The Purdue Enterprise Reference Architecture and Methodology (PERA)

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Abstract

PERA (the Purdue Enterprise Reference Architecture) is a complete Enterprise Reference Architecture as defined by the IFAC/IFIP Task Force on Enterprise Integration. This chapter describes PERA in relation to the requirements for such architectures and shows how PERA can fulfil each of such requirements.

Keywords

Enterprise Integration, Enterprise Reference Architecture, Methodology, Framework

1 INTRODUCTION

As developed in a companion paper in this volume (Williams and Li, "The Life Cycle of an Enterprise," there are several major concepts which are common to all enterprises and which readily show the interrelationship of all aspects of the life history of any of them. These are reproduced here as Table I for completeness and to obviate the necessity for the reader to continually refer back to another paper for reference. These concepts form the basis for the development of an architecture (a descriptive framework) and its associated methodology as needed for planning and carrying out all of the enterprise integration engineering tasks needed to produce and operate any enterprise regardless of its own particular nature or employment.

2 WHAT IS AN ARCHITECTURE

The universal applicability of the systems engineering concept of a life cycle (Items 10 and 11 of Table I) allows one to develop a sketch or graphical model to illustrate most of the concepts and tasks involved in enterprise integration. This gives all the individuals involved a common and easy way for describing, planning, and carrying out all aspects of this very complex endeavor in the easiest way possible. The other concepts listed establish the overall form and content of the resulting sketch. This sketch will be called an "architecture" here since it describes the form or structure of the process of carrying out the life cycle of the enterprise or entity involved. Please see Figures 1–3 and 15 later in this paper. or entity involved.

An architecture in its general sense is a drawing or discussion of the structure of something, generally physical such as a building, an electronic system, etc. These just listed we will call Type 1 architectures. Note that these are descriptions of the system at any one point in time. Change of the system at some time in the future will require a new sketch or other representation. There is still another diagram which we can also call an architecture. This is the diagram describing the form (structure and relationship) of a life cycle process. These we will call Type 2 architectures. By means of phases these Type 2 representations present all the processes involved in the life cycle of the enterprise represented by the discussion of Table I.

In its early analysis of the field, the IFAC/IFIP Task Force on Architectures for Enterprise Integration (Task Force, 1993) found that there were only three major architectures in the open literature at that time which would fall into the category Type 2 as defined above. They were:

1. CIMOSA. The Open Systems Architecture for Computer Integrated Manufacturing as developed by the European CIM Architecture Consortium (AMICE -- a backward acronym) under ESPRIT Projects 688, 2422 and 5288 of the European Community. This work was initiated in 1984 (hereafter called CIMOSA) (AMICE Consortium, 1988, 1989, 1991, 1992; Beeckman, 1989).
2. GRAI-GIM. The GRAI Integrated Methodology as developed by the GRAI Laboratory of the University of Bordeaux in France. This work resulted from production management studies initiated at the GRAI Laboratory as early as 1974. It has taken its current form since about 1984 (hereafter called GRAI-GIM) (Doumeingts, et al., 1984, 1987, 1992).
3. PERA. The Purdue Enterprise Reference Architecture and the related Purdue Methodology as developed at Purdue University as part of the work of the Industry-Purdue University Consortium for CIM. This latter work started formally in 1989 but bears on the Purdue Reference Model for CIM (Williams, 1988) developed in 1986 and on earlier work of the Purdue Laboratory for Applied Industrial Control dating back to the mid-seventies (hereafter called Purdue or PERA) (Industry-University Consortium, 1992; Williams, et al., 1991, 1994 (a, b, c), 1995; Li, et al. (1994).

Each of these architectures is described in a separate chapter of this text. Any one of them can already, or with suitable modification and updating, satisfy all of the concepts listed in Table I. The Task Force in its work thoroughly compared the three architectures, pointed out their strong and weak points, and recommended how each can be updated to fulfil any of the concepts presently lacking (Task Force, 1993).

It has already been shown (Williams and Li, 1995) that PERA fulfills these requirements without further modification or additions. This chapter will discuss PERA in relation to the concepts listed above.

3 DEVELOPMENT OF PERA AS ONE FORM OF THE ARCHITECTURE

The structure of PERA (Williams, et al., 1991, 1994, 1995) will be developed here to show how PERA as a reference architecture and methodology can be used to satisfy all of the concepts of enterprise integration as listed in Table I.

As noted in Concept 10, all enterprises throughout their lifetime fulfil a "life cycle." Figure 1 shows the form of the architecture describing this as expressed by PERA. The life cycle proceeds from top to bottom of the figure, i.e., from initial identification of the project down through all intermediate phases to the final act of enterprise dissolution. The structure and form of the architecture will now be explained. (The numbering of nodes and boxes used here will be explained later.)

Figure 2 illustrates Concept 3 concerning the existence of two and only two classifications of functional tasks in the enterprise. It is well known by this author that most computer scientists and information specialists prefer to separate information (databases and data handling) from control or decision theory. However, since "the only use for information is to effect control now or in the future," we hold to our premise. This axiom may be considered a little farfetched when we consider history, but even here it holds if one believes, "history is to help us avoid the mistakes of the past," i.e., to help us have as much control of the future as is possible.

Concepts 4–7 are illustrated by the progressing life history of Figure 2 showing requirements leading to the tasks necessary to fulfil them. These tasks then lead to functional networks. The networks (material and energy flow diagrams and data flow diagrams) are directly analogous to each other.

