clamping force		I

Table E.13 Mold vs. Mold (Cont.)

Cavity_Core Material Cavity_Core Material	Name	Density	Specific Heat Capacity	Thermal Conductivity	Wear Resistance
Name	I	L/L	L/L	L/L	L/L
Density		I	M/L	M/L	M/L
Specific Heat Capacity			I	L/L	L/L
Thermal Conductivity				I	L/L
Wear Resistance					I

Table E.14 Cavity_Core Material vs. Cavity_Core Material

Mold Coolant / Mold Coolant	Name	Density	Specific Heat Capacity	Thermal Conductivity	Viscosity
Name	I	L/L	L/L	L/L	L/L
Density		I	M/L	M/L	M/M
Specific Heat Capacity			I	L/L	L/M
Thermal Conductivity				I	L/M
Viscosity					I

Table E.15 Mold Coolant vs. Mold Coolant

Mold Maker / Mold Maker	Name	Address	Equipment Condition	Equipment Specs	Design Facilities
Name	I	L/L	L/L	L/L	L/L
Address		I	L/L	L/L	L/L
Equipment Condition			I	L/L	L/L
Equipment Specs				I	L/L
Design Facilities					I

Table E.16 Mold Maker vs. Mold Maker

Mold Maker / Mold Maker	Work force Size	Sampling facilities	Simulation facilities	Track Record
Name	L/L	L/L	L/L	L/L
Address	L/L	L/L	L/L	L/L
Equipment Condition	L/L	L/L	L/L	L/L
Equipment Specs	L/L	L/L	L/L	L/L
Design Facilities	M/L	L/L	L/L	L/L
Workforce Size	I	L/M	L/M	L/L
Sampling facilities		I	L/L	L/L
Simulation facilities			I	L/L
Track Record				I

Table E.16 Mold Maker vs. Mold Maker (Cont.)

Part **Part**	Part #	EC level	Assembly level	Description	Aesthetic Reqts	Structural Reqts	Quantity req/system
Part #	I	L/L	L/L	L/L	L/L	L/L	L/L
EC level		I	L/L	L/L	L/L	L/L	L/L
Assembly level			I	L/L	L/L	L/L	L/L
Description				I	L/L	L/L	L/L
Aesthetic Reqts					I	L/L	L/L
Structural Reqts						I	L/L

Table E.17 Part vs. Part

Part Part	Demand/ month	Environ. Res	Finish req	Cost	sink marks	weld line location	warpage	shrinkage
Part #	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
EC level	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Assembly level	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Description	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Aesthetic Req.	L/L	L/L	M/L	M/L	M/L	M/L	M/L	L/L
Structural Req.	L/L	L/L	L/L	M/L	M/L	M/L	M/L	L/L
Quantity reqd/system	M/L	L/L	L/L	M/L	L/L	L/L	L/L	L/L
Demand/month	I	L/L	L/L	M/L	L/L	L/L	L/L	L/L
Environ. Restrictions		I	L/L	M/L	L/L	L/L	L/L	L/L
Finish reqd			I	H/L	M/L	L/L	L/L	L/L
Cost				I	L/L	L/M	L/M	L/L
sink marks					I	M/M	M/M	H/M
weld line location						I	M/M	M/L
warpage							I	H/M

Table E.17 Part vs. Part (Cont.)

Cavity_Core Geometry / **Cavity_Core Geometry**	Ejection Type	Sprue Specs	Runner Specs	Gate Specs	Delivery System Volume	Water Line Diameter	Water Line Pitch
Side Action Mechanism	M/L	L/L	L/L	L/L	L/L	L/L	L/L
Ejection Type	I	L/L	L/L	L/L	L/L	L/L	L/L
Sprue Specs		I	M/L	L/L	H/M	L/L	L/L
Runner Specs			I	M/M	H/M	M/L	M/L
Gate Specs				I	M/M	M/L	M/L
Delivery System Volume					I	L/L	L/L
Water Line Dia						I	M/M

Table E.18 Cavity_Core Geometry vs. Cavity_Core Geometry

Part Geometry / **Part Geometry**	Wall Thickness	Undercuts	Tolerances	Internal Threads	Blind Holes	Gate Locations
Wall Thickness	I	L/L	L/L	L/L	L/L	H/M
Undercuts		I	L/L	L/L	L/L	L/L
Tolerances			I	L/L	L/L	L/L
Internal Threads				I	L/L	L/L
Blind Holes					I	L/L
Gate Locations						I

