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3. SHEET METAL DESIGN

This case study describes information system designed for a sheet metal design/manufacturing environment. The case study was conducted on site of a major computer manufacturer. A CAD based environment was developed where a designer can interface with the database for design/manufacturing information. The modeling methodologies used were DFDs and EER model. A relational database was selected to hold the shared information and act as a communication channel between several design agents. The following paper describes the case study in detail.
A Data Management Strategy to Control Design and Manufacturing Information

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Abstract. This paper presents an information-based approach to integrate the parallel and serial functions that occur in a typical design and manufacturing environment. EMTRIS (Engineering and Manufacturing Technical Relational Information System), a relational data base application designed using ORACLE [1], was developed to cater to the engineering data needs of practicing designers and engineers working in a large industrial setting. The design and manufacturing activities within a large computer manufacturing plant provided a realistic case study environment for implementing some of the strategies discussed here. A description of the methodology that was employed in designing and implementing EMTRIS and the numerous issues that arise while undertaking such endeavors is presented. Strategies to coordinate the data transfer between different groups of individuals as well as mechanisms to ensure data consistency in such environments are discussed in this context. Various techniques used in documenting the data flows and the interrelationships between different forms of data are also reviewed. The end result is a plantwide database system that integrates the information requirements of multiple groups and disciplines.

1 Introduction

EMTRIS (Engineering and Manufacturing Technical Relational Information System) is a relational data base application that attempts to provide an environment to manage and coordinate the miscellaneous text information that is constantly being generated in a typical design and manufacturing CAD/CAM (computer aided design/computer aided manufacturing) arena. The primary paradigm adopted in designing EMTRIS is to cater to the needs of practicing engineers and designers, who are constantly burdened with locating and retrieving relevant engineering information. Many times this information is available but is difficult to locate. This leads to a loss in productivity, and there is a tendency to base certain decisions on assumptions; the relevant information although available is invariably inaccessible. EMTRIS was designed in close collaboration with a core team identified within the case study site (NCR Corporation), and this ensured that the system would perform reflect the needs of the users.

This paper briefly describes the methodology employed during this research and highlights some of the important observations relative to the information needs of the design process. The principal capabilities of EMTRIS are then described.

2 Background

In developing computer-based tools to aid the designer, the importance of studying the engineering design process cannot be overemphasized. From this standpoint it is necessary to model the activities surrounding the design process. The data flow in any multidisciplinary design activity is dependent on many factors, for example:

- Data transfer media richness
- Information availability and information accessibility
- Data completeness
- The evolving nature of the design
- Constraints imposed by one function on another
- Degree of coupling between different design and manufacturing groups
- Common data sets and specific data sets
- Organizational protocol in dealing with priorities and conflicts
- Changes resulting from downstream feedback

Due to the uncertainty associated with different data sets as a result of the interdependency between tasks (groups), there is a need to formalize this data transfer. This may be partially accomplished by reducing the gap between data availability and data accessibility, by developing information systems that permit available data to be easily accessed. Figure 1a shows a typical situation where accessible
data is only a subset of the generated data. Furthermore, in such situations, information accessibility is permitted locally but not globally. The nature of engineering design is such that the design freedom is constantly redefined due to the interdependency between tasks (Fig. 1b). These results were obtained from surveys and questionnaires administered to several designers and engineers at the case study site.

It is important to view engineering design as both a parallel and a serial process. Ebert et al. [2] state that success in the engineering design process depends on patterns of information flow—the sources, timing, intensity, transmission modes, and quality of information—among diverse specialists and managers. As a result of the complex nature of engineering design and manufacture, there are various serial and parallel activities that define the design process (multidisciplinary design and manufacturing). These activities work toward a common goal (the product) and interact via the exchange of information. It is therefore imperative that the available “interactivity” information be accessible as and when it is created. In typical cases such information, although present, may not be easily accessible. This usually leads to incomplete information transfer leading to ambiguous interpretation and changes in the original design and is usually the primary source of downstream delays. Often there is a duplication of effort in achieving the same results leading to conflict between the various serial and parallel activities. The interdependence between various design activities requires a more formal information exchange media that is reliable, complete, easily accessible, and well integrated with the design process.

It has been documented by Daft and Lengel [3] that “high rich” media (verbal communication) is better at eliminating ambiguity associated with design data than “low rich” media (rules, equations, reports). However, the high rich media is seldom practical in large organizations. The use of a multidisciplinary information exchange media that is formalized to reflect the data needs of the different groups within the organization will, however, ensure high reliability, completeness, and availability of data. The organizational structure severely affects the implementation of such information systems. Some of the issues that arise in the implementation of such systems in large design and manufacturing organizations are discussed herein in the form of a case study.