Table I The Simplifying Concepts of Enterprise Integration

1. While the early work in CIM, and of enterprise integration as well, was largely confined to the field of discrete manufacturing, it can readily be shown that the basic principles involved apply to any enterprise, regardless of its size and mission or any of the other such attributes involved. These are generally principles which apply to all aspects of the field of systems engineering. In addition, it is a mistake to confine the integration discussions to information and control systems alone. Often there are problems within the mission system (manufacturing or other customer product and service operations) whose solution would greatly ease the overall plant system problem (i.e., it must involve both information and mission).
2. No enterprise can long exist without a business or mission, i.e., it must produce a "product(s) or service(s)" desired by a "customer(s)." It usually must also produce these product(s) or service(s) in competition with other enterprises also vying for this same business.
3. There are only two basic classes of functions involved in operating any enterprise:
   a) Those involved in operating the "processes"* which result in producing the "product" which fulfills the enterprise's mission, i.e., the customer product or service business in which the enterprise is engaged. In the manufacturing plant these would include all material and energy transformation type tasks and the movement and storage of the same materials, energy, goods in process and products.
   b) Those involved in the "control" of the mission in an "optimal" manner to achieve the necessary economic or other gains which assure the viability or continued successful existence of the enterprise. These comprise the collection, storage and use (i.e., transformations) of information concerning the business processes in order to control them, i.e., to develop and apply necessary changes to the business processes to achieve and maintain their required "optimal" operation. Thus it includes all planning, scheduling, control, data management, etc., functions.
4. Normally, information or data will undergo multiple transformations, i.e., many separate tasks (where a task defines each transformation) in fulfilling the information-handling requirements for an enterprise or CIM system. These transformations or tasks are usually successive operations forming sets of sequential and parallel networks.
5. The same is true of the material and energy transformation tasks for fulfilling the physical production or plant operations requirements for the enterprise.

(continued)

* The use of quotation marks on several of the terms used here indicates they are defined in the most general manner possible in order to cover the extremely wide range of aims, methods and conditions covered.

Table I (continued)

6. In each case the networks involved can be combined, if desired, to achieve one major network of each type (Informational Transformations or Material and Energy Transformations, respectively), the totality of which defines the functionality of the enterprise or other business entity being considered (i.e., the totality of the information network, plus the manufacturing networks, both of which can be developed separately but used conjointly).
7. The two networks interface in those tasks that develop operating variable state or status from the manufacturing processes (sensors) and those that deliver operational commands to the operational units (actuators and related devices). Except for these tasks and their related requirements, which do affect the other networks, each network can be developed independently of the other.
8. Initial functional analysis or general study of either or both classes of functions above can be carried out without knowledge or concern of how they will ultimately be implemented in the operating enterprise.
9. For many technological, economic, and social reasons, humans are involved in the implementation and execution of many business processes of all types in both classes above. Others, of course, may possibly be automated or mechanized. Thus there must be three classes of implemented tasks or business processes:
   a) Those of the information and control type which can be “automated” by computers or other “control” devices.
   b) Those of the mission tasks or business processes which can be automated by the “mission fulfillment” equipment.
   c) Those functions carried out by humans, whether of the control or mission fulfillment class.

   There must be a simple way of showing where and how the human fits in the enterprise and how the distribution of functions between humans and machines is accomplished.
10. All enterprises, of whatever type, follow a “life cycle” from their initial concept in the mind of an entrepreneur through a series of stages or phases comprising their development, design, construction, operation and maintenance, refurbishment or obsolescence, and final disposal.
11. Not only does this life cycle apply to the enterprise but also to the enterprises’ products as well. Thus, carried further, one enterprise can be the product of another. For example, a construction enterprise could build a manufacturing plant (enterprise) as its product. The manufacturing plant would then manufacture (produce) its own product, such as an automobile. The automobile also has its own life cycle, which goes through similar steps to those discussed here

(continued)

Table I (continued)

12. Once the integration of all of the informational and customer product and service functions of an enterprise have been properly planned (the Master Plan), the actual implementation of such an integration may be broken up into a series of coordinated projects, any and all of which are within the financial, physical, and economic capabilities of the enterprise, which can be carried out as these resources allow as long as the requirements of the Master Plan are followed. When these projects are completed, the integration desired will be complete.
13. All tasks should be defined in a modular fashion, along with their required interconnections, so they may later be interchanged with other tasks that carry out similar functions but in a different manner should this be desirable.
14. Likewise, these latter tasks should also be implemented in a modular fashion, again permitting their later substitution by still other different methods of carrying out the same function. The choice of these implementation methods can be governed by independent design and optimization techniques as long as the task specifications are honored.
15. Provided the modular implementation just noted is used, the interconnections between these modules can be considered interfaces. If these interfaces are specified and implemented using company, industry, national and/or internationally agreed upon standards, the interchange and substitution noted in Item 13 and 14 will be greatly facilitated.
16. A diagram or other representation describing the interrelationship of all the tasks, networks, and processes noted above, all arranged in their proper place in the several phases of the development or life cycle of the enterprise, can be called an Architecture. This since the resulting diagram shows the <u>project</u> <u>structure</u> of the overall set of tasks for developing and using the enterprise. As noted in the text these architectures can be called Type 2 architectures to distinguish them from those architectures describing the <u>physical</u> <u>structure</u> of a system <u>at</u> <u>one</u> <u>point</u> <u>in</u> <u>time</u>. These latter we have called Type 1.
17. By considering that manufacturing is a type of customer service, i.e., production of goods for purchase by the customer, and then expanding the definition of customer service to include all possible goods and services the enterprise may render to the customer, we can expand the applicability of the Architecture to cover all possible types of enterprises. Thus the mission execution side of the Architecture would then represent the customer service rendered by any enterprise even if that service itself involved the supplying of information type products to the customer.

