The Cost Modeling of Automotive Body-in-White Assembly Using Relational Databases

by

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Submitted to the Department of Materials Science and Engineering in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

A methodology was developed for the technical cost analysis of the assembly of the automotive body-in-white. This methodology involved using a body-in-white subassembly based strategy to simulate the flow of parts through an assembly line. This flow was used to estimate the cost of assembling a body-in-white. It was found that the new modeling strategy could not be implemented using traditional computer spreadsheet software packages. The implementation of the new modeling strategy required the creation of a model using a relational database software. This model was created and tested using the test case of the 1989 Ford Taurus steel unibody construction.

Annual production volume sensitivity analysis performed on the per vehicle cost of the test case demonstrated the greater accuracy of the new subassembly modeling strategy. The increase in the robustness and analytical power of the new relational database model when compared to previous spreadsheet body-in-white assembly models was also shown.

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This thesis is dedicated to the loving memory of my grandmother, Annapurna Marti.
Introduction

Recent increases in governmental restrictions on automotive fuel emissions such as the Corporate Average Fuel Economy (CAFE) standards have forced the automotive industry to investigate vehicles that are more fuel efficient and environmentally friendly than their predecessors. This push for greater fuel economy has resulted in greater interest in reducing the weight of automobiles through the use of alternative materials. The automotive body-in-white (BIW), defined as "consisting of the body panels which contribute to the torsional and bending stiffness of the structural unit [of the car body]"[1], contributes 25% to the curb weight of an automobile. Much of the efforts of the automotive industry have been directed at reducing the weight of the BIW, through the use of aluminum, polymers and hybrids of steel and aluminum as alternatives to the current steel unibody construction. In reducing the weight of the BIW, the possible costs incurred through the use of more expensive materials and joining technologies are a vital issue.

One area of special interest is the assembly of the BIW. BIW assembly involves the joining of various pre-formed parts using a variety of processes. When substituting non-steel parts for steel ones within the BIW, the automotive industry tries to retain the joining process used for the steel part (usually resistance spot welding). However, experience has shown that there are several key areas in which alternative joining processes must be used, including adhesive bonding and laser beam welding.

The use of resistance spot welding to join alternative materials as well as the use of new joining processes results in a variety of different cost scenarios. In order to better
understand these scenarios, there must be an analysis of all of the elements that contribute to the cost of production. These include materials selection as well as the changes that must be made in welding and joining techniques in order to accommodate the use of different materials. Given these new factors, a model which provides the user with the ability to compare the cost of a traditional all-steel and an alternative material BIW is extremely useful.

There has been some work done on providing such a tool in the past but most previous tools were lacking in sophistication and flexibility. A tool which estimates the cost of BIW assembly must be able to model many different assembly processes, as well as to incorporate new joining technologies into the estimation of cost. Recently Laser Beam Welding (LBW) has come to be seen as one of the joining processes of choice in the near future. The costs associated with new processes such as LBW which are still in their experimental phase are vital to the designer of future BIW assembly lines.

In this thesis, a framework will be provided where the requirements of cost modeling in general and the cost modeling of BIW assembly in particular are discussed. The implementation of these requirements in the form of a relational database cost model and the demonstration of the effectiveness of the model are also explored. The relational database model that has been created for this thesis is meant to address many of the issues and problems outlined in the introduction. The limitations and needed improvements on the cost model are the final point of discussion.
1. The General Principles of Cost Modeling

1.1 Technical Cost Modeling: Some Background

There are a wide variety of different modeling strategies that can be used to study the cost of industrial processes. Each different modeling strategy has its unique advantages and disadvantages. The commonly used modeling strategies include: case studies, optimization techniques, simulation models, engineering studies, judgment studies and technical cost models. Case studies are detailed studies of a specific problem within a certain context. Case studies provide large amounts of detailed information but due to their depth and specificity, few broad conclusions can be drawn from the results of a case study.

Optimization techniques generate optimal scenarios based on user inputted constraints and optimization criteria. Models which utilize optimization techniques have two key drawbacks. The first is that such models assume an optimal world where inputs can be perfectly controlled. The second is that often given a certain number of constraints, the optimization model will have several solutions, out of which it will select one which best suits the input data. These solutions may have vastly different consequences but which solution is picked is influenced by very slight variations in inputs. Therefore, if the inputs are changed slightly, the model could return a vastly different result.

Simulation models attempt to use relationships between different processes to explain the specific phenomena being studied in each different process. Simulation models are extremely flexible as they are not restricted to data from one source, and can give reasonably
accurate results even in cases where there is a lack of complete data. This becomes a disadvantage, however, when greater depth of analysis is needed.

Econometric methods use previously compiled statistical data to construct hypothetical interrelationships between different inputs. This method is very useful when there can be reasonable assurance that past events are good predictors of future ones. Of course, this is not always the case in modeling BIW assembly because often modelers are exploring experimental designs about which no past data is available.

Engineering models use scientific and empirical formulae to relate experimental data and historical results. It is a scientific equivalent of econometric analysis. Since engineering models rely on quantified information, it is very easy to compare the results of different processes, and different solutions to a given processing problem. The engineering study is highly quantitative. However, there are many factors that must be taken into account when estimating automotive cost which cannot be analyzed through the use of engineering formulae. Therefore, engineering studies may not be able to account for some of these intangible factors involved in cost modeling.

Judgment studies are those studies which are based on a polling of various expert opinions and empirical evidence. This method is relatively easy to implement but may have very controversial results which are difficult to prove and easy to challenge. For instance, if the cost of a new experimental BIW design was being estimated by calling up materials suppliers, machinery manufacturers, automotive manufacturers and line designers, each individual would have a bias towards their own products. This would result in the study publishers having to sift through data and make judgment decisions on which data is biased.
and which is not. Regardless of the results, one of the manufacturers can easily claim that the study does not take into account some key factor which they consider important. All cost modeling results, especially comparative studies are likely to result in some controversy. The primary weakness of judgment study is that they are based on opinions and therefore there is nothing that is irrefutable.

TCM combines the benefits of many of these different forms of analysis into one comprehensive modeling strategy. TCM combines "the flexibility of simulation models, the statistical verification of econometric models, the scientific/engineering relationships of engineering studies and the tacit knowledge derived from judgment studies."[2] TCM provides a model which uses empirical data, regression analysis, theoretical formulae and the knowledge of industry experts. This combination of theory and empiricism is especially important in modeling BIW assembly because of the many new joining technologies and alternative BIW materials which are now being proposed. The ability to combine empirical data from tried and tested BIW assembly techniques with theoretical formulae and approximated data for cutting-edge alternative technologies makes TCM a powerful modeling tool for industrial processes in general and BIW assembly in particular.

1.2 Technical Cost Modeling: Fixed and Variable Costs and their Calculation

In TCM, costs are separated into two classes: fixed costs and variable costs. Every contributor to the cost of a particular assembly joining technology is divided into one of these two categories. Fixed costs are effected by changes in production volume, while variable costs are not. For example, the cost of energy consumed while making each vehicle is independent
of production volume. For every new vehicle produced there is a fixed cost in energy consumption. This cost is the same for every additional vehicle. Therefore, when viewed as a per vehicle cost, an increase in production volume does not change the cost. Fixed costs, on the other hand, do change with production volume. This is because there are economies of scale associated with an increased annual production volume. Therefore, as the production volume increases, there is a decrease in the per vehicle cost of equipment. At first glance, this seems as if the labels "fixed" and "variable" have been reversed. The reason that those costs which vary with production volume are called fixed is that they are fixed dependent on a given capacity of production. For example, if $1 million worth of equipment is needed to make 100,000 widgets, then even if only 80,000 widgets are produced, the total cost of equipment will still be $1 million. On the other hand, if the cost of material for each widget is $10, then no matter how many widgets are produced, the cost will be $10.

In modeling the cost of a given industrial process, the modeler must decide which elements of cost contribute meaningfully to the total cost of the process. There are several basic costs associated with every industrial process. Every industrial process will have fixed costs such as main machine, building, energy and maintenance costs, and variable costs such as the cost of labor and energy.

If any assembly joining technology is analyzed by itself, it may be possible to only consider the fixed and variable costs which effect the cost of that particular process. However, a single assembly line often uses many different joining technologies. Each of these have different factors which have the largest effect on the total cost of joining. For instance, the cost of consumable materials, namely filler material and electrodes, is a large portion of the cost of
joining when metal inert gas (MIG) welding is used. On the other hand, RSW does not use a filler material to weld parts together. The major contributors to cost in RSW are the cost of applying the welds themselves. This cost is due to the cost of the RSW gun, the cost of electrodes, and many other costs that are unique to RSW. Given the diverse array of joining processes used, an assembly model must be able to analyze the costs which are vital to many different joining technologies. An accurate assembly cost model must have the capacity to account for the contributions of each of this wide array of elements to the total BIW assembly cost.