3 Methodology: A Case Study Approach

Every design and manufacturing environment is unique. The environments exhibit characteristics that are indicative of the organizational structure and culture, the type and size of industry, the complexity of the products generated, the level of expertise and technology involved, in addition to several other parameters. In undertaking a study of such environments, it is imperative that the dynamics of the environment be thoroughly understood and analyzed.

In studying issues related to information management in CAD/CAM environments the process and control models may be indigenous to a particular environment. However, the general problem of defining an information management CAD/CAM strategy must generate generic frameworks for integration. The dependencies between data entities and the desired levels of abstraction are also local to a particular environment, and this will always be the case. The challenge lies in identifying generic strategies that may be applied across these environments.

The following methodology was used to address these two focus areas:
- Isolation of a thin slice of the problem domain for
detailed study
- Activity modeling: Data collection using protocol
studies
- Data analysis and data modeling
- Prototype implementation

3.1 Method Step: Isolation of Thin Slice: The
Case Study Environment

We require several characteristics that the case
study environment must exhibit in a study of this
nature, namely:
  Must exhibit the characteristics of a design orga-
nization
  Must involve design of complex systems such as
aircraft, computers, and so on
  Must exhibit multidisciplinary interaction and
dependencies
  Must exhibit complex data interactions involving
several media
  Must recognize computerized facilities and use
of CAD/CAM technology
  Must exhibit serial and parallel function struc-
tures
  Design must be viewed as a collaborative effort
  Must utilize locally defined standards
The sheet metal design and fabrication activities at
NCR, Wichita, formed the domain of the case
study. The nature of this environment satisfies the
characteristics identified earlier. The large number
of groups involved in the activities and the complex
nature of the information exchanged provides a rea-
listic environment for studying the needs and im-
plementation issues associated with such engineer-
ing information systems. Figure 2 shows an IDEF 0
model [4] of the activities at the case study site.
The sheet metal design function receives a re-
quirements specification as its input data and also
receives configuration data from the VLSI design
group, the components group, and the systems en-
gineering group (not shown) on a continued basis
during the early stages of design. This is a dynamic
process and there is a high incidence of data interac-
tions and design iterations. On completion of the
design the detail design data is communicated to the
various serial functions (manufacturing and systems
assembly). Thus, the mechanical design functions
are implicitly constrained by the capabilities of the
manufacturing groups.

The focus of the case study is the mechanical de-
design/manufacturing engineering area and involves
the conceptual design, preliminary design, detailed
design, and the process planning and fabrication of
sheet metal housing for computers and disk file sub-
systems. The collaborative nature of the study is
provided by observing the interactions between the
mechanical design and several other design agents.

The mechanical designers are assigned the task of
packaging electromechanical and electronic compo-
nents while maintaining constraints originating from
process limitations (assembly and manufacture) and
electromagnetic compatibility requirements and hu-
mans factors. The disciplines involved in this re-
search effort included mechanical design, manufac-
turing engineering, components engineering, drive
engineering, and subsystems engineering. Due to
the large scope of the research program, a team of
experts were identified as representatives of the
groups involved from within NCR Corporation.
This team included a CAD/CAM administrator, a software engineer, a manufacturing engineer, an automation engineer, an information system support specialist, and an administrator from upper management. The initial phases of the project helped define the scope of the system, and this work was done in close collaboration with the NCR team.

3.2 Method Step: Activity Modeling

Purpose. To understand the prevailing design process and to define formally descriptive models of the data flows associated with the design process.

Background. The purpose of design process models has been to define systematic methodologies that seek to externalize design thinking. Various researchers have formulated descriptive and prescriptive models of the design process [5–7]. It must be noted [8,9] that the study of the design process is a very tedious and expensive process and may not yield viable results. This is particularly true of cognitive studies where most conclusions and data are obtained from protocol analysis. The veracity of such data is questionable, and although certain completeness criteria have been established by Ericsson and Simon [10], the nature of many such studies are inconclusive.

The current study calls for models of information and control flows—the nature of the collected data is dependent on the designer’s long-term understanding of the issues and is more complete than associated cognitive studies. Wallace [8] has extensively studied the design process and notes that few processes fit standard models.