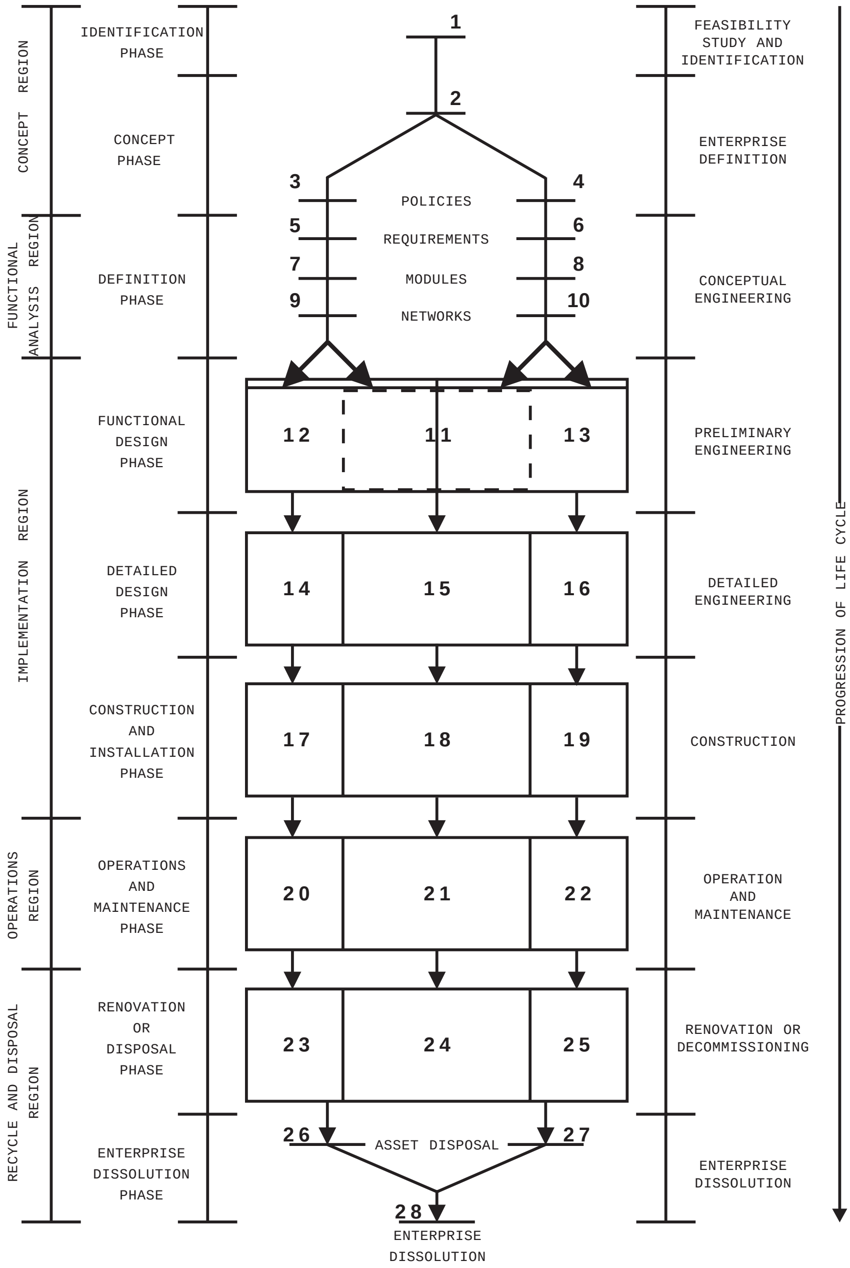


Figure 1 The overall form of the Purdue Reference Architecture diagram showing various examples of labelling of the life cycle phases

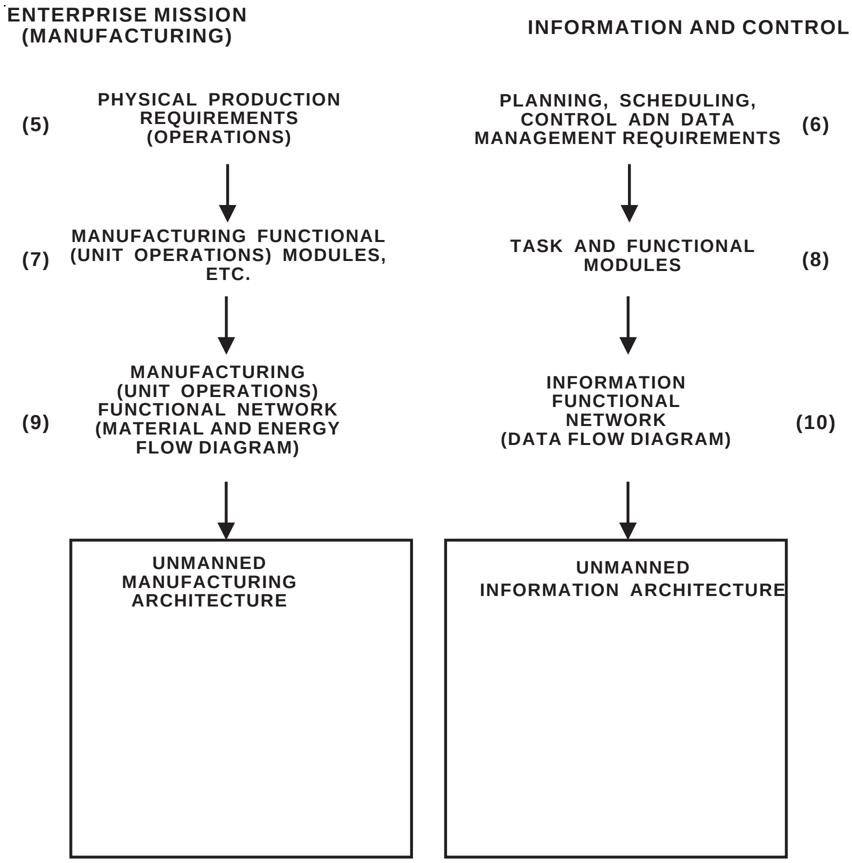


Figure 2 Developing the relationships of the several sub-architectures of the Purdue architecture for manufacturing systems