Applying TCM to assembly requires the modeler to make important choices between the level of detail included and the amount of input information required from the user to run the model. A model that is extremely robust and accurate but requires thousands of entries from the user is unrealistic. However, a model that takes two or three user-specified parameters and makes rather wild extrapolations from them is also undesirable. The striking of a balance between model complexity and usability are the topics of the next section.
2. Technical Cost Modeling as Applied to BIW Assembly

2.1 Modeling Assembly: Previous Modeling Methodology

Modeling assembly requires the analyst to make the choice between modeling detail and the relevance of various inputs on the ultimate outcome: the cost of assembly. In a perfect world, a modeler would easily be able to access all information on a given a process and input all of this information into the model. The modeler would then simply sit back and let the model "decide" which variables effected costs and which did not. In such a world, the model would include every detail from the cost of disposing the container which carried adhesive bonding glue to the cost of hiring a night security guard to protect the plant.

The real world requires the modeler to make choices as to which inputs are relevant and which are not. This decision making process is key to the success of any model in predicting cost. A model is ineffective if it requires information which is not readily available to the users of the model. A model is also of little use of it does not take into account all key elements of total cost. In devising a modeling strategy, previous modelers of BIW assembly have laid a foundation from which assembly models can be further refined.

All previous TCM/Material Systems Laboratory (MSL) assembly models were constructed using computer spreadsheet software packages. In these previous spreadsheet models, a separate "worksheet" was used to model each different subassembly. Each worksheet contained prompts for various user-supplied values. These included global variables like production volumes and energy costs and a total length for which a given joining technique was used. Each worksheet also contained data on different joining methods. For example, the user might specify that 120 inches of weld were done using Resistance Spot Welding Robotic (RSW(R)). The entered data as well as the information which the model contained on different joining methods was easily changed. The user simply needed to go to the cell which contained the data to be changed and change that data.

Assembly models were often constructed as appendages to parts fabrication models (e.g. a stamping model in which the cost of assembling the stamped parts is also modeled). The stamped parts were categorized according to where in a vehicle they would be used and
then joined together. Parts, therefore, were divided into groups based on the type of part they were. For instance, all of the parts that were fabricated for the floor were grouped together.

![Diagram](image)

Figure 2.1: Old assembly modeling strategy.

As explained in section 1.2, most TCM models account for costs in two categories: fixed cost and variable cost[3]. The same is true for previous assembly models. Within the domain of fixed costs, the model calculates main machine costs for a given method. The main machine here is defined as the equipment actually used to perform a certain join. This may include items such as a robot arm and a welding gun. The cost of additional equipment used to complete the join such as transformers and adhesive bonding tanks is defined as the auxiliary equipment cost. These main and auxiliary equipment costs are usually thought of as being annualized payments on loans taken out by the plant owners to pay for the equipment. The cost of investing in the capital is paid off at an annual amount, which has a rate, R. The equation for this rate is:

\[
R = P \times \frac{\left(1+i\right)^N \times i}{\left(1+i\right)^N - 1}
\]
P is the principal amount, i is the opportunity cost of capital as an annual rate, and N is the number of years before the "payoff". This rate is incorporated into various costs as shown in Section 3.2. Often the calculation of the cost of auxiliary equipment is simplified by assuming that the cost of auxiliary equipment is a fixed percentage of the main machine cost.

Each joining process also has associated material costs. For processes which use a filler material, there is a filler cost. For processes which use weld tips there is an electrode cost. Previous modeling strategies also accounted for the cost various ancillary processes associated with joins like fixturing, tacking and induction curing within the processes themselves. For instance, RSW would have an associated tack welding cost. The cost of ancillary processes were grouped into one cost called the tooling cost.

Labor is another cost which is associated with specific processes, through an assignment of a certain number of laborers necessary to operation a given joining unit. Often this is a fraction of a worker (e.g. 0.25 workers are needed to run a RSW(R) joining unit). The hourly wage paid to workers includes the wages that must be paid to supervisory and support staff. There is also an investment cost associated with the building space's cost/unit area. This cost can be reflected in the cost of producing various parts through an equations such as:

\[
\text{BUILDING COST} = \text{ANNUAL INVESTMENT} / \text{ANNUAL PRODUCTION}
\]

The spreadsheet model also accounted for the cost of maintaining the joining equipment as a percentage of the sum of the equipment, building, tooling, and loading costs. All of these costs are spread out over a given production volume, so that a per vehicle cost is obtained.

2.2 Problems with the Old Modeling Strategy

There are four fundamental problems with the way in which the previous assembly model worked. The first is the way in which equipment and tooling costs are calculated. The second is the manner in which parts were grouped. The third is the manner in which the model
itself was constructed. The fourth is an inability to examine the rise in per unit cost as a plant built for given capacity production volume is increasingly underutilized.

2.2.1 The Grouping of Parts

The most fundamental problem with the modeling strategy employed in previous assembly models is that it is unrealistic. The assembly model was devised as an afterthought to the cost of stamping and many of its results could not be justified because it had been constructed according to the specifications of the stamping model and not according to the way in which BIW assembly is actually performed. Subassemblies are groupings of parts that are joined with each other before they are joined to other parts. A subassembly may be joined to another subassembly. In the real-life BIW assembly, parts are grouped by subassembly, not by type of part, as was previously done. This has some very important effects. Going back to the example of only one subassembly for the entire floor of the BIW, some parts that will end up in the floor of the BIW may actually be grouped with other parts that may end up in the lower part of the door frame.

In such a schema, parts are grouped according to ease of joining and transport, not according to where the parts will end up in the BIW. A model that does not operate on the basis of subassemblies is highly unrealistic and will not take into account all of the complexities of BIW assembly. A transition needed to be made from the schema described in Figure 2.1 to the schema described below, in Figure 2.2.

Previous modelers had not examined the subassembly approach for a reason. They had assumed that the way in which parts were grouped, and the resulting number of subassemblies would have little effect on the total cost of BIW assembly. That is, it would not matter whether there were five, ten or twenty different subassemblies used. There would be no greater level of accuracy or realistic simulation achieved. In reality, the small number of subassemblies used grossly overestimates the efficiency with which joining units are used. Therefore, both in conceptual and practical terms the cost of capital incurred through the use of many joining units was grossly underestimated.
The unrealistic nature of the model was compounded by the amount of time that a user needed to add new joining methods or new subassemblies to the previous model. Due to the spreadsheet platform of the old model, connections between subassemblies needed to be reassigned and the final assembly worksheet had to be redone in order to accommodate new joining methods or new subassemblies. This is clearly an undesirable defect in the old modeling strategy.

2.2.2 Calculation of Equipment and Tooling Costs

The structure of certain cost inputs in previous modeling strategies was incompatible with the way that model users are likely to think of cost inputs. While the calculation of tooling, building and maintenance costs are done in a manner which is intuitive to the user, the same cannot be said for equipment and capital costs. The separation of equipment into main and auxiliary components does not correlate well with the way in which assembly line joining equipment is purchased. Generally speaking the robot is purchased in a set along with the necessary auxiliary equipment. The gun or applicator are bought separately. Therefore, it makes a great deal more sense to divide equipment cost between robot (if there is one) and guns. There also exist pieces of equipment which need not be dedicated to a single joining unit. The sharing of these pieces of equipment, such as adhesive bonding tanks, has an important impact on cost. Within shared equipment, some equipment can only be shared within a given station while other equipment can be shared across stations. Equipment that can be shared across stations shall be referred to as line shared equipment. Dedicated equipment like guns and robots are referred to as unshared equipment. In resolving this very different cost structure, the model has been redesigned to ask for three different types of cost: unshared, shared and line shared equipment costs. Within each type of equipment cost there are three different possible inputs, so that a given process can have up to three types of shared, unshared or line shared equipment.

2.2.3 Sensitivity Analysis on Percentage of Capacity Used

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Assembly plants are often built to handle a certain annual production volume. After having been built, they are often run at a production volume that is far less. It is of interest to modelers to be able to evaluate the additional cost per vehicle of running a production line at a volume below its capacity. In previous models, this was quite difficult to do. The user would have to run the model at a given capacity production volume and down time and note the equipment cost. Then, the user would have to run the model at the actual production volume and change the down time until an equipment cost equal to the capacity equipment cost was achieved. This was a roundabout manner through which the relative increase in the per vehicle cost due to under utilization of the line could be calculated. A model which could be run at different capacity and actual production volumes is extremely useful in analyzing issues relating to efficiency of use of resources and increase in per vehicle assembly costs.
3. The New Modeling Approach

3.1 The New Modeling Strategy

In order to solve many of the problems associated with the old modeling strategy described in Figure 2.1, and implement the new modeling strategy, a larger number of subassemblies are needed. For instance, in assembling the 1989 Ford Taurus steel unibody construction, 31 subassemblies are used to replace the previous 5 subassemblies[4], as shown below.