Techniques and tools. The literature cites [11] several video-based protocol studies. However, for a study of this nature, it is felt that data obtained from case histories and direct observations (interviews, monitoring) is more economical and easy to obtain. The data collection techniques were derived from two approaches, namely:

Case histories. Data from previous designs, drawings, reports, and other documentation Observation data. The data derived from case histories identifies the finished design documentation entities but does not describe the process itself. By directly observing the design process, it is possible to document the activities. The interview process was effectively employed to augment data obtained from direct observation.

3.2.1 The Interview Process

There were three chief objectives of the interview process:

1. To understand the processes within each function
2. To determine the data needs (input and output flows) of each function
3. To identify additional needs, problems, inconsistencies, and anomalies within each function

The interview process was used as a walk through aimed at understanding the design activities from an information-driven perspective. Various team members and participants were interviewed. Information transfer mechanisms, deficiencies, and data access channels were identified in addition to descriptions of the activities themselves. These interviews were documented using data flow diagrams (DFD) [12]. This is essentially a diagramming technique that attempts to document the data flows between different processes. The conventions used in this technique are very simple to understand and permit users to participate very effectively in the interview process. This contrasts with the SADT (structured analysis and design technique) approach used in IDEF 0 [4], which is much more complicated, although it captures a richer mixture of information. The DFDs do not model control constructs since the control data is absorbed as a data flow. In order to account for this deficiency, the process was later modeled using the IDEF 0 model. These process models were periodically reviewed by the NCR staff. The time duration for this phase of the project exceeded 4 months. Overall, 30 designers and engineers were interviewed.

The interviews were conducted on a one-to-one basis. After a brief introduction to the nature of the pilot program the interviewees were requested to identify the chief processes occurring in their groups and provide a detailed account of the data flows between each of the processes that had been defined. The participants were also called upon to relate any data- or activity-related problems. These “problems” were addressed subsequently during the implementation phase of the project. The activity analysis helped reveal inconsistencies within the context area. It became apparent that each group had only a vague idea of the functions and processes associated with other supporting groups. On a few occasions it was found that the same activity was perceived differently by different groups.

The results of these interviews were then refined to depict a more formal picture of the operations in
the context area. These were reviewed and modified by the NCR team members. The final "AS-IS" data flow model was then defined after a few iterations. It is important to note that although this phase of the project appears simplistic, it is imperative that it be conducted thoroughly. The results and the knowledge gained from this exercise will determine the effectiveness of the remaining phases and consequently the effectiveness of the program itself.

Figure 3 shows sections of the activity models in the mechanical design and manufacturing areas and identifies the important processes, the data entities, the information transfer medium, and the principal participants. The activity analysis thus established an unambiguous process definition on which further data analysis could be performed. Various interaction mechanisms were also observed and are discussed in the following section.

3.2.2 Interaction Mechanisms

**Purpose.** To identify and characterize various forms of data and information transfer mechanisms.

**Background.** The integration of software applications in the CAD/CAM environment is complicated due to the disparate nature of the data, diverse file systems, hardware and software environments, and context-specific data requirements [13]. The modes and media of interaction between individuals raise several questions relative to data transfer ambiguities [3]. Few studies have addressed the engineering design process from an information exchange standpoint.

**Techniques and tools.** Using activity models, the various types of data flows (paper, verbal, etc.) and different information and control transfer mechanisms were also recorded. The subjects were asked the following questions:

- What is the source of the relevant information?
- In what form is this information received?
- How is this information applied toward the current task?
- What type of processing, if any, was done?
- What type of data conversion, if any, is done?
- How easy/difficult is it to access relevant data?
- How is the information conveyed to downstream/parallel functions?

3.2.3 Conclusions

The activity modeling phase established a working model of the design process from an information transfer perspective and was principal in identifying relevant entities and related attributes and in isolating deficiencies in the design process. The inadequacy of current design process data transfer protocols becomes more apparent when viewed against this picture. Although such issues may at first seem unrelated to the design activity, it has been found that such protocol studies are critical in identifying ad hoc communication processes. It is imperative that computer-based systems designed to support the engineering design process intrinsically support these information transfer mechanisms. Therefore, such studies, although time consuming, are critical.

3.3 Method Step: Data Modeling

**Purpose.** To identify various data entities and characterize the relationships between these data entities and their attributes within the context of the design process.