Table E.19 Part Geometry vs. Part Geometry

Molder **Molder**	Address	Equipment Condition	Equipment Specs	Design Facilities	Workforce Size	Simulation facilities	Track Record
Name	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Address	I	L/L	L/L	L/L	L/L	L/L	L/L
Equipment Condition		I	L/L	L/L	L/L	L/L	L/L
Equipment Specs			I	L/L	L/L	L/L	L/L
Design Facilities				I	M/L	L/L	L/L
Workforce Size					I	L/M	L/L
Simulation facilities						I	L/L

Table E.20 Molder vs. Molder

Process **Process**	Barrel temp-zone 1	Barrel temp-zone 2	Barrel temp-zone3	Mold temp	Injection Pressure	Packing Pressure	Holding Pressure Profile
Barrel temp-zone 1	I	M/M	M/M	M/M	H/M	M/L	M/L
Barrel temp-zone 2		I	M/M	M/M	H/M	M/L	M/L
Barrel temp-zone3			I	M/M	H/M	M/L	M/L
Mold temp				I	M/M	M/L	M/L
Injection Pressure					I	L/L	L/L
Packing Pressure						I	M/L
Holding Pressure Profile							I

Table E.21 Process vs. Process

Process **Process**	Clamp. force	Fill time	Pack time	Holding time	Cooling time	Open time	Shot size
Barrel temp-zone 1	H/L	H/M	H/L	H/L	H/L	L/L	L/L
Barrel temp-zone 2	H/L	H/M	H/L	H/L	H/L	L/L	L/L
Barrel temp-zone3	H/L	H/M	H/L	H/L	H/L	L/L	L/L
Mold temp	M/L	M/M	M/L	M/L	H/L	L/L	L/L
Injection Pressure	H/L	H/H	L/L	L/L	M/L	L/L	L/L
Packing Pressure	H/L	L/L	M/M	L/L	L/L	L/L	M/M
Hold Press. Profile	H/L	L/L	M/M	H/H	L/L	L/L	M/M
Clamping force	I	L/M	L/L	L/L	L/L	L/L	L/M
Fill time		I	M/L	M/L	M/L	L/L	L/L
Pack time			I	M/L	L/L	L/L	M/M
Holding time				I	L/L	L/L	M/M
Cooling time					I	L/L	L/L
Open time						I	L/L
Shot size							I

Table E.21 Process vs. Process (Cont.)

Material **Material**	Comp Name	Grade Code	Specific Heat v/s Temp	Thermal Cond. v/s Temp	Density	Transition Temp	Vis. vs. sheer Rate
Name	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Company Name	I	L/L	L/L	L/L	L/L	L/L	L/L
Grade Code		I	L/L	L/L	L/L	L/L	L/L
Specific Heat			I	L/L	L/M	L/L	L/L
Thermal Cond.				I	L/M	L/L	L/L
Density					I	M/L	M/L
Transition Temp						I	M/L

Table E.22 Material vs. Material

Material Material	Izod Strength	Elastic Modulus	Shear Strength	Flexural Strength	Mold Shrink. - flow direction	Mold Shrink. - perp to flow	MFI	Hardness
Name	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Company Name	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Grade Code	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Specific Heat v/s Temp	L/L	L/L	L/L	L/L	L/L	L/L	M/L	L/L
Thermal Cond. v/s Temp	L/L	L/L	L/L	L/L	L/L	L/L	M/L	L/L
Density	M/L	M/L	M/L	M/L	M/L	M/L	M/L	M/L
Transition Temp	L/L	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Viscosity vs. Sheer Rate	L/L	L/L	L/L	L/L	L/L	L/L	H/H	L/L
Izod Strength	I	L/L	L/L	L/L	L/L	L/L	L/L	L/L
Elastic Modulus		I	L/L	L/L	L/L	L/L	L/L	L/L
Shear Strength			I	L/L	L/L	L/L	L/L	L/L
Flexural Strength				I	L/L	L/L	L/L	L/L
Mold Shrink - flow direction					I	M/M	L/L	L/L
Mold Shrink to flow						I	L/L	L/L
MFI							I	L/L

Table E.22 Material vs. Material (Cont.)