A large number of subassemblies gives the user a much better idea of the actual costs of assembly. The new strategy is also far more realistic than previous ones. Additionally, it is far easier to transfer parts from one location to another in a subassembly schema, because it is a
transparent process. In spreadsheet models, only a total length of welding was specified for a grouping of parts. In a subassembly schema, these groupings are far smaller, making it easier to identify the effects of the cost of including individual parts in the assembly line on total BIW cost. In a real assembly line parts are loaded into initial subassemblies. These smaller subassemblies, along with some new parts, are joined together in larger subassemblies and so on and so forth until final assembly. There are numerous costs associated with this flow of parts which are not adequately represented in the spreadsheet-based model due to the small number of subassemblies, as explained in section 2.2.1. Specifically, capital costs are severely underestimated. There increase in the number of stations required, due to an increase in the number of subassemblies (see section 4.3 for an explanation of the relationship between the number of stations and the number of subassemblies). The underestimation of capital costs is demonstrated in Section 5's analysis of the costs associated with assembling the 1989 Taurus.

3.2 Problems Encountered When Implementing the New Strategy

Attempting to construct a spreadsheet model that contains so many subassemblies can be a problem. As new joining technologies and alternative BIW designs are proposed, users will want to test their cost. For instance, the newest version of the spreadsheet-based assembly model contained five subassemblies: the door subassembly, the quarter-pan subassembly, the floor subassembly, the roof subassembly and the final assembly -- where all of the parts are combined. If a user felt that this was an inadequate level of detail, and wanted to add another subassembly, then a whole new worksheet would have to be created. Each of the field references would have to be copied onto this new sheet, and so would all of the information
about the joining methods. The final assembly sheet would then have to be updated so that all of the subassemblies flow into it, including the new subassembly.

The spreadsheet-based model allows the user to select different joining methods by referencing the cells which contain the pertinent data. When new methods are added, the user must reconstruct these references. In order to use the model, the user must scroll through large worksheets, whose contents are largely relevant only to the modeler and whose properties the user rarely must change. The appearance of the model makes it extremely user unfriendly as the user must scroll through cell upon cell of cryptic inputs and references. There is also a real danger of the user changing a cell which then renders the results highly unreliable. While an easy solution would be to lock such cells, this cannot be done since at times the user must change these cells in order to add new joining technologies.

3.3 The Solution: Relational Database Modeling

Many of the improvements that were seen as necessary in order to produce a model which would estimate cost in a meaningful manner are most easily implemented if a relational database-based technical cost model is used instead of the current spreadsheet-based format. Databases in general are:

"A large, integrated, shared pool of information in a form suitable for handling by a computer which is a basis upon which the computer user community within an organization can draw inferences in conducting business"[5]

Databases are essentially tables with rows and columns. The rows contain records and the columns contain information that is relevant to the records. Each table in a database is
dedicated to listing a certain entity. For instance, if a table lists the name of a certain list of automotive parts to be assembled, a corresponding ID, the weight of each part and the material out of which each part is made, then it is a table of entities called "Assembly Parts". Each table contains two separate elements: the header and the body. The body is a series of tuples. Tuples are a series of records, each of which has the same number of fields. All of the fields in the tuples are of the same size. When a tuple (for ease of use, from this point onwards, tuples will be referred to as records) intersects a column of the table, as shown in Figure 3.2, an attribute value is assigned for the particular entity that is being described in the database.

![Figure 3.2: The Structure of a Relational Database Table](image)

The header contains attribute (attributes will be referred to as fields from this point onwards) names. Each of these names must be unique and corresponds to a series of field values in the body. One field name must be the primary key attribute (primary key for short)
name. The primary key is used to differentiate between different records, and therefore must be a unique value. In the case of the "Assembly Parts" table, the part ID is the primary key.

There is often a need for one database table to make use of data from another table. When there are several databases which are related to one another, the entire set of tables is referred to as a relational database. The relational link between databases is accomplished by tying data in the tables together using joins. A join is a link between a field of one table, and that of other tables. Joins are often made on primary keys but do not have to be. The effect of joining two tables is that if a change is made to one table, then that change will transfer to the equivalent records of all the other joined tables. For instance, in Figure 3.2, if information relating to a record with a Group ID of 1 in the groups table is changed then all of the corresponding records with Group ID of 1 in the group/methods table would be changed as well.

Keeping different attributes in separate tables while having the tables joined allows for different types of information to be stored in different tables. For instance, there can be several tables that are constantly changed, joined to a table which has a bank of information which can be applied to each of these ever-changing scenarios. Joins also link the calculated fields defined for each table, thus allowing calculations across fields. Calculated fields are one of the many data types that can be used in a relational database. Relational databases have data types which are attached to each field. These data types tell the database software how much space to allocate to each field. The different relevant data types are described in the section below.
3.4 Data Categorization in a Relational Database Software Package

There are a wide variety of data types available within the relational database software used to construct the models used in this thesis (i.e. Lotus Approach). However, only five different data types are relevant to the modeling of BIW assembly. These include text, numeric, variable, calculated and Boolean data types. When using the text and numeric types, the number of bytes that are allocated to each record within the record must be specified. Boolean data tuples contain binary 1/0 information that is used in case a Yes/No or On/Off relationship has to be defined. These data types are useful in implementing If/Then formulas in calculated fields. Variable data tuples contain a universal variable which is used globally for all records, such as production volume, or hourly wage. These values are reset to null values every time the model is closed unless an initial value is assigned to them. Calculated fields have formulae attached to them and use numeric, variable, Boolean and text tuples to calculate a value. The calculated value is then stored in the field.

Both variable and calculated fields reside across joined tables. This is extremely beneficial because values contained in tuples which reside in different tables can then be combined. However, because calculated fields reside across tables they will perform and store these calculations for every field in every table. Therefore, the calculations will be done for the maximum number of fields. For example, if there is only one subassembly in a given assembly line process, there will be only one record in the groups table. If this subassembly uses five different joining methods, there will be five records in the group/methods table. If a cost is calculated for this process, it will be done for five records. In Section 5.2, the
implications of this aspect of Lotus Approach's relational database structure for calculating and totaling group specific costs are examined.
4. The Implementation of a Relational Database Assembly Cost Model

4.1 The Structuring of Tables

How can the advantages of relational databases be applied to BIW assembly? In answering this question, a basic structure must be formulated that can be used to implement the subassembly strategy while also solving the other issues detailed in Section 2.2. In formulating the tables, three different types of data must be kept in mind: data relevant to specific subassemblies, data relevant to the use of specific joining technologies and data relevant to both. These different categories are described as group, method and group/method specific data. These three different categories of data are explained below.

4.1.1 Method Specific Data

Method specific data includes all of the inputs which describe a certain process. These include the cost of various pieces of main equipment, transport equipment and consumable materials. It also includes labor and building costs as well as energy consumption rates. There are also several control variables, which are used to determine cost such as production volume, station space, the maximum line rate and the cost of energy. The material of the parts that the method will be used to join must also be specified. This is because, as can be imagined, the costs involved in Resistance Spot Welding steel parts are very different from those for the Resistance Spot Welding of aluminum. Method specific data only needs to be entered once because it does not change with the process being modeled, but is simply a set pool of data which is used in calculations. Methods specific data resides independent of part specific data. It can be made to
adhere to a defined input structure, to which exceptions can be made where necessary. In cases where the process is too far removed from the methods table paradigm, like induction curing, new fields must be added and calculated fields must be manipulated to produce the desired results. It is therefore desirable to have a table which can accommodate a fixed set of data which is sporadically updated, but whose structure is rarely, if ever, changed.

4.1.2 Group Specific Data

Group specific data is that data which is associated with the structure of the subassemblies which make up the assembly line. This structure is something that changes with every scenario and could be changed every time a different assembly scenario is run. Group specific data is not based on inputs in the same sense as method specific data. While method specific data involves simply obtaining numerical data and entering it into a set input structure, group specific data is slightly more complicated. The permutations and combinations of groups data that a user can input are far greater. This flexibility gives the relational database assembly model its power. It also requires some reflection from the user. Within group specific data, there are two distinct categories. The first is the initial parts that make up the groups, and the second is the subassemblies into which the parts flow.

Parts loading is not usually considered to be part of the transport involved in the assembly line. Therefore, the loading of parts into specific subassemblies need only have information relating to the subassembly to which each new part is destined for. As shown in Figures 2.2 and 2.3, the structure of an assembly line is such that new parts as well as smaller subassemblies flow into larger. Subassemblies may have a series of new parts being assembled within them, or a series of different, smaller subassemblies or a combination of the two. Groups must therefore
contain information on how many parts and subassemblies flow into the group into which larger subassembly it will subsequently flow. This information, as well as the number of joining units used in a group as well as the number of stations these joining units take up must be stored in a table, separate from the methods table.

4.1.3 Group/Methods Specific Data

The joining operations used in a specific group determine the final BIW assembly cost. The cost of these joining operations is determined by a combination of the joining operation used and the length of the join. Due to the fact that the length of join does not reside except as integral parts of a group and the methods used in that group, a separate group/methods table must be created to combine these two aspects.