Figure 3 extends Figure 2 upwards (earlier in the life cycle and at a higher level in the company) to show the initial steps of the life cycle and the origin of the Requirements Level of Figure 2. Mission, Vision and Values (Node 2) gives management's desires for economic and other gains from the contemplated project. Policies (Nodes 3-4) show how management expects to gain the desired benefits. The resultant policies lead to the requirements on the system proposal which would ultimately enable those policies and management's expected benefits. Figure 4 shows that each node must be enriched from external sources to supply missing information from upper level sources as well as external requirements such as environmental, health and safety concerns, etc.

Figure 3 also shows the split of the two classes of functional tasks into three classes of implemented tasks to account for the place of the human worker in the enterprise. How this is determined will be discussed next.

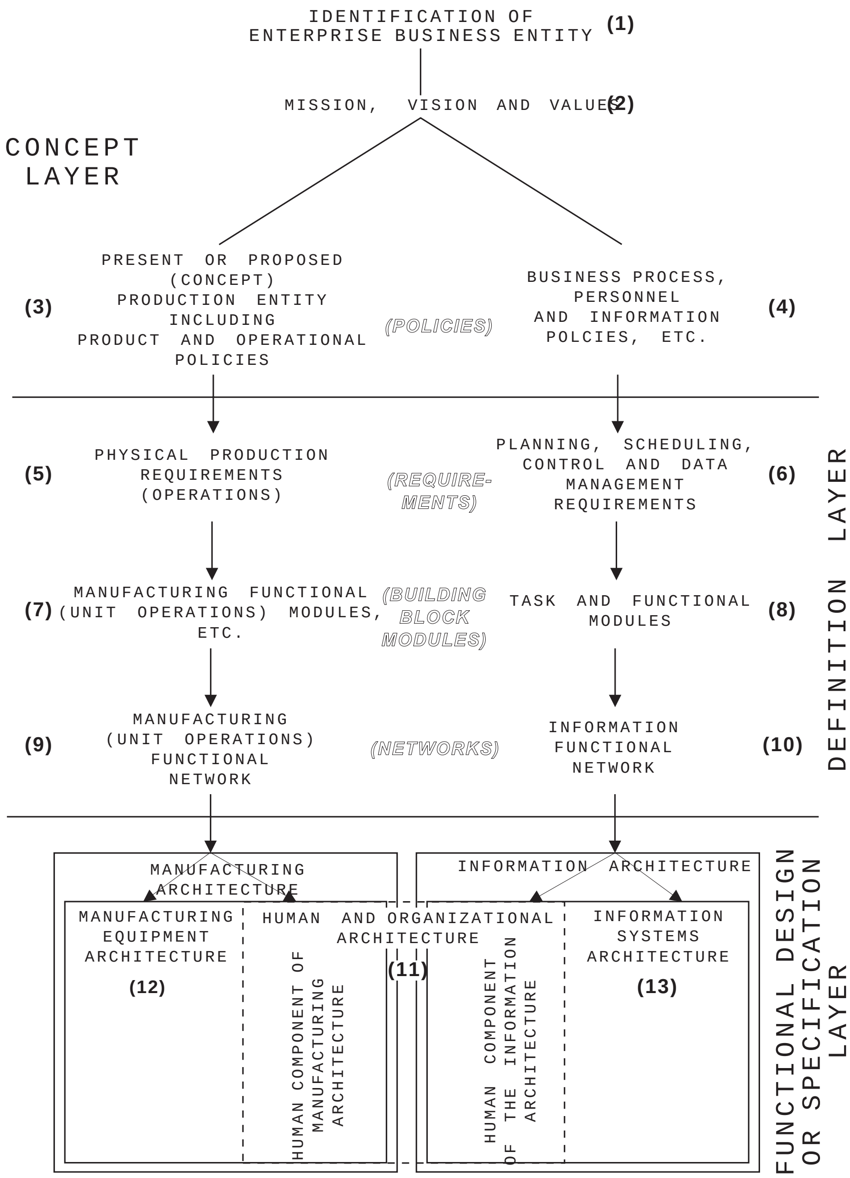


Figure 3 Definition of the components of the concept and definition layers for the manufacturing case