Machine	Max	Max	Max	Max Screw	Max

Machine	Shot size	Injection Rate	Injection Pressure	Speed	Clamping Force
Max Shot size	I	L/L	M/M	M/M	H/M
Max Injection Rate		I	M/M	H/H	M/L
Max Injection Pressure			I	M/M	H/M
Max Screw Speed				I	M/L
Max Clamping Force					I

Table E.23 Machine vs. Machine

Machine / Machine	Daylight Opening	Min. Mold Thickness	Max Mold Thickness	Tie Rod Distance	Max Coolant Flow Rate
Max Shot size	M/L	L/L	L/L	L/L	M/L
Max Injection Rate	M/L	L/L	L/L	L/L	M/L
Max Injection Pressure	M/L	L/L	L/L	L/L	M/L
Max Screw Speed	M/L	L/L	L/L	L/L	M/L
Max Clamping Force	M/L	L/L	L/L	L/L	M/L
Daylight Opening	I	M/M	M/M	M/M	L/L
Min. Mold Thickness		I	M/M	M/M	L/L
Max Mold Thickness			I	M/M	L/L
Tie Rod Distance				I	L/L
Max Coolant Flow Rate					I

Table E.23 Machine vs. Machine (Cont.)

Appendix F

EXPRESS

F.1 EXPRESS Overview

EXPRESS is a formal information modeling language that specify the requirements of the International Standard STEP 10303. The EXPRESS was constructed with several goals in mind:

1. The language should by parsable by computers
2. The language should be able to partition the diverse material addressed by modeling mechanical products
3. The language should be focused on the definition of entities
4. The language should avoid any linkage to specific implementation views

EXPRESS is a conceptual schema language as defined in ISO TR. 9007. EXPRESS is a data definition language model the information about products along their life cycle.

EXPRESS is not a programming language, it is facilitating object definitions and constraints. However the EXPRESS language does not contain elements which allow input or output.

F.2 EXPRESS Selected Definitions

1. Attribute: A Quality or property that is a characteristic of an entity.
2. Entity: A type which represents a collection of conceptual or real world physical object which have common properties
3. Function: An algorithm that operates on parameters and produces a resultant value of the specified type.
4. Instance: A particular value of a type
5. Model: A formal description of a universe of discourse
6. Object: A conceptual or physical thing which may exist in the real world
7. Rule: A specification of one or more constraints between entity instances
8. Schema: A collection of items forming part or all of a model.
9. Type: A representation of a domain of valid values.

F.2.1 EXPRESS Data Type

Selected data type are:

1. Simple data types that describes, number types, string, logical, boolean, etc.
2. Aggregation types that describes ordered or unordered collection of types, e.g. array data type, bag data type, list data type, etc.
3. Named data types: that describes, defined data types, entity data types, data type, etc.

F.2.2 EXPRESS Schema

A schema declaration creates new scope in which , Constants, entities, functions, rules or types can be declared.

F.2.3 EXPRESS Entity

An entity type declaration create a new meta data description that can be described via attributes. The entity behavior can be captures via constrains.

F.2.4 EXPRESS Attribute

Can be declared in an entity framework. The sole purpose of an attribute is to describe a specific aspect of the described entity

F.2.5 EXPRESS Relation

Relation in the EXPRESS domain is a description of an entity as an attribute of another entity.

F.2.6 EXPRESS Supertype - Subtype Relationship

Supertype - Subtype relation is for specifying classification. A subtype is more specific type than its supertype. A supertype is more general type than its subtype. Subtype is a more specific kind of its supertype. Therefore, every instance of a subtype is an instance of its supertpye.