**Background.** The modeling of data dependencies, compatibility conditions, and constraint conditions between various data entities and design agents is a prerequisite to building control into the design process. The modeling of dependencies between sets may be formulated using the entity relationship model [14,15]. The concept of abstraction and generalization [16] is useful in modeling certain types of hierarchical relationships. However, these models focus on cardinality relationships and do not explicitly state the exact form of relationship. In most engineering situations, the exact form of these relationships is very complex and may or may not be fully understood [17]. They may be combinations of heuristics, mathematical formulations, or equations. However, from a data management perspective, the point of interest are the entities and their attributes—hence such relationships are modeled at the entity level. By modeling such data as macro objects, it is possible to apply such controls at higher levels of abstraction. At this stage data abstraction plays an important role since we need to catalog data at various levels. In the current model the product level, the unit level, the discipline level, and the individual part/subassembly level define these levels of abstraction.

**Techniques and tools.** Several data modeling techniques are available. The need for semantic richness presents a major barrier since most data modeling techniques were developed for static business and administration data. All techniques examined produce data base designs up to the third normal form. Smith [18] presents a simplified diagraming
Fig. 3. The AS IS activity model of the design process.
technique that yields relations up to the fifth normal form. ICAM's IDEF 1X [19] provides an excellent modeling tool that is specifically geared toward the design and manufacturing area. Many commercial CASE tools [20] are also available that will automatically yield normalized relations. Principal among these is the NIAM system [21]. For the purpose of this case study, the extended entity relationship model [15] was used to obtain normalized relations.

Data description. At the end of the activity analysis, a preliminary entity list was created. This list was then refined until it reflected the complete information needs within the context area. The various attributes defining the entities were resolved by allowing the principal participants in each group to define their specific data fields. Figure 4 lists typical entities and attributes of some of these entities.

Figure 5 shows the entity relationship model relating several macro entities associated with the design and manufacture of sheet metal parts. The cardinality relationship between the various entities are shown in the model. This model shows the complex nature of coordination and control associated with each part. Each detailed part is related to many subassemblies and features. We note that changes to a single part will trigger changes to several associated entities and initiate a complex chain of constraint propagation effects. This preliminary investigation has identified the need for conceptual centralization of data and a need to ensure consistency against changes in the data. The objects have been modeled as macro objects and may represent large quantities of data in themselves. At this level of abstraction it is appropriate to view engineering drawings as an entity identified by a drawing name and the revision level.

3.3.1 Conclusions
The data modeling activity provides the infrastructure for the data base design and defines the control mechanisms that must be maintained to ensure consistency between the various data entities and attributes in the data base. This is particularly significant during the development of the prototype design environment. This data may be present in different file systems and have different contextual representations, and may be useful over different time frames. This phase provides the representational base for conceptual centralization of data associated with the design and manufacture of the product.

![Fig. 4. Typical entity lists and attribute lists.](image)

3.4 Method Step: Prototype Development
The capabilities of the prototype system were determined from several interviews and informal conversations with various staff members of mechanical design and system assembly. The prototype system was subjected to several reviews and demonstrations by various members of the NCR team. Frequent meetings were scheduled to monitor the progress of the system.

4 General Observations on the Design Process
The protocol studies reveal that during the conceptual and initial stages of design there is a need to retrieve data from related design agents. These data determine design decisions. The data dependencies between these design agencies have not been well studied or introduced into the design process leading to problems in ensuring consistency between
related data sets. Such problems usually manifest as engineering change orders from downstream or parallel design agents. Most of these anomalies occur due to changes that do not percolate between dependent design agents. We may conclude that the need for dependent updates between such related design agents is a critical requirement of the design process. Issues such as data availability, control, coordination, and management are dependent on the desired levels of abstraction:

Design object data management
Individual's data management
Team (related individuals) data management
Discipline (related teams) data management
Product-related (multiple disciplines) data management
Organizational data management (business, engineering, manufacturing, purchasing etc.)

Within these levels the granularity and the levels of detail vary and are governed by the degree of control and data management desired. The design object data management problem is chiefly concerned with the data at the design object (aggregations of curves and surfaces) and attribute and configuration levels. The individual data management problem is primarily a bookkeeping activity that identifies entities and design (geometry) model files as required by the individual. Requirements include consistency between design files for insertion, updates, and deletes in the current session. With the team environment there may be relationships between the entities stored by different individuals. A uniform data access facility must be available for individuals to manage entities relative to other individuals. The data management and control problem with the design organization at an administrative and management/control level is more dependent on the level of abstraction desired. They may be at the file level, the module level, or the product level, or may refer to classes of products. In general, the relationships are extremely complex at the lower levels and usually involve both functional and dimensional considerations (formula based, inference based). At higher levels of abstraction the controls are based on cardinality and dependency relationships involving flag and pointer-type manipulations. However, we note that the design organization as a whole must integrate these various levels of abstraction and create an environment where data can be accessed in a uniform manner.