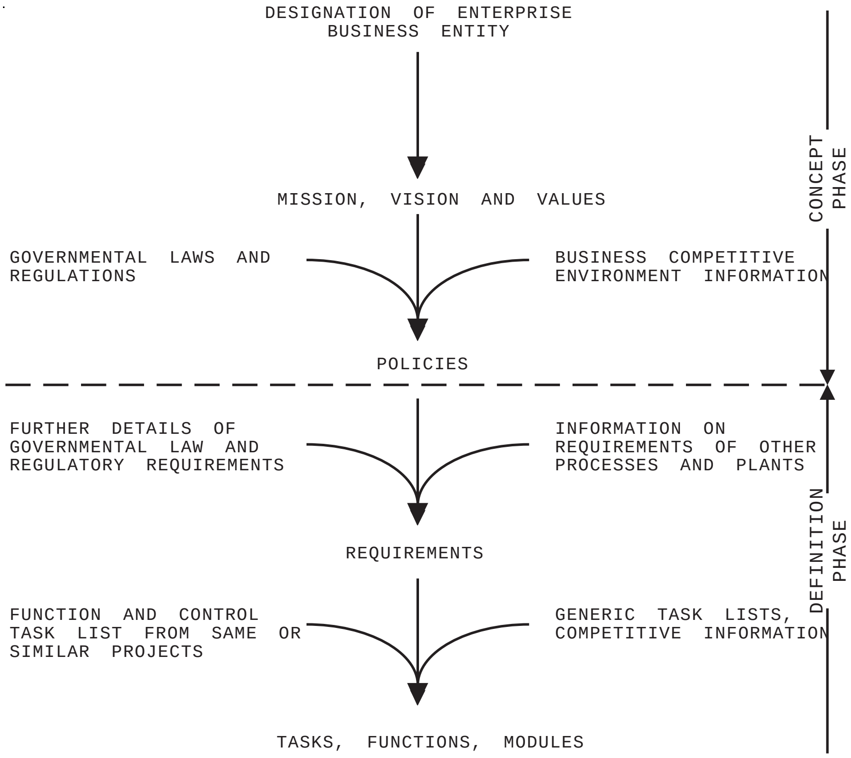


Figure 4 Development of enterprise requirements

3.1 Integration of Human and Organizational Factors

A singularly important contribution of the PERA Enterprise Integration Reference Architecture has been its presentation of a very simple yet again intuitively correct method for accounting for the place of the human worker in any automated system. The system works as listed in Table II and in the following discussion.

In order to show the true place of the human in the implementation of the enterprise functions, we need to assign the appropriate ones of these functions to the human element of the system. This can be done by considering the functional tasks as grouped in three boxes in the preliminary engineering or specification phase. These are separated by defining and placing sets of three dashed lines in the graphical architecture representation. This action will separate the two functional analysis streams into three as shown in Figure 5 and thus assign the tasks or functions involved to the appropriate boxes. The resulting columns of boxes then define the automated information tasks which become the Information Systems Architecture functions and the automated manufacturing tasks which become the Manufacturing Equipment Architecture functions. The remainder (non-automated) become the functions carried out by humans as the Human and Organizational Architecture.

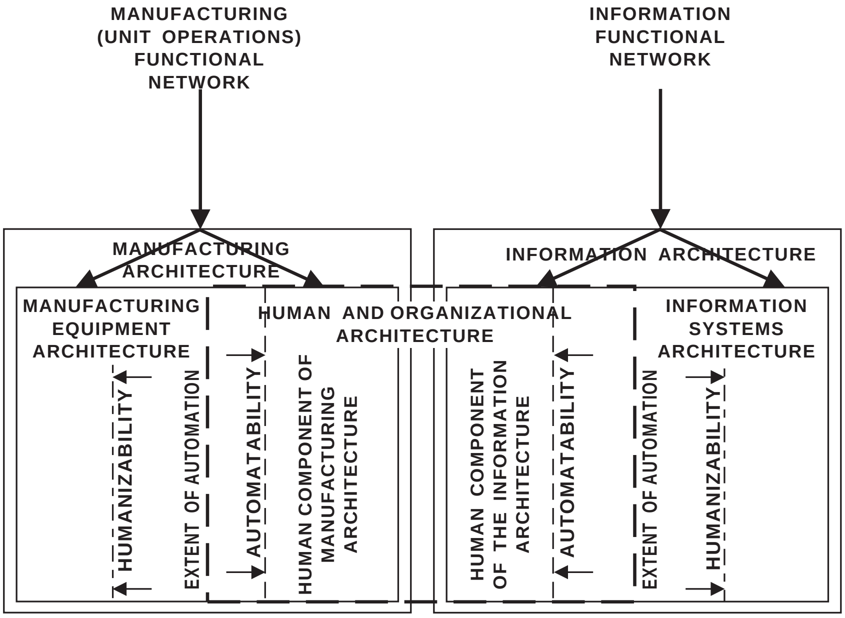


Figure 5 Introduction of the automatability, humanizability and extent of automation lines to define the three implementation architectures

The Automatability Line on Figure 5 shows the absolute extent of pure technologies in their capability to actually automate the tasks and functions. It is limited by the fact that many tasks and functions require human innovation, etc., and cannot be automated with presently available technology.

The Humanizability Line (see Figure 5) shows the maximum extent to which humans can be used to actually implement the tasks and functions. It is limited by human abilities in speed of response, breadth of comprehension, range of vision, physical strength, etc.

Still a third line is presented which can be called the Extent of Automation Line (see Figure 5) which shows the actual degree of automation carried out or planned in the subject Enterprise Integration system. Therefore, it is the one which actually defines the boundary between the Human and Organizational Architecture and the Information Systems Architecture on the one hand, and the boundary between the Human and Organizational Architecture and the Manufacturing Equipment Architecture on the other side.

The location of the Extent of Automation Line is influenced by

- Economic
- Political
- Social
  - -- Customs
  - -- Laws & Directives
  - -- Union Rules

as well as Technological factors. The actual choice of the location of the Extent of Automation Line must be made by management based upon all of these factors.

The Automatability Line showing the limits of technology in achieving automation will always be outside of the Extent of Automation Line with respect to the automation actually installed (see Figure 5). That is, not all of the technological capacity for automation is ever utilized in any installation for various reasons. Thus, the Human and Organizational Architecture is larger (i.e., more tasks or functions) and the Information System and Manufacturing Equipment Architectures are smaller (less functions) than technological capability alone would allow or require. One actual distribution of the tasks and functions of the Human and Organizational Architecture can be as shown in Figure 6.