4.2 The Implementation of the Structure

The modeling detailed in Section 4.1 resembles the structure outlined in Figure 4.1 below. The highlighted fields in Figure 4.1 are those which are used in joining the tables.
Figure 4.1: The Linking of Tables in a Relational Database Model. Although the Groups and Methods tables are not directly linked, they are linked commutatively, as described above.

The Parts table contains a part name, a part ID and a next group field. The part name is simply a useful way of identifying the nature of the part. The part ID is a unique set of letters and numbers by which a part can be identified. There are also fields which can be used to store information on the weight of the part and the material from which the part is made. These numbers are not used in calculations, and these fields do not, therefore, have to be filled out. The next group field specifies the subassembly into which the part is loaded and initially joined to another part. This field is linked to the group ID field in the Groups table. The Groups table's records determine the flow of subassemblies. Initially, the Parts table determines which parts flow into which subassemblies, then the Groups table determines which subassemblies flow into larger subassemblies. The next group value is linked back to
the group ID field. Thus, the Groups table references itself. This is a very important aspect of
the model because this self-referencing allows for realistic modeling of the progression of
subassemblies in an assembly line and the eventual joining of two subassemblies, as shown in
Figure 3.1. The groups tables also store information on the number of joining units (or
operators, as they are referred to in the BIW assembly model itself) and stations are used in
each group. The number of parts loaded into each group is also specified. The fixturing cost
associated with each group is also selected within here. This is done by entering a number
from 1 to 3, where 1 corresponds to a relatively low fixturing cost and 3 corresponds to a high
fixturing cost.

The Group/Methods table contains a group ID, which is joined to the group ID of the
Groups table, as well as a method ID, which is linked to the method ID in the Methods table.
In the Group/Methods table, the model user can specify which method/s are used in which
groups. The Group/Methods table also contains information on the joining length needed for
each method in each group, as well as an ID number which is used to link the sensitivity
analysis table to the rest of the schema. This calculation of sensitivity will be discussing in
greater detail in Section 4.4.

The Methods table contains a method name, and a method ID, as well as numerous
other fields which are needed to calculate the cost of joining associated with a given method.
The fields used in the methods table are detailed in Appendix A. Through the various joins, all
of the tables are linked. This linking is used to calculate final BIW assembly cost, through the
use of the inputs from each table. These inputs are combined using various equations which
are specified as calculated fields. These calculated fields are described in Section 4.3.
4.3 Calculating Costs

In order to understand how the inputs and information given by the user is converted into a good estimate of automobile assembly cost, the functioning of the model must be more closely examined. In calculating the cost of performing a certain joining process on two parts made of a certain material of a given length, the assembly model makes use of some key components. Many of the model's calculations are based on time. Time is the central variable that determines the amount of vehicles produced. This in turn determines how much these vehicles cost to produce, as the per vehicle fixed cost decreases with increasing production volume (as demonstrated in section 5).

Methods are divided up into continuous and discontinuous processes, due to the fact that these two types of processes react very differently to changes in joining length. The time necessary to complete a discontinuous weld is dependent on the number of welds needed to perform the join. In continuous processes, the time necessary to complete a weld is dependent on the joining length and the number of segments that need to be welded. For discontinuous processes:

\[ t_C = \frac{n_C}{r_C} \]

(4.1a)

where \( n_C \) is the number of connects and \( r_C \) is the rate at which these connects are applied (welds/second). For continuous processes:

\[ t_C = \frac{L}{f} \]

(4.1b)
where \( l \) is the length of the weld and \( s \) is the welding speed.

Each joining operation has a joining time associated with it. There is also a time that is associated with the robotic (or human) arm coming down to make a weld and then either moving to the next weld in the case of discontinuous processes, or continuing to weld and finishing the segment, in the continuous process. This time is associated with the performance specifications of the joining instrument used. In the case of a robot, it is assumed that there is some relationship between the cost of the robot and the relative speed at which the robot is able to move from one joining operation to the next. This relationship is represented in a regression equation of the form:

\[
C = C_0 t^x
\]  

(4.2)

where \( C \) is the cost of the robot, \( C_0 \) is the regression coefficient, \( t \) is the time it takes for the robot to move from one joining operation to the next, and \( x \) is the regression exponent. A similar regression relationship relates the cost of transport equipment to the amount of time it takes to move parts from one joining station to the next.

The time available to perform joining operations must be calculated. This available time is used to calculate the number of joining units, and stations which are required to complete the joining operations specified in a given group. The time available is based on a number of global variables. These variables include the time available to run the plant, the production volume capacity that the plant is being built for and the reject rate of the plant. The yearly time is defined as:

\[
t_Y = H \times S \times D \times (1 - t_D) \times 3600
\]  

(4.3)
where $H$ is the number of hours per worker shift, $S$ is the number of these shifts per day, $D$ is the number of working days in a year, and $t_{D}$ is the down time due to work stoppages. $t_{Y}$ is used to calculate the station time. The throughput rate is:

$$t_{S} = \frac{t_{Y}}{[P_{C\times(t+R)}]}$$

(4.4)

The throughput rate is amount of time that it takes to produce each vehicle in order to maintain the specified production volume, given a yearly time, $t_{Y}$. The transport and station times are used to calculate the available time:

$$t_{A} = t_{S} - t_{T} - t_{F}$$

(4.5)

where $t_{T}$ is the transport time (calculated using a regression, as in (1)) and $t_{F}$ is the time it takes the joining unit to initially prepare to join the parts and the time it takes the unit to retract after completing its joining operations. For example, in the case of RSW(R), it would be the time it takes for the robotic arm to engage itself in a position from which it can come down to weld a part, plus the time it takes for the arm to withdraw from this position so that the part can move on. The user must also enter a maximum line rate. This is the maximum number of vehicles that can be produced in a hour by a given line. If the station time exceeds the maximum line rate, then $t_{S}$ is substituted by the maximum line rate in seconds. This is simply a minimum boundary to ensure that the user does not specify an unrealistic production volume, given a certain maximum line rate.

The model also calculates the time required to perform a certain join. This is calculated using the time it takes to perform a join and the time it takes for the joining unit to move between joins. The required time is defined as:
The model also calculates the time required to perform a certain join. This is calculated using the time it takes to perform a join and the time it takes for the joining unit to move between joins. The required time is defined as:

\[ t_R = t_M * n_C + t_J \]

(4.6) for discontinuous processes (e.g. RSW(R)). In this equation, \( t_M \) is the time it takes for the joining unit (e.g. robotic arm) to move between welds. \( n_C \) is the number of connects, or joins necessary, and \( t_J \) is the time it takes to perform the joins themselves. The equation is exactly the same for continuous processes, except that \( n_C \) is replaced by \( n_s \), the number of welding segments. The equation:

\[ n_O = \text{Trunc}(\frac{t_R}{t_A} + .99) \]

(4.7) defines the number of joining units, or operators, needed to complete a specified length of join. For example, an \( n_O \) value of 4, results in the time required to do a certain join was four times the time available in one joining unit. Since there cannot be fractions of joining units, the number must be rounded up to integer form. This manner of finding the number of units results in the full utilization of all but the last joining unit. This is a fairly good approximation of how a real line works. Given that no station will ever be completely efficiently utilized, the chances are that there will be one station that will have inefficient usage. Line balancing is an attempt to minimize this effect.

Each method has a specified maximum number of operators that a station can accommodate. For instance, four RSW(R) operators can be accommodated in one station. Some methods can be combined together in one station, like RSW(R) and MIG Welding.
While others, such as Laser Beam Welding (LBW), require a dedicated station. These factors are combined and the number of stations is calculated through the equation:

\[ n_S = \frac{n_o}{O_{MAX}} \]  

(4.8)

\( n_S \) is the number of stations and \( O_{MAX} \) is the maximum number of a given operation which can be performed in one station. Equation 4.8, is used to calculate the number of stations needed to perform each different type of join within a subassembly. A macro then goes through each group and sums the total number of stations used in the group and rounds this number up. This number is then stored in a field which is group specific (see Section 2.1 for an explanation of this term). In the case of those processes which require dedicated stations, the number of stations is rounded up before being stored, since a station that only has half the capacity of LBW cannot also support RSW(R) even if there is space to permit it. In subsequent formulas, the rounded group specific number of stations shall be referred to as \( S \).

Some equipment used in joining can be shared by more than one joining unit in order to save cost. These units are usually shared in two different ways: either across stations or only within one station. Most items that can be shared fall into the first of these categories, but the model has the capability to calculate cost of any items that might fall into the second category as well. Items that can be shared across stations include adhesive bonding pumps and tanks. These items are assumed to be fully utilized. Their costs are calculated using:

\[ C_{SA} = Trunc\left(\frac{n_o}{n_{SA}} + .99\right) \times U_{SA} \]  

(4.9)

\( n_{SA} \) is the number of joining units that can be connected to a given piece of shared equipment and \( U_{SA} \) is the unit cost of the shared equipment.
\( n_{SA} \) is the number of joining units that can be connected to a given piece of shared equipment and \( U_{SA} \) is the unit cost of the shared equipment.