Several information transfer mechanisms are apparent: verbal (meetings, direct one to one), paper (reports, manuals), electronic text (messaging systems, spreadsheets), geometry and processed files (NC machine code, model files), and standard data bases.

The following are some general conclusions on the role of information in design, based on direct and participant observation of the design process. Since these observations have been derived from the protocol studies, they reflect the needs of individual designers as well as the design process as a whole. These issues have been broadly categorized along two functional capabilities, namely, information management and compatibility enforcement.

4.1 Information Management

1. Data context reference. Most designers are aware only of the immediate data sources and sinks. They are rarely aware of all flows of this data. Complex dependencies are not recognized and on occurrence are usually handled in an ad hoc manner. It is important that all participants be aware of the data flows relative to their function.

2. The available data from other disciplines/groups are obtained through one of the information transfer mechanisms. Mechanisms to incorporate such data within the design context is carried out through manual means.

3. Mechanisms to ensure engineering change consistency between different design agents rely on human information transfer mechanisms.

4. Most large-scale design organizations rely on formalized communication channels for interaction between design agents. However, our observations indicate that there is a large amount of ‘adhockery’ in the information transfer mechanism.

5. Large amounts of data need to be stored and managed even for relatively simple designs. For example, the entity relationship model (Fig. 5) clearly indicates the items of information associated with a single part over its life cycle.

6. Multidisciplinary design information is seldom available as and when needed—this is particularly true during the initial stages of design where it is most critical. This invariably results in a suboptimal design. There is little formal exchange of data during the initial developmental stages. The different groups work in parallel and little information passes between these
groups. Frequently this leads to compatibility problems during production stages.

7. The current media of information exchange during these initial stages is through meetings, reports, and personal verbal contact. There is little cross-communication between the groups except after the event. This results in engineering changes that could have been avoided if the relevant information were made available as generated. There is a general problem with respect to information accessibility between teams and across disciplines. Therefore, the concept of building capabilities to externalize information transfer into the design action becomes intrinsically appealing.

8. Due to the multidisciplinary and multifunctional nature of typical "designs," data originates from different sources and in disparate forms. Such data is usually stored in provincial data bases and file systems. Information is also stored in documents, technical references, test result tables, and drawings. This results in the formation of "data islands" and restricts the transfer of information between groups belonging to different disciplines or functions. To compound this problem further, this data appears in different forms (graphical, text, verbal) requiring more sophisticated data storage strategies.

9. The conceptual centralization of data associated with past designs, change requests, and previous problems is of critical importance. This will provide a uniform mechanism for accessing product-related data and maintain the design evolution. The centralized system must provide a forum for interacting design agents to communicate and must also support a shared data base that defines the state of the product design, at any point in time, to an expandable community of design agents.

10. While interacting with serial and parallel design agents, designers perceive collaborative information sets as macro objects and are largely interested only in the macro definition. For example, the mechanical engineer is rarely concerned with the detailed design specification of the PCB. Any changes relate only to macro attributes such as critical dimensions, mounting characteristics, connectors, and adaptors. Thus, the addition of a new element such as a transistor will not signal changes in the mechanical design function unless these macro attributes are also changed.

11. Current practice is geared toward a serialized design process. A parallel approach is not possible since information flow is determined by this serial mode.

12. During the design function the evolving design is rarely checked for consistency across different disciplines and functions.

13. Past experience and knowledge, and information about previous designs and their evolution, are seldom available in a readily accessible form.

14. It is widely agreed that the problem does not lie in finding the relevant information—rather, in the time it takes to find this information.

4.2 Compatibility Enforcement

1. Most review processes and compatibility checks are carried out as a postdesign function—such techniques are rarely available at the source of the design action. These may involve task groups or rely on automated computer-based simulation and analysis tools. These issues need to be addressed as they become relevant during the initial design phases.

2. The issue of compatibility of data consistency from the standpoint of updates, insertion, and deletion must be addressed throughout the various levels of abstraction. This is complicated by the disparate forms of data—geometry, text, procedural code, test results, and so on. From the standpoint of design it is imperative that the geometry data is integrated with the centralized information communication data base to ensure consistency.

3. Downstream functions, such as manufacturing and supportability, are unable to impact the "design" due to unavailability of evolving information. This leads to increased costs, delays, and "change requests" due to design errors.

4. Since the design is extremely fluid during these stages, up-to-date "design status" data is rarely available. Considerable effort has been wasted in designing to certain requirements that have since changed. The need for a change signaling and notification mechanism will prove very useful in managing changes especially at higher levels of abstraction.