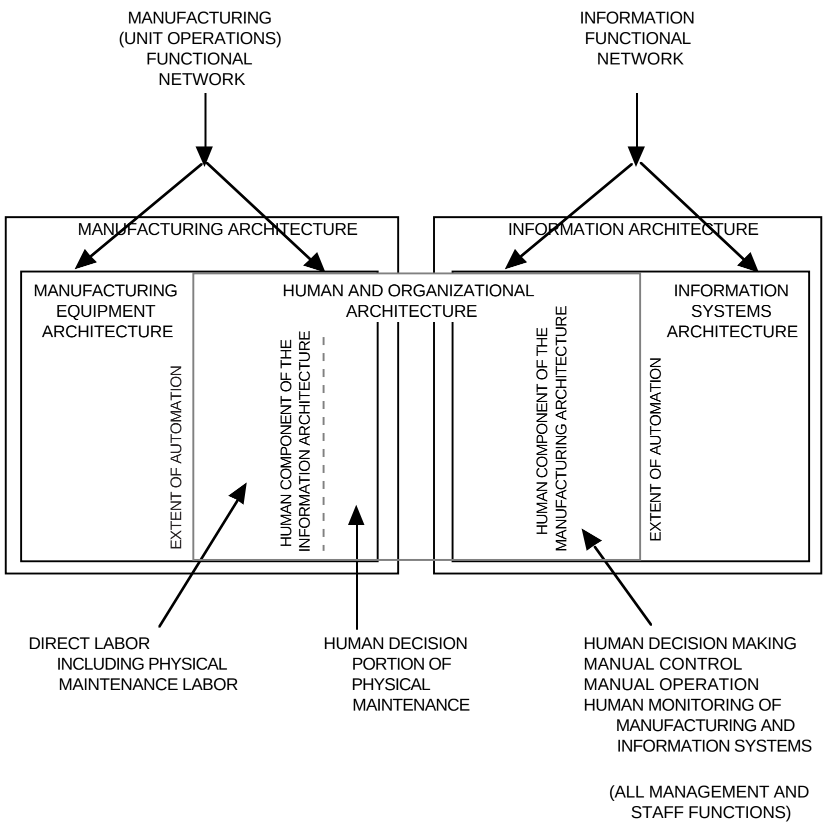


Figure 6 Definition of human task types in the several areas represented in the human and organizational architecture

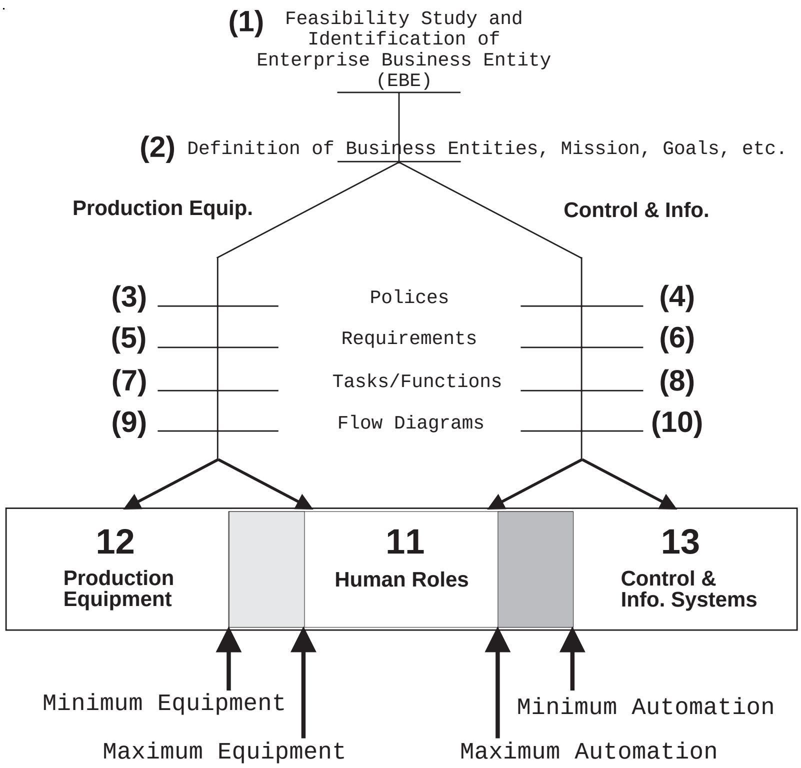
Note that for a completely automated plant as an extreme case, both the Automatability Line and the Extent of Automation Line would coalesce together and move to the left edge of the Information Architecture block and correspondingly to the right edge of the Manufacturing Architecture block. Therefore, the Human and Organizational Architecture would disappear and the Information Systems Architecture and the Manufacturing Equipment Architecture would coincide with the unmanned Information Architecture and the unmanned Manufacturing Architecture, respectively. This would then be the case illustrated by Figure 2. Table II summarizes the steps outlined above.

Table II Some Additional Concepts of the Purdue Enterprise Reference Architecture that Establish the Place of the Human in the Enterprise

1. The split of functions for implementation between humans and machines (on both the information and manufacturing sides of the diagram of Figure 2) forms the first definition of the implementation of the resulting manufacturing system. Because of the inclusion of humans, there must be three separate elements in the implementation scheme: the Information System Architecture, the Human and Organizational Architecture, and the Manufacturing Equipment Architecture. See Figure 3.
2. Provided all timing, coordination, etc., requirements are fulfilled, it makes no difference functionally what functions are carried out by personnel versus machines *or* what organizational structure or human relations requirements are used.
3. The split in assignment of these functions (i.e., between humans and physical equipment) can be expressed on a diagram by an *Extent of Automation* line.
4. The ultimate split of functions between humans and machines is determined as much by political and human relations-based considerations as by technical ones.
5. The diagrams noted above can be extended to show the whole life history of the manufacturing enterprise.
6. All tasks in the Information Architecture can be considered as *control* in its very broadest sense, either immediately or at some future time. Likewise, all data collected and information generated is ultimately to effect *control* of the overall system being considered, either now or in the future.