1. A subtype may have more than one supertype.
2. A supertype may have more than one subtype.

3. A supertype maybe itself subtype of other entities.

4. A subtype can not be the supertype of any type in the list of all its supertype [STEP Part 11, 1992]

F.3 EXPRESS Example

```
SCHEMA drawing;

ENTITY point_3D;
    x1:    REAL;
    x2:    REAL;
    x3:    REAL;
UNIQUE
    pnt_name:  name;
END_ENTITY;

ENTITY circle;
    center_point:   point_3D;
    radius:         REAL;
UNIQUE
    circle_name:   name;
END_ENTITY

ENTITY line;
    start_point: point_3D;
    start_point: point_3D;
UNIQUE
    line_name: name;
END_ENTITY

ENTITY line_shape;
    start_point: point_3D;
    start_point: point_3D;
    have_line:   line;
UNIQUE
    line_shape _name:    name;
END_ENTITY

ENTITY line_shape;
```

```
    start_point: point_3D;
    start_point: point_3D;
    have_line:   line;
UNIQUE
    line_shape _name:    name;
END_ENTITY

ENTITY single_draw;
    have_point: point_3D;
    have_line_shape: line_shape;
    have_line:   line;
    have_circle:     circle;
UNIQUE
    single_draw _name:  name;
END_ENTITY


END_SCHEMA;
```

Appendix G

Selected C-FAR Algorithms

G.1 Algorithm to Find Paths between A Source Node To A Target Node

G.1.1 Problem Statement

Given:

1. A graph, G(V,E), that can have at most one self-loop at each node
2. A source node, S
3. A destination node, D

Find:

All simple paths that connect S to D.

A path is represented as a list of nodes that are passed through from S to D.

This algorithm finds all simple paths between

a given source node to a given destination node.

Find_Source2Destination_SimplePaths (Graph ,Source ,Destination)

-. Mark all nodes as Non-Active

-. Mark Source node as Active

-. Distance = Dijkstra(Graph, Destination)

G.1.2 Problem Solving

These paths have a maximum length of number of nodes in

```
# graph - 1.
  -. MaximumPathLength = Find_Number_Of_Nodes (Graph) - 1


# Main loop
Do Iteration = 1 to MaximumPathLength
  For all nodes marked Active
      # Send all paths received during last iteration on all
      # outgoing links from the node
      Group_Paths (Node)
      Prepare2Send (Node)
      Send (Node, Paths2Send)
  For every node in Graph
      if (!Destination or !Source or
          MaximumPathLength-Iteration <= Distance[Node] or
          received a path during this iteration or
          Number of outward edges in node > 0)
           SimplePaths=FindSimple(ReceivedPaths, Node)
           PreparePaths2Send(Node)
           if SimplePaths != NULL
             Mark node as Active
          end
      else
```

Mark node as Non-Active

end

Return (all paths in that are currently stored in

Destination node)

G.1.3 Paths Representation

A node gets an indication that it is part of a specific path whenever it gets a ***path-message*** from a neighboring node. A path-message contains the ***path-number*** the node is connected to. A path-number is a unique number that identifies each path. The receiving node concatenates the link from which the path-message arrived to the path-message, generating a ***path-link***. Thus, path-link is formally defined as follows:

path-link := path-number + link.

Every node that receives a path-message during an iteration checks whether the path is legal (see below for more details). If the message is legal, the receiving node will send a path-message on all of it's outwards edges on the next iteration.

As long as a node has only one outward edge, that is, there is only one node that might get a path-message from this node at every iteration, it does not change the path-number. The path-number that is sent in the next iteration is identical to the path-number received.

If a node has one or more inward edges, it receives a different path-number on each. The node records all the coming path numbers in a table, and chooses one of them -- say the smallest one -- to represent them. This number is called the ***common-path***. If a node has only one inward edge, the common-path-number is the received path-number. The process of choosing a path number and creating a table is done in **Group_Paths**. The common-path is entered as an entry to a table of all path numbers that passed through this node. The entry contains all the path numbers that were grouped into the common-path, and the link that needs to be followed in order to get to the preceding node of this path. Each of these paths has a ***state*** attribute, which can be in one of the following two states:

1. Valid – if the path number is still legal.
2. Invalid – if the path number was found to be illegal.

The common_path has also a state flag assigned to it. The flag is at Valid state as long as at least one of the paths that are grouped into the common_path is Valid.

If the node has more that one outward edge, a new path-number is assigned to each one of path-messages that will be sent on each one of the edges except one. The common-path number is called the ***parent-path*** and the new path-numbers are called ***child-paths***. The node stores the parent-children relationship. The path numbers are assigned such that a parent path number is always greater than its children's path numbers. This process is called **Prepare2Send**. As a result of this procedure, only one number is sent on each one of the outward edges. All paths sent are legal for the route from Source node to the sending node.

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