5. The user interface must externalize the compatibility enforcement capabilities sufficiently to provide interactive capabilities rather than batch-oriented postprocessing capabilities.
5 The Scope of EMTRIS

The capabilities of EMTRIS were based extensively on data derived from the protocol studies. The task was to design a conceptually centralized engineering information system to control, manage, and coordinate the design data generated during the initial stages of the design process. Several local data bases were also incorporated to reflect the standardization requirements of individual functions and groups. The primary consideration was to provide a uniform forum for various disciplines and groups and application program to interact. In effect, this provides the functionalities of an information-based blackboard system by permitting various design agents to post and extract data from a common data base structure.

The following aspects were strategic in deciding the structure and capabilities of EMTRIS:

- Bridging the wall between design and manufacturing by enhancing the communication links; incorporating design guidelines and establishing a new communication protocol
- Linking peripheral application programs and data files
- Providing a centralized data repository
- Facilitating ‘‘PART-based information” retrieval and historic data retrieval
- Linking disparate functions: design, manufacturing and MRP
- Establishing a disciplined control mechanism in maintaining engineering information
- Moving away from past data management practices that were predominantly subservient to the personal discipline adopted by engineers
- Establishing an information-based blackboard system that allows several related design agents to interact (people and application programs)

The data that EMTRIS has sought to capture resided in different application programs and personal file systems and sometimes was not available at any fixed source. In cases where the data was tied very closely to specific application programs it was decided that EMTRIS would merely fulfill a meta data retrieval function by storing a pointer that would locate these data files. Since data access is based on the “part number,” this provided an excellent means by which one could access all data related to a particular part. Previously this data was available only through interactions with individuals responsible for that specific task.

6 EMTRIS Capabilities

The primary intent in implementing EMTRIS was to provide a plantwide engineering information base. A complete documentation of this system implementation is available in Ref. [22]. The following paragraphs briefly highlight some of the capabilities supported by EMTRIS.

6.1 Program Structure

EMTRIS was designed to support a distributed computing environment. The data kernel is implemented using the ORACLE DBMS and contains the various relation definitions, clusters, and indexes [1]. The various data dependencies required for consistent updates, inserts, and deletes are defined in the trigger mechanisms in the SQLFORMS application utility [1]. EMTRIS has been implemented on an NCR Tower minicomputer and may be accessed plantwide by personal computers over the factory network system (Fig. 6). Links to different applications are implemented using modules that manipulate the data base.

6.2 User Interface

The user interface is essentially a forms-based application where the user navigates through several
related screens. The user may access a HELP utility that provides basic information about each attribute entry and also defines various programmed function keys. A few sample screens follow in Fig. 7. For example, the critical part data combines several relations defined in the data base and ensures that the associations are maintained for data base operations (update, insert, delete, query). Thus, the part data is combined with standard material data as well as paint and coating information, along with the assembly parts list if it is an assembly. Subsequent screens (not shown) specifically display the paint/material/coating data as well as the assembly parts list.

6.3 Control Levels

The connectivity between the entities as identified by the ER model is enforced at various levels of abstraction—the field or attribute level, the block or relation level, or at a cluster level, identified by several blocks. The update, insert, and delete consistency controls are incorporated using various programmable triggers. Related data entities are organized into clusters and indexed for fast response times. At times these controls involve the instantiation of standard components or parts.

6.4 Collaboration

The EMTRIS menu is shown in Fig. 8 and follows the relationships identified in the ER model (Fig. 6). The ER model (Fig. 6) The ER model identifies and relates entities from different groups. The model relates data generated throughout the life cycle of a product. By conceptually centralizing this data to support the design life cycle data (data from both previous designs as well as the various subset and generalization hierarchies), a uniform data access methodology is available to the designer or engineer. Most data base entries were identified after a thorough analysis of each group’s engineering information needs and are very specific and of immediate use to the concerned parties.

EMTRIS stores data generated by various groups, namely, design, drafting, advanced manufacturing operations, and production planning, and also acts as a communication medium. In addition to storing the critical design and manufacturing data, pointers to various drawing files, geometry files, and NC programs are also stored. This strategy was adopted because of the need by different groups to view the same geometry or drawing retrieved by part number. In the past this was achieved by contacting the designer or engineer responsible for creating the part geometry since these files are closely tied to the CAD or CAM applications.

In order to improve the manufacturability of products, it was determined that an information-driven approach would produce the best results. Although many of the DFM (design for manufacturability) concepts espoused by Starkey and Florin [23] were relevant to this case, it was decided that an error-checking data base retrieval system could solve many of the issues that appeared in this area.