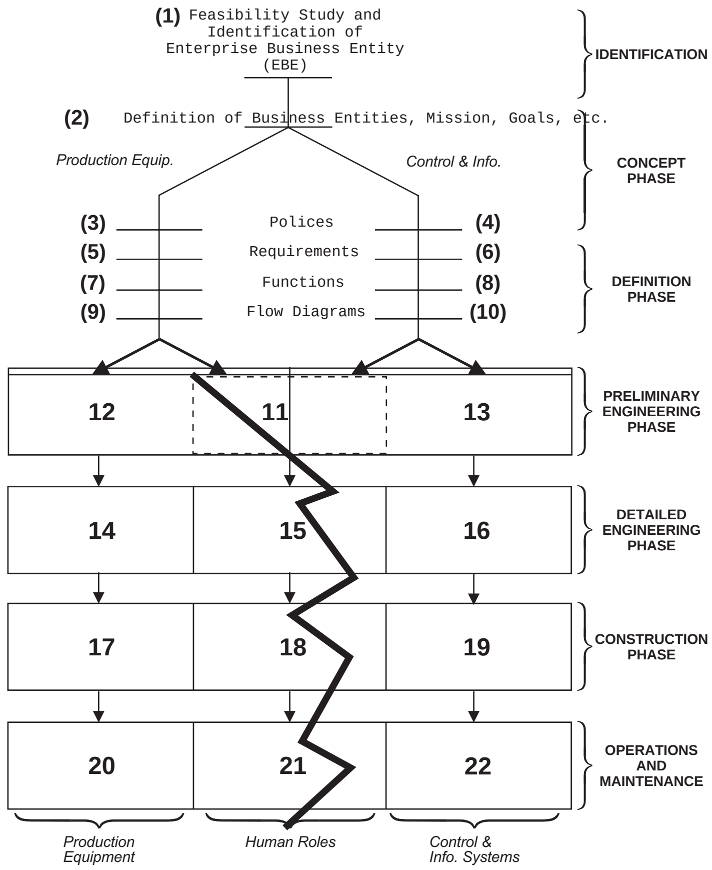
   The only other use of this data and information is in the context of a historical record.
7. Likewise, all operations on the manufacturing side can be considered *conversions*, the transformation (chemical, mechanical, positional, etc.) of some quantity of material or energy.

Figures 7 and 8 continue our discussion of the place of the human in relation to automation and mechanization (Rathwell and Williams, 1996). Figure 7 is another version of Figure 5 with the automatability and humanizability lines relabelled. Figure 8 points out the very incomplete state-of-the-art at present in terms of human factors and the present inadequacy of administrative assignment of the topics in many companies.



- Define Human & Organization Factors at Preliminary Engineering Phase
- Equipment, Automation and Human Roles are Interdependent
  - Equipment - A Conveyor vs. Manual Bag Dumping
  - Control - Automatic Sequencing vs. Manual Valve Actuation
- Must "Put Stake In Ground" for Downstream Design, i.e., Make Decisions Early and Keep Them.
- Policies Define Consistent Automation or Payback Goals

Figure 7 Integration of human and organizational factors



- No "Human Factors" or Organization Design Discipline.
- Many Disciplines have Input (Controls, Process, Mech, etc.)
- Plant Operations Expertise, Training, etc., not yet Assigned to Specific Company Groups.

Figure 8 Human and organizational responsibility is split

4 INTERFACES IN PERA AND THEIR RELATIONSHIP TO THE PURDUE METHODOLOGY

Review of any diagram of the Purdue Enterprise Reference Architecture, particularly Figure 15, reveals that it consists of a number of major blocks or nodes arranged in Regions and Layers or Phases. Each of these blocks and/or nodes transmits major amounts of information to their neighbors, particularly those immediately beyond them in the Life Cycle. The interconnection between any two of these blocks is termed an interface, in this particular case, a Program Interface since it represents an interconnection in the engineering program of development of the enterprise or entity in question. This is true of all Type 2 Architectures which represent the Life Histories of an enterprise or entity. The corresponding interfaces are called Type 2 interfaces.

The enterprise itself also contains a multitude of interfaces which represent the transfer of information, material and energy between the components of the enterprise. Since the Physical Architecture of the enterprise itself can be represented by a Type 1 architecture, the latter interfaces are naturally designated as Type 1 interfaces.

Each of these is important in the Purdue Methodology and will be briefly discussed here.

4.1 A Discussion of Internal Interfaces

Type 1 Interfaces will also be called Internal System Interfaces. In addition, they can be called Interarchitectural or Intraarchitectural Interfaces depending upon whether they are connecting components within one implementation architecture or the components of two separate implementation architectures. Human/Machine Interfaces would be classified as Interarchitectural Interfaces since they connect the Human and Organizational Architecture with the Information System Architecture. Communication Interfaces within the Information Systems Architecture would be Intraarchitectural Interfaces.

Internal, or Type 1, Interfaces can be divided into two further categories as follows:

1. Transfer of information between components of the Information Systems Architecture and/or between those and components of the other Architectures is classed as a communications function. (Such communications functions would also occur in information handling elements of the Customer Product and Service Architecture)

   All of these Interfaces are Communications Interfaces, i.e., the propagation of a satisfactory interpretation and comprehension of information transferred through an appropriate transformation of the signal involved.
2. Transfer of materials and/or energy between modules of the Product and Customer Service Architecture through material handling and energy conversion and transfer.