Almost every process used in assembly has a material that is consumed while joining. This material can range from electrodes to filler to fasteners to gas. The cost of these materials is a user input. Each of these consumable materials has a different unit associated with its cost. While the cost of filler beads may be measured in terms of dollars per meter of join, the cost of an electrode may be measured in terms of dollars per weld. Due to this variation and the fact that some processes use more than one consumable material, there cannot be just one consumable material field. There must be one for each type of consumable material. All of these different consumable materials are combined in the material cost equation.

In order to calculate labor cost, the model must first calculate the number of laborers needed for a given process, and then calculate the wages that these laborers receive. The wages are dependent how much overtime wage must be paid in order to ensure the completion of a specified production volume. If the station time required to produced a certain volume falls below the minimum amount of time necessary to complete the assembly, then workers must be paid overtime. Therefore, the equation to find the wages due to the laborers must include this fact. If the station time is more than the minimum station time then the calculated wage is simply the user inputted hourly wage. If the station time is less than the minimum station time, however, the wage is calculated by using the equation:

\[
w = \left[ w_O \ast \left(1 - \frac{t_y}{t_{y_{\text{min}}}}\right) \right] + \left[ w_h \ast \frac{t_y}{t_{y_{\text{min}}}} \right]
\]

(4.10)
$w_o$ is the overtime hourly wage, $t_{y_{\text{min}}}$ is the minimum number of seconds needed per year to produce vehicles at the maximum line rate and $w_h$ is the hourly wage during normal work shifts. The number of laborers is calculated using:

$$n_L = \text{Trunc}\left[\left(l_o \ast n_O\right) + .99\right]$$

(4.11)

where $l_o$ is the number of laborers necessary for a given operation. The labor cost is simply:

$$C_L = w \ast n_L \ast H \ast S \ast D$$

(4.12)

The consumption of energy can be broken down into two different categories of costs. The first is the cost of the energy consumed when joining parts. The second is the cost of the energy consumed when transporting parts through the assembly line. The first cost is joining operation dependent and the second is station dependent. Therefore, the two costs have to be determined separately. The cost of the energy consumed in joining is obviously highly dependent on the energy efficiency of the joining system being used. It is fairly difficult to accurately pinpoint this efficiency but due to the relatively small contribution of energy usage to the final assembly cost, the efficiencies used by the assembly model are adequately accurate. The cost of energy consumed while performing joins is:

$$C_{EJ} = \left(\frac{e_C \ast t_{IC}}{E_C}\right) + \left(\frac{e_R \ast t_R}{E_R} \ast n_C \ast (1 + R) \ast P_E \ast \frac{1}{3600}\right)$$

(4.13)

$E_C$ and $E_R$ are the connect and robot efficiencies respectively. These are the efficiencies at which electrical energy is converted into energy which can be used to perform the join in question. $e_C$ and $e_R$ are the rates at which the performance of the join and the movement of
robot consume electrical energy. \( P_E \) is the price of energy per kilowatt hour. The cost of energy consumed while transporting parts is:

\[
C_{ET} = e_T * t_T * S * (1 + R) * P_E * \frac{1}{3600}
\]

(4.14)

\( e_T \) is the rate at which transporting a part a meter consumes electricity.

The cost of the capital equipment used in the assembly line are calculated using a discount rate as ordinary annuities. The loading cost is calculated as the cost of the loading equipment used and the labor used to run the loading equipment. The cost of loading is an area where a reasonable approximation has been made as to how much the sum of all loading costs, including labor, equipment, energy, and building costs would contribute to the total cost of assembly. The cost of loading is calculated using the formula:

\[
C_L = 100000 \times P \times \left( \frac{d}{1 - (d+1)^{-L_{LF}}} \right)
\]

(4.15)

\( P \) is the number of parts being loaded into a specific group, \( d \) is the discount rate and \( L_{LF} \) is the life of fixturing and loading equipment. In the case of equipment cost, the principal is the equipment used throughout the assembly line in both shared and unshared equipment. The rate of interest is still the discount rate but the maturity is determined by the life of the equipment, referred to as the investment life.

\[
C_E = \left( (C_{UE} \times n_O + C_{SA} + C_S) \times \left( \frac{d}{1 - (d+1)^{-L_I}} \right) \right) (1 + P_I)
\]

(4.16)

\( C_{UE} \) is the cost of all unshared equipment needed for a certain joining unit and \( C_S \) is the cost of the equipment shared (if any) within stations. \( P_I \) is the fraction of initial cost which defines the cost of installation. Some creators of technical cost models have separated the cost of
cost of installation. Some creators of technical cost models have separated the cost of capital from the cost of equipment. These modelers have accounted for the cost of purchasing a piece of equipment separately from the cost of financing the purchase (through a loan or other financing). In this assembly model, the equipment cost includes the cost of paying for the loan. Thus, there is a need to amortize the cost of repaying the principal.

The transport cost, as stated before, is dependent on the number of stations needed to complete the necessary joining processes. The formula used to determine the cost of transport is:

\[ C_T = C_{TE} \times T \]

(4.17)

where \( C_{TE} \) is the cost of the transport equipment and \( T \) is the transfer increment. The cost of fixturing parts before joins are applied to them is determined by a formula similar to (4.15) the principal is the sum cost of fixturing. The user can choose between three different fixturing categories. These categories range from simple fixtures, to more complicated ones to very exotic fixtures needed on occasion in assembly. Like the loading cost, the fixturing cost is an approximation of total cost and is not a detailed analysis of the cost of fixturing.

The building and tooling costs are also determined through the use of payment equations. In the case of the building cost the formula:

\[ C_B = 2 \times S_S \times S \times P_B \times \left( \frac{d}{1 - (d+1)^{-L_B}} \right) \]

(4.18)
is used. $S_s$ specifies the space required to construct a station and $L_\theta$ is the life of the equipment being built. The tooling cost, which accounts for the cost of using riveting and other mechanical fastening equipment, is:

\[ C_T = T_{UC} \times n_T \times \left( \frac{d}{1-(d+1)^{-r_L}} \right) \]  

(4.19)

The overhead cost is simply:

\[ C_O = r_O \times (C_E + C_R + C_B + C_M + C_L + C_F) \]  

(4.20)

$C_R$ is the cost of tooling, which is only relevant when rivets or other mechanical fastening devices are being used. The maintenance cost is calculated using a similar formula where $r_o$, the overhead rate, is replaced by $r_m$ the rate of maintenance. The total variable cost associated with a certain joining process as used in a given group is equal to:

\[ C_V = C_M + C_L + C_{EJ} + C_E \]  

(4.21)

The total fixed cost associated with the joining process is:

\[ C_F = C_E + C_T + C_{Mn} + C_O + C_T + C_B + C_{Fix} + C \]  

(4.22)

The total cost is simply the sum of the fixed cost and the variable cost. In order to obtain the cost per vehicle from the above costs, the model simply divides the costs by the production volume at which the model is being run.

As seen when the cost of transport equipment is calculated, there are certain costs which are associated with stations, while there are other costs, like equipment cost, which are associated with specific joining processes within stations. The different types of cost and the way in which they are dealt with is discussed in the next section.
associated with specific joining processes within stations. The different types of cost and the way in which they are dealt with is discussed in the next section.

4.4 The Combination of Groups and Methods

Group, method and group/method specific data is used to calculate the final cost of assembling a vehicle. This total cost is composed of fixed and variable costs. The fixed costs include equipment, fixturing, loading, transport, maintenance, building and overhead. The variable costs include material, labor and energy (from both transport and joining). In combining information from groups and methods to give results, there are two categories of results which emerge.

The first category contains results which are unique to every joining process performed within a group. This includes such items as material cost. For example, a group which requires the use of RSW(R), ASW(R) and LBW will have a different material cost associated with each of these processes.

There is a second category of results which is dependent on the number of stations being used, and not the number of unique combinations of group and method. This category includes the transport equipment cost. The amount of transport equipment needed is completely dependent on the number of stations being used, and has no relation to the joining processes being performed within these stations.

In the case of results which are specific to a joining process, each combination of group and method has a unique value associated with it. Therefore, a value is simply calculated for every one of these fields. The station specific values are more complicated, due...
calculated for every one of these fields. The station specific values are more complicated, due to their dependence on calculations made for the group as a whole. The transport cost, for instance, is dependent on the number of stations in a whole group. The report format in Lotus Approach has the ability to calculate trailing summaries. For instance, the material cost of every method used in every group can be displayed. The total cost of all consumable materials used in a given assembly line can then be determined using the "grand summary" function. The user can also create trailing summaries of each of the groupings. That is, the total cost of the materials used in each group can be determined as well. The values obtained from the summaries, however, are not meaningful outside of the report. This is problematic when station specific values are needed. If a subassembly contains three methods -- RSW(R), ASW(R) and Adhesive Bonding(R) -- they will each have different method specific costs associated with them. Values such as the transport cost, however are not meaningful except as a number assigned to the subassembly as a whole. When transport cost is calculated, however, the value that is meant to be associated only with the subassembly, will be stored in the transport cost fields of all three methods. The total transport cost of an assembly process which contains only this one hypothetical subassembly would then be three times too large. In order to deal with this problem, the transport cost must be divided amongst these three groups. Of course, this divided cost has no real meaning but when it is totaled the correct number will be achieved. It was decided that the cost would be divided in terms of the number of operators that each joining method required as a percentage of the total number of operators required by the group. This multiplication of the station-specific costs by an "operator ratio" before totaling them is not meant to be representative of an actual cost but is
circumventing a limitation in the software being used. The use of the operator ratio is further discussed in Section 5.2.

Each cost of assembly is associated with a given production volume. As production volume increases, the per vehicle BIW assembly cost decreases. In order to examine the effect of production volume on BIW assembly costs, a macro had to be written which would iterate through various production volumes. The structure of this macro is described in the next section.

4.5 Sensitivity Analysis

Performing sensitivity analysis on data in a spreadsheet model is quite simple. Running sensitivity analysis on data in a relational database model is more complicated. This is due to the requirement of linking databases to one another in order to share data. The Sensitivity table is linked to all of the other tables through the Group/Methods table. When the sensitivity macro is run, all of the IDs in the Group/Methods table are initially set to the same number: one. Since the first record in the Sensitivity table has an ID of one as well, all of the records in the Group/Methods table correspond to a single record in the Sensitivity table. The macro uses this relationship to find the sum of the BIW assembly fixed and variable costs. These values, like total equipment cost and total building cost, are stored in fields in the Sensitivity table. The IDs of all of the Group/Methods records are then supplemented by one. This new ID is joined to the ID number of the new record. This process is repeated until all of the iterations are completed.

5.1 Measuring the Effects on Cost of Increasing Capacity Production Volume

Three scenarios were constructed to test the relational database BIW assembly model. All three scenarios were based on the 1989 Ford Taurus steel unibody BIW design. This BIW design was chosen because there has been much research done on its cost of assembly. $300 per vehicle at an annual production volume of 100,000 is widely considered a minimum bound for BIW assembly cost of the 1989 Taurus steel unibody. It is assumed that joining process data which was obtained from industry sources such as automobile manufacturers, machine suppliers and materials suppliers is accurate. Therefore, any assembly modeling structure which is more than a few dollars below $300 must be considered to underestimate some significant element of BIW assembly cost.

Table 5.1 provides a background to the formulation of each scenario.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Subassemblies</th>
<th>Join Length (m)</th>
<th>Laborers</th>
<th>Joining Units</th>
<th>Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>241.17</td>
<td>32</td>
<td>108</td>
<td>27</td>
</tr>
<tr>
<td>B</td>
<td>5</td>
<td>241.17</td>
<td>40</td>
<td>114</td>
<td>33</td>
</tr>
<tr>
<td>C</td>
<td>31</td>
<td>241.17</td>
<td>83</td>
<td>145</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 5.1: Information from scenarios A, B and C. The number of stations, laborers and joining units are calculated based on the length of joining and the joining processes used -- which are kept constant -- as well as the grouping of parts, which is varied. The annual production volume for this table is 100,000 vehicles.

In order to examine the increase in level of detail of the assembly model due to the increase in the number of subassemblies in the assembly model, three scenarios were run. Each scenario used the same amount of RSW(M), RSW(R), ASW(R) and Tack welding. The lengths
to be joined were also the same. This was done so that the effect of grouping of parts on the total BIW assembly cost could be isolated and examined.

In scenario A, all of the joining was done in one large subassembly. Scenario B simulates previous assembly models by using four groupings of parts: door, floor, roof and quarter panels. These four groupings flow into a final assembly. This totals to five subassemblies. Scenario C uses a much larger number of groupings and follows a more logical subassembly approach, where subassemblies are based on the required sequencing of parts. The following table outlines the resulting per unit BIW assembly costs from these three scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total Fixed Cost</th>
<th>Total Variable Cost</th>
<th>Grand Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$147.00</td>
<td>$46.16</td>
<td>$193.16</td>
</tr>
<tr>
<td>B</td>
<td>$162.29</td>
<td>$57.16</td>
<td>$219.46</td>
</tr>
<tr>
<td>C</td>
<td>$248.94</td>
<td>$117.30</td>
<td>$366.24</td>
</tr>
</tbody>
</table>

Table 5.2: Per vehicle BIW assembly fixed, variable and total costs at an annual production volume of 100,000.

As can be seen from Table 5.2, the BIW assembly cost does not increase significantly when the one large group is broken into five groups, but increases substantially when the process is broken down into 31 subassemblies in scenario C. The obvious conclusion that can be drawn from these results is that the manner in which parts are grouped has a significant effect on BIW assembly cost.

Constructing a model which only contains one large group, as in the case of Scenario A, results in a gross underestimation of the cost of BIW assembly. The per vehicle cost of producing 100,000 vehicles a year using Scenario A is $214.63. Why is the cost so low? What makes Scenario A so unrealistic? What factors does it not account for? The main flaw of Scenario A is that it assumes an assembly line that is extremely efficient in its use of joining units.
Efficiency of Joining Units

For instance, in Scenario A 96 RSW(R) joining units are used to perform 104.71 meters of joins. All but one of these joining units is fully utilized, making their efficiency of usage almost 99%. 54.56 meters of tack welds are performed using 17 stations, yielding a tack welding efficiency of over 97%. These numbers are clearly not representative of the realities of an assembly line. The high level of efficiency of the joining units is due to all of the RSW(R) required in a Taurus Steel unibody construction being done in a row. All of the resistance spot welds are finished at once. Given that the need for additional joining units is determined by the amount of time required to complete a certain length of joining, if all of the welds are done in a row then they can all be 100% efficient except for the last joining unit. Of course, if there is just one subassembly, then there will be just one inefficient joining unit. The inefficiency of joining units seen in scenario C reflects the inefficiency in the assembly line caused by the need to sequence the joining of parts in a very specific way.
The question then becomes: is it enough to simply group parts by the area of the BIW in which they will end up, as in scenario B? From the results in Table 5.2, and from the various figures which illustrate the results of a sensitivity analysis performed on production volume for each of the scenarios, it is fairly clear that there is no significant difference in per unit BIW assembly cost between scenarios A and B.

In Scenario B, 98 RSW(R) joining units are used to perform 104.71 meters of join (the same as in Scenario A). This is only 2 more joining units than were used in Scenario A. The series of equation in Section 3.2 show the direct relationship between equipment, building and maintenance cost and the number of stations. This, in turn is related to the number of joining units used. Predictably, when the per unit equipment costs of Scenarios A and B are compared (see Figure 5.2), there is little difference between them.

![Graph: Unit Grand Total Cost v. Production Volume](image)

Figure 5.2: Unit grand total cost versus the annual plant production volume from 100,000 to 290,000 vehicles per annum.
Scenario C, however, is more representative of a realistic per unit cost of assembly. The equipment and other fixed costs are much higher, due to the lower efficiency of utilization of stations. The best indicator of the more realistic nature of Scenario C is the efficiency with which Tack welds are performed in this scenario. Tack welds have a 44.01% efficiency in Scenario C. The manufacturer has to pay quite a high price for the ability to hold parts together with tack welds. Parts often only need a few tack welds to hold them together but one needs to build an entire tacking station to execute these welds. Therefore, there is much inefficiency in this process. Scenarios A and B have tack welding efficiencies well over 90%. This high level of efficiency is unrealistic, and is primarily due to much of the tack welding being done in successive joining units. As tack welding is a process which is meant to temporarily hold together parts before they are permanently joined using other processes, this modeling strategy is doubly unrealistic.

![Unit Equipment Cost v. Production Volume](image)

Figure 5.3: Unit equipment cost versus the annual plant production volume from 100,000 to 290,000 vehicles per annum.
In analyzing grand total cost, the per unit grand total assembly cost was plotted against capacity production volume in Figure 5.3. It was assumed that the plant was being run at full capacity production volume. As the production volume increases, the cost decreases. At approximately 190,000 units (as shown in Figures 5.2 and 5.3), the curves from Scenarios A, B and C all take on the same characteristics. The gradual decline in per unit grand total cost from this point onwards is due to the increased component of labor cost. As the capacity production volume increases, the required time increases. This causes an increase in the number of joining units required and leads to an increase in the number of laborers necessary to complete a given assembly process. This cost increases steadily until the point is reached where it is necessary to pay laborers overtime wages in order to keep up with increasing production demands. At this point, the number of laborers no longer increases but the annual labor cost per worker does. This is illustrated in Figures 5.4 and 5.5.

![Cost/Laborer/Year v. Production Volume](image)

Figure 5.4: The annual cost attached to each laborer used in the assembly line.
Figure 5.5: The number of laborers used versus annual production volume.

This comparative analysis illustrates the dramatic increase in per unit cost and level of detail when there is a more detailed examination of how the assembly line is balanced. The cost of BIW assembly has a very significant component which is dependent on the way in which parts a grouped together in order to be joined.

This is a factor which was not adequately accounted for in previous assembly model paradigms as shown in this case study. In order to further examine the effect of capital cost on production volume, a case study was performed using the same subassembly groupings used in scenarios A, B and C but where the per unit cost of assembly was calculated for a plant built for a given capacity, which was run at actual production volumes which ranged from 50% to 100% of the capacity production volume.
5.2 Measuring the Effects on Per Unit Vehicle Costs of Under Utilizing Plant Capacity

Three scenarios were run. The first, Scenario D included only one large subassembly. The second, scenario E included five subassemblies and the third Scenario F included 31 subassemblies. All three scenarios had a capacity production volume which was held at 200,000 vehicles a year. Capacity production volume is the production volume for which the plant is built. This is the maximum number of vehicles that a plant is built to produce in a year and for which joining equipment is bought to accommodate. Therefore, the capital costs (including equipment, building and maintenance), are dependent on capacity. Of course, one would expect that if a plant assembled BIWs at an annual rate under this capacity, the per vehicle costs due to capital would increase. Scenarios D, E and F examine this phenomenon. In the sensitivity analyses performed on scenarios D, E, and F, the per vehicle cost was determined for actual production volumes which ranged from 50% of capacity to 100% of capacity.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Subassemblies</th>
<th>Join Length (m)</th>
<th>Laborers</th>
<th>Joining Units</th>
<th>Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>1</td>
<td>241.17</td>
<td>32</td>
<td>108</td>
<td>27</td>
</tr>
<tr>
<td>E</td>
<td>5</td>
<td>241.17</td>
<td>40</td>
<td>114</td>
<td>33</td>
</tr>
<tr>
<td>F</td>
<td>31</td>
<td>241.17</td>
<td>83</td>
<td>145</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 5.3: Some information from the three scenarios. The annual production volume for this table is 100,000 vehicles.

The resulting unit grand total costs are shown in Figure 5.6.
Figure 5.6: Grand total cost versus production volume for a plant used at below capacity. The capacity here is 200,000 vehicles per annum and utilization starts at 50% and goes to 100%.

As can be seen from Figure 5.6, unit costs of all three scenarios decrease gradually as they approach full capacity utilization.

Much like in the analysis run in section 5.1, there is little difference between the unit costs of using five subassemblies and one subassembly. The cost of using 31 subassemblies is significantly more where the difference in grand total unit cost between scenarios F and E and between scenarios E and D are examined. The unit cost is relatively much higher in F when the plant is less efficiently utilized due to the larger equipment cost per unit of vehicle produced, as shown by Figure 5.7.
Figure 5.7: Equipment cost versus annual production volume. Capacity production volume is 200,000, and actual production volume goes from 50% to 100%.

The relative difference in cost is also well illustrated by Figure 5.8, which shows the difference in cost between F and E, as compared to the difference in cost between E and D.
Figure 5.8: The difference in grand total cost between scenarios F & E as well as E & D in dollar terms versus annual production volume, starting at 50% of a capacity of 200,000 and ending at 100% capacity.

The results of the capacity analysis show the important effects of capital cost on total BIW assembly cost. As is evident from Figure 5.8, the cost of capital is what makes up the largest chunk of the difference between scenarios F and E. As the capital is more fully utilized, the relative per vehicle burden of the capital -- which was built for a 200,000 annual vehicle capacity -- decreases. Apart from demonstrating the need for a subassembly-based modeling structure, which includes more groups, the analyses in this section also show the ease with which a user can manipulate the new relational database assembly model. It is very easy to change the number of groupings and to change the groups to which parts are initially loaded. Additionally, it is easy, albeit time-consuming to run sensitivity analyses on annual production volume.
6. Future Work and Improvements

6.1 Problems with the Relational Database Modeling Approach

6.1.1 Calculation of Costs

Despite the numerous advantages of modeling assembly using relational databases there are some disadvantages. Relational databases have the ability to total the sum of a given field. In the report format of Lotus Approach, the user also has the option of creating running summaries. A running summary is useful when summing fields according to certain categories. For instance, if the user wants to know the total number of stations needed in a certain group, then a running summary of the methods within the group is necessary.

In relational databases, a defined field runs through every record. Therefore, every record will have within it the same number of fields, and each field will be of the same data type. This is a difficulty for calculated fields because a certain cost may not be calculated in the same way for two different records. For instance, the equipment cost resulting from the use of an induction curing furnace is not calculated in the same manner as that of using RSW(R). In a spreadsheet, one would simply have different mathematical operations associated with the cell in which the equipment cost is finally calculated. In a relational database model, the same formula is applied to the equipment cost field in every record. This problem can be solved by using an "If-Then" statement. This solution is adequate for calculated fields in which most of the records conform to one formula, with some exceptions, which conform to another. When there are three possible formulas or more, however, the relational database approach becomes cumbersome.
can be avoided by manipulating the input data or splitting a cost into several input components, many of which will only relate to one record, but which can be left blank if they are not applicable to a particular group. This is the solution that was devised for the material cost due to the wide variety of consumable materials used in different joining technologies.

6.1.2 The Running of Sensitivity Analysis

The relational database model gives the user the ability to run sensitivity on the underutilization of a given capacity production volume. There are, however, limitations to the ease with which users can run sensitivity in the relational database. If the user wishes to run sensitivity on a cost which is not included in the sensitivity analysis macro, then the macro code itself must be changed. Also, every time a new production volume is chosen by the user, the number of stations must be recalculated, using another macro. This makes the running of the sensitivity macro extremely time consuming. It takes approximately one minute for every iteration of the macro. This is far more than the instantaneous feedback which the user receives from sensitivity in a spreadsheet model.

6.1.3 The Need to Split Group Specific Costs Between Joining Units

As explained in section 3.1, certain costs are associated with groups while others are associated with a specific joining process within a group. When a group cost is calculated it is stored multiple times if there are multiple joining methods in the group, as explained in Section 3.2. If the cost of transport equipment is $1,000 for a given subassembly and this subassembly uses RSW(R) and ASW(R), then the transport cost field would contain a value of $1,000 in both the RSW(R) and ASW(R) joining methods. A relatively simple solution would be to use the "Report" format to sort the costs according to subassembly and then average these costs by
"Report" format to sort the costs according to subassembly and then average these costs by subassembly in the summary tables. Unfortunately, due to the structure of Lotus Approach and other popular relational database packages, the summary tables do not contain values that can be used for calculation outside of the report in which they were created.

In order to combat this problem, the operator ratio approach was implemented, as described in Section 3.3. The dividing of group specific costs into different components that are supposed to relate to joining methods does not make much sense. There is very little meaning in these separated costs, since group specific costs are not truly associated with the use of the joining processes themselves, but with the cost of building another station.

6.2 Future Improvements

The changes made to the manner in which assembly was modeled have been significant both in terms of the modeling strategy used and in terms of the tools used to implement that strategy. The use of a large number of subassemblies results in a more realistic estimate of cost, as shown throughout this thesis. The use of a relational database software results in a model which is more flexible, more powerful and better suited for the modeling of BIW assembly. There are also problems which occur due to the use of a relational database software package, as explained in Section 5.2. Some of these problems are simply minor side effects of the great benefits reaped by the modeler through the use of relational databases. For instance, the need to gather data in such a manner as to be able to apply formulae in calculated fields as universally as possible, as explained in Section 5.1.1.

Most of the problems encountered in modeling BIW assembly, however, are a function of the inflexibility of the software chosen. Lotus Approach was chosen as the
software within which the model would be designed because it is commonly available and is very user friendly. The software is not, however, designed to be used to make complex cost models such as the one constructed here. Therefore, there is a need for a relational database software package which will enable the user to specify which tables a given calculated field refers to, something that cannot be done in Approach as explained in 5.1.3. A relational database software that did not have some of the report-creation and presentation capabilities of Approach, but has more flexibility would be an ideal platform for future BIW assembly models.
Conclusion

TCM of BIW assembly has been shown to be a vital and important tool in determining the feasibility of new BIW designs. It has also been shown that given the importance of a flexible, rigorous model, which allows the user great control, relational database modeling is the best software solution to TCM of BIW assembly. While there are some problems with using relational database software, such as the inability to distinguish between station and joining process related costs, overall relational databases provide an excellent platform for constructing detailed models.

It was shown that a subassembly-based approach is far superior to one based on a categorization of parts. It has also been shown that previous modeling of the 1989 Ford Taurus steel unibody BIW assembly cost lacked detail and precision. The assumption that the structure of the assembly line in terms of subassembly divisions and parts flow does not significantly affect the BIW assembly cost was shown to be incorrect. This incorrect assumption was shown to severely underestimate the cost of capital, and its contribution to the total cost of BIW assembly. Various additional features and further details on the cost of using various joining processes were also added to the BIW assembly model. This added robustness to the model and allowed greater user control of the types and degrees to which various joining processes are used.

The use of the model to analyze the Taurus steel unibody BIW in the manner examined in Section 5, proves the flexibility and usability of the model. The restructuring of the model to accommodate 1, 5, and 31 groups shows the ease with which users can examine the effects of subassembly changes, as well as changes in the joining process used. So, for example a user can
analyze the effect of using LBW in place of RSW on total BIW cost without doing more than changing one number in the Group/Methods table.

The ability to easily examine new assembly structures and new joining processes is a vital aspect of any BIW assembly model, and ensures the usefulness of such a model into the future, regardless of the changes made to the way in which BIWs are assembled. It is hoped that this model will prove useful in attempts to design automotive processes which seek to lower curb weight and thus decrease fuel consumption of automobiles while maintaining an affordable final product. It is also hoped that such a model will be used in the future to design automobiles which can be produced at lower production volumes, and at a cheaper cost, so that such vehicles can reach as yet untapped markets in the developing world, where vehicles presently available are very expensive and extremely fuel efficient.
Appendix A: Joining Method Inputs

The following are inputs in the Methods table, which can be used to describe a variety of different methods.

**METHOD_NAME:** The name of the methods that you wish to add. The name can be up to 30 characters in length.

**METHOD_ID:** Each method must have a unique numerical ID.

**MAX_OPS_METH:** The maximum number of joining operators (e.g. Adhesive bonding robot with gun and controller) that can be used in one station.

**UNSHARED_EQUIP_1:** The name of the first type of unshared equipment used in the specified process. For instance, a gun or laser optic device.

**COST_1:** The total cost of UNSHARED_EQUIP_1.

**LIFE_1:** The operating life, either in joins or years, of UNSHARED_EQUIP_1. This field is not used in any calculation and therefore the user does not need to fill it out.

**UNSHARED_EQUIP_2:** This field is used to specify the type of machine being used to implement the joining technology. This is usually a robot. In the case of manual operations, this field should be either filled in as MANUAL or left blank.

**COST_2:** The total cost of UNSHARED_EQUIP_2. This field should be set to zero for manual operations. If the user wants to use a time input for UNSHARED_EQUIP_2 to calculate the cost, then see UE2_TIME_INPUT.

**LIFE_2:** See LIFE_1

**UE2_COST_TIME_TOGGLE:** This is a user set toggle that specifies whether the user wants to use the cost of the machine to calculate its operating time, or use its time to calculate its operating cost. If the user has specified the cost in the COST_2 field, then the toggle should be set to 1. Otherwise, the toggle should be set to 2.

**UE2_TIME_INPUT:** This field needs to be filled in ONLY IF the user wants to specify a use time for UNSHARED_EQUIP_2 and have the cost of the machine calculated from it.

**UE2_COST_TIME_COEFF:** This regression coefficient is necessary to find either the cost or the time of UNSHARED_EQUIP_2, depending on which the user inputs.

**UE2_COST_TIME_EXP:** This regression exponent is necessary to find either the cost or the time of UNSHARED_EQUIP_2, depending on which the user inputs.
UNSHARED_EQUIP_3: This field is an optional one that allows the user to specify a third unshared equipment type, if such a piece of equipment exists.

COST_3: See COST_1.

LIFE_3: See LIFE_1.

LINE_SHARED_1: This is a field where the user may specify pieces of equipment that may be shared across stations in the assembly line (e.g. Adhesive bonding tanks for holding the adhesive material).

LINE_SHARED_NO_1: In this field the user must specify the number of machines that can be supported by one line shared machine. For instance, the number of adhesive bonding guns that can be attached to one adhesive tank can be specified as 5.

LINE_SHARED_COST_1: The cost of one of the line shared pieces of equipment specified in LINE_SHARED_1.

LINE_SHARED_2: See LINE_SHARED_1.

LINE_SHARED_NO_2: See LINE_SHARED_NO_1.

LINE_SHARED_COST_2: See LINE_SHARED_COST_1.

PROCESS_SHARED: This is a YES/NO switch which tells the model whether the process being specified can share a station space with other processes. For instance, Resistance Spot Welding and MIG Welding can be performed at the same station but Laser Beam Welding needs a separate station.

SHARED_EQUIP_1: This field allows users to specify equipment that may be shared by different machines IN THE SAME STATION but not across stations, as in LINE_SHARED_1. If this field is used then the user must fill out MAX_SHARE_1, REG_COEFF_1, and REG_EXP_1, all described below.

MAX_SHARE_1: This field specifies how many machines can share the piece of equipment being described in SHARED_EQUIP_1.

REG_COEFF_1: This field specifies a regression coefficient used in the calculation of the total shared equipment cost.

REG_EXP_1: This field specifies a regression exponent used in the calculation of the total shared equipment cost.

SHARED_EQUIP_2: See SHARED_EQUIP_1.
SHARED_EQUIP_2: See SHARED_EQUIP_1.

MAX_SHARE_2: See MAX_SHARE_1.

REG_COEFF_2: See REG_COEFF_2.

REG_EXP_1: REG_EXP_2.

CONTINUOUS_PROCESS_TOGGLE: This is a toggle that enables the user to specify whether the method being created is a discontinuous (e.g. Resistance Spot Welding) or continuous (e.g. MIG Welding) process. The number 2 corresponds to a discontinuous process and the number 1 to a continuous process.

START_AND_FINISH_TIME: This time is the amount of time it takes for the joining machine to move towards the part and prepare to weld plus the time it takes for the joining machine to move away from the part after ALL welds are completed.

TRANSPORT_COST_TIME_TOGGLE: The same as UE2_COST_TIME_TOGGLE, but for transport equipment.

TRANSPORT_EQUIP_COST_INPUT: The Dollars/Meter cost of the transport equipment.

TRANSPORT_TIME_INPUT: See UE2_TIME_INPUT.

TRANSPORT_COST_TIME_COEFF: See UE2_COST_TIME_COEFF.

TRANSPORT_COST_TIME_EXP: See UE2_COST_TIME_EXP.

FILLER_COST: The cost of any filler material being used in $/Kg.

FILLER_WEIGHT: The total weight of filler used per meter of join in Kg/m.

ELECTRODE_COST: The cost of any electrode material being used in $/electrode.

ELECTRODE_LIFE: The life of an electrode. This number should be given in terms of total number of welds for discontinuous processes and in terms of total length that can be welded for continuous processes.

GAS_COST: The cost per liter of any gas being used in the process.

GAS_FLOW_RATE: The flow rate of the gas being used in terms of liters of gas/meter of weld.

FASTENER_COST: The cost of any fasteners being used in the process, in $/fastener.
COIL_COST: This is only used for induction curing processes and is the cost per induction heating coil.

COIL_SPACING: This is only used for inductio curing processes and is the spacing in between induction heating coils.

CLAMP_COST: The cost of any clamps used in units of $/clamp.

CLAMP_SPACING: See COIL_SPACING.

CONNECT_SPACING: The spacing between connects for discontinuous processes.

LABORERS_PER_OPERATOR: The number of laborers needed to supervise/perform the method being created, per joining unit.

ENERGY_CONSUME_CONNECT: The amount of energy used, in KW per join. For instance, the number of KW used in a single Resistance Spot Weld.

ENERGY_CONSUME_U2E: The amount of energy used by the robot, in KWh.

ENERGY_CONSUME_TRANSPORT: The amount of energy used by the transport system in KWh.

CONNECT_EFFICIENCY: The efficiency with which the energy consumed in performing the join is used.

ROBOT_EFFICIENCY: The efficiency with which the robot specified in the UE2 fields uses its energy.

MAINTENANCE_PERCENT: The cost of maintenance, as a percentage of final infra structural costs.

OVERHEAD_RATES: The rate of overhead costs, as a percentage of final infra structural costs.

TOOL_LIFE_IN_PARTS: The life of any tools being used, in terms of the number of parts.

TOOL_LIFE_IN_YEARS: The life of any tools being used, in terms of years.

TOOL_COST: The cost per tool.

CONNECT_RATE: The rate at which the joining process proceeds for discontinuous processes in terms of connects/second.

WELDING_SPEED: The speed of welding of continuous processes in terms of meters/second.
EXTRA_COST_INPUT: An additional factor which can be used to add any additional costs that are involved in the method being created that are not properly accounted for in the model.
Endnotes

[4] This approach to assembly was used by Helen Han in her doctoral dissertation. See Han, Helen N. "The Competitive Position of Alternative Automotive Materials" May 1994, Materials Systems Laboratory, MIT.