In order to facilitate the communication between the two groups (design and manufacturing), EMTRIS provided three features that were specifically geared toward this function:

1. A "COMMENT" form by which engineers and designers could communicate using the class number and/or part number as the key. This also provided a permanent record of all comments made against the part or class serving as a history of the design evolution. This may be likened to an electronic mailing system addressed by part number.

2. Notification. Problems, changes, deletes, notes, and other status-oriented communication are
posted as records—against a form-based notification system. VLSI, components engineering, mechanical engineering, and manufacturing engineering groups can communicate using the product ID as the key.

3. A "STATUS" form indicating the status of designs was also made available. This essentially acts as an unofficial link between design and manufacturing by indicating the drawing number of parts for which the design functions have been completed. By notifying manufacturing of the design status before an official release is made, manufacturing is in a position to review the drawings over the network and provide DFM/DFA (design for assembly) input. Since at this stage the part number is available, manufacturing may use EMTRIS to access further information about this part.

The objective here is not to curtail the designer’s creativity but rather to force the designers to interact heavily with manufacturing. In this regard, it has been noted that an efficient communication link will offer the best DFM strategy.

6.5 Integration with Applications

EMTRIS is also able to import data from local spreadsheet applications. For example, the routings are generated using a spreadsheet application on a personal computer. This data is then transferred over the network and uploaded to the NCR Tower and imported into the EMTRIS data base.

Specific data useful to the MRP function (routings, bill of materials, BOM) are automatically exported from EMTRIS on a daily basis and are transmitted to the computer maintained by the MRP group. In the past the manufacturing engineers would convey this data on paper. By automating this procedure, a crucial bottleneck has been eliminated.

During the initial design stages simulation of manufacturing activities such as flat pattern generation require the IGES drawing files to be transferred across the network. An application program to automate this operation utilizes the release status and drawing file relations within EMTRIS to locate these files within the file systems as per the release directives.

6.6 Standard DBMS Values
(Subset/Generalization Hierarchies)

A list of standard parts, materials, and tools supported by manufacturing is maintained by EMTRIS (Fig. 9a). Critical properties, design guidelines, and manufacturing recommendations have also been added to this feature. Manufacturing is responsible for maintaining this data base and is in a position to impose a light constraint on the design by forcing only these standard components to be used. The design may, however, call for other components, but EMTRIS requires that manufacturing be informed before such a move is made. The critical part data links to this standard data base and incorporates standards whenever necessary and available. In the event that the design calls for a nonstandard part/component (sheet metal gauge), the relevant groups are intimated before these entries can be made in EMTRIS. This ensures that the downstream functions are aware of the requirements of the design much ahead of time.

A similar strategy is applied while dealing with standard components maintained by the different groups. The designer may choose from a list of standard components as per the needs of the design and ensure that it will be available during production. The standards data may be manipulated using typical DBMS operations. They are also linked to individual part entities through relationship attributes and may also be retrieved as defined by the generalization hierarchies (Fig. 9b).
6.7 BOM Structure

The classification system adopted by NCR Corporation is heavily dependent on the "part number" method, which is typical in such establishments. The various product lines are classified into "class numbers" at the highest level of the bill of materials hierarchy. The class/part number system was used as the basis for determining the uniqueness of the primary keys while designing the data base. The part, subassemblies, and units are stored in a BOM hierarchy, thereby allowing the designer to navigate the hierarchy for data retrieval and insertion/update/delete operations. Figure 10 shows the BOM hierarchy relating systems to units and features and parts. The "many-many" relationships are modeled using connection relations (tables) in EMTRIS.

6.8 Design Evolution

Data regarding engineering changes, manufacturability reports, comments, and other notes (as shown in Fig. 5) provide status information about the product and maintain a design evolution. It is possible to retrieve problems that may have been associated with previous designs, and so on. This facility provides historic data retrieval and defines a basis for facilitating group technology-based retrieval using different part classification systems.

6.9 Query Operations

A keyword retrieval feature has also been incorporated into EMTRIS allowing the designers to examine previous designs based on part similarities. This permits a review of past problems, comments, and mistakes before starting work on new designs. Query operations may be performed on any particular field or set of fields reference by EMTRIS. Usually the part number or class number is used as the query condition. However, the user is free to query against any attribute defined by EMTRIS. Associated data is also presented whenever relevant. The entity relationship model associativity is reflected in the queries relative to standards. For example, the critical part data form retrieves the part information in addition to material data and material standards, the assembly parts list if the part is an assembly, and the paint and coating standards used for the part if relevant.