The following general statements can thus be made co ncerning interfaces within and between the several implementation architectures.

4.1.1 Interfaces within the Manufacturing Equipment Architecture

In this Architecture, all of the interfaces are those which permit the physical flow of either material or energy or both across the boundaries between the individual units of the manufacturing equipment. For example, a heat exchanger works as an interface between the fuel combustion system and the heated fluid system; an in-process storage works as an interface between two units of the manufacturing equipment.

4.1.2 Interfaces between the Manufacturing Equipment and Information System Architectures

The interface problems here will basically involve only the wiring problems between the equipment of the two Architectures. Under PERA, the wiring configuration directly connects the sensors or controllers on the side of the Information System Architecture to the related subject element (such as a control valve) of the Manufacturing Equipment Architecture. See Figure 9 discussed below.

4.1.3 Interfaces between the Manufacturing Equipment and Human and Organizational Architectures

Human involvement with the Manufacturing Equipment Architecture always involves the human operator acting as another machine component (direct labor) of the process equipment, such as an additional material moving and placing device. The special position and capabilities of humans enables them to directly handle the material flow of the manufacturing process. Physically, the human operator joins the material handling system within the Manufacturing Equipment Architecture. Traditional Human Factor researches have provided many popular and detailed instructions on the compatibility design of such Man/Machine interfaces to facilitate and safeguard the human operator from the physical inputs and to further assure his physical safety. Under PERA, this Human-Factor Man/Machine interface would be considered as part of the Manufacturing Equipment Architecture.

4.1.4 Interfaces within the Human and Organizational Architecture

In this architecture, only one type of interface exists, that of the human to human interface. This interface relates to that information representation and communication where an established dictionary, or other standard semantics, and a standard graphical semantics and symbology may be necessary when people from different backgrounds are involved for informational interactions.

4.1.5 Interfaces between the Information System and Human and Organizational Architectures

Human interaction with the Information Systems Architecture always involves the transfer of data or information across an interface which allows the information system device and the human to interpret (process the results of) the operations of the other with exactly the same meaning in passing information between these entities across the interface. Therefore, each of them has to follow certain prescribed syntax and semantics, or communication protocol(s) to ensure the consistency and unambiguity required for the interaction or the transaction. The Man/Machine interface is here considered to be part of the Information System Architecture as noted in Figure 9.

4.1.6 Interfaces within the Information System Architecture

In order to execute the input of information or to process data within the computer system, interfaces between the elements of the information system are always involved to allow the computer(s) or other devices on either side of the interface to correctly interpret or process the results of the operations of the other party across the interface. Therefore, these interfaces have to meet certain requirements from the aspects of the communication protocols involved which specify the functional, electrical, and mechanical features of all signal and power lines which cross that boundary. Thus, the parties on each side of the interface will be able to follow the preagreed-upon syntax, semantics or communication protocol(s) as insured by the interface.

However, because of the extremely wide range of transfer requirements, it is difficult to define a uniform interface or develop one standard to cover all computer peripherals. Although there are many workable alternatives to define certain classes of interconnections that are suitable for both computers and peripherals, this very proliferation means that decisions on interface standardization must still be carefully made in order to obtain the maximum degree of compatibility for possible system expansion.

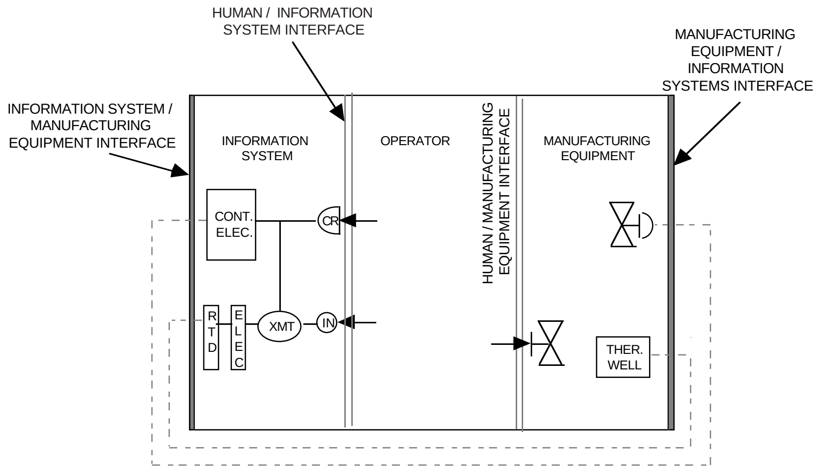
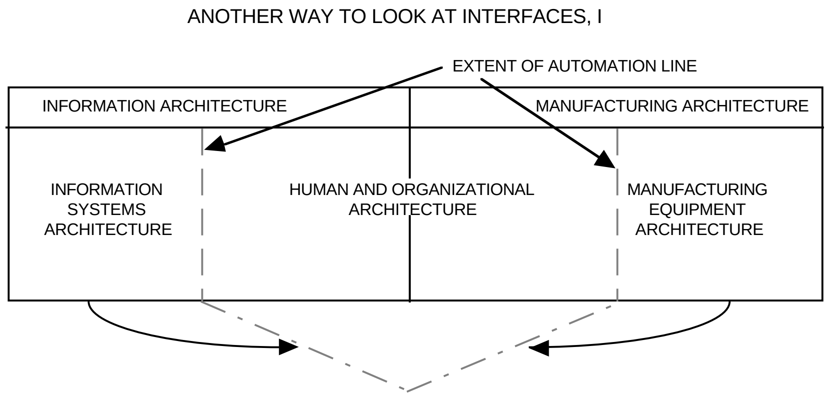


Figure 9