6.10 Security Control

Data ownership is preserved by allowing each group to insert and update only those records relevant to its operations. All groups have been given query access to the entire data base. Thus, the design group can change only those data base relations associated with their group's operations. The access privileges were determined on the basis of the protocol studies.

6.11 The TO-BE System

Subsequent to implementing EMTRIS, a new "desired" activity model was defined. This essentially replaces all miscellaneous data flow paths with a new EMTRIS data flow schema. This model (not shown here) serves as a prescriptive model of the design process from a data transfer standpoint.

6.12 Current Status

EMTRIS was very well received by the NCR staff. At the time of this writing EMTRIS is operational at the NCR, Wichita, site and is being actively used.

7 Deficiencies and Future Enhancements

A primary deficiency inherent in EMTRIS is that it is not integrated with the design action. This severely limits its utility as a true concurrent engineering tool. In the current environment the design action is personified by the geometric modeling system. To provide a truly integrated system, it is imperative that the design action provide capabilities relevant to the prevailing design process. This requires that systems such as EMTRIS, which are designed to conform to the engineering design pro-
cess, be well integrated with the operations associated with the design action.

The need to integrate geometric data in the CAD systems with data base systems such as EMTRIS without sacrificing the CAD system's response characteristics introduces an additional layer of complexity. Furthermore, if such systems are augmented with inferencing capabilities, then additional issues related to data representation schemas must be addressed. We are currently investigating strategies to integrate the data base with the geometric design action, and it is hoped that the future enhancements will overcome some of these issues. Specific work is being carried out to understand the data flow between parallel activities (such as sheet metal design and printed wiring board design) and in combining heuristic and qualitative reasoning with data base needs. These capabilities are geared toward externalizing the designer's information retrieval and constraint enforcement capabilities. This will result in an information-based CAD environment. In such an environment EMTRIS acts as an information-driven blackboard system that is linked to several applications such as mechanical CAD, electrical CAD, MRP systems, and so on, allowing each of these systems to function in consonance with the engineering design process.

Several issues are being investigated within this framework:

- Multidisciplinary updates in a distributed computing environment among geometry driven systems, data base systems, and expert systems
- The representation of geometric entities as geometric objects with textual attributes
- The interdependency between geometric entities and with their attributes
- A two-way, real-time link between the CAD system and the DBMS that supports multidisciplinary updates
- The conversion of parametric data into geometric forms using a feature-based design approach whenever appropriate

8 Conclusions

EMTRIS has been successful in tackling the information needs of practicing designers and engineers working in a CAD/CAM environment. By tackling the problem from an information perspective, this exercise has helped bridge the gap between the design and manufacturing groups. A review of some of the results from the protocol studies of the design process suggests that there is a critical need to control and manage the information generated during the various stages of the engineering design life cycle. A structured methodology for developing such systems has been defined by using different modeling tools. These modeling tools are fairly easy to use and should provide a means to help design a prototype system before a full-scale project is undertaken. The data management approach has also proved extremely effective since it allows scope for modular development. A coordinated effort toward implementing such systems following the "information integration" paradigm will go a long way in raising the productivity levels of large manufacturing plants.

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References


managing computer aided design and computer aided manu-
facturing data bases. Ph. D. dissertation, UCLA, CA

unified view of data. ACM Trans. Database Syst. 1(1), 9–36

for relational databases using the extended entity-relationship
model. Comput. Surv. 18(2), 197–222 (June)

gregation and generalization. ACM Trans. Database Syst.
2(2), 105–133 (August)

17. Rinderle, J.R. et al. (1988) Form-function characteristics of
electro-mechanical designs. Design Theory '88. In: Proceed-
ings of the 1988 NSF Grantee Workshop on Design Theory
and Methodology

18. Smith, H.C. (1985) Database design: Composing fully nor-
malized tables from a rigorous dependency diagram. Com-
mun. ACM 28(8), 826–838 (August)

19. Integrated information support system (IIS). (1985) In: In-
formation Modeling Manual, Extended (IDEF 1X). Manhat-
tan Beach, CA: D. Appleton Company

20. Special edition on computer aided software engineering.
CASE, IEEE Softw. March

model. Database Program. Des. (December)

information modeling in a CAD/CAM environment.
OCA E25-M38, Georgia Institute of Technology

23. Starkey, J.M.; Florin, G.J. (1986) Design for manufacturabil-
ity. ASME Paper, 86-DET-121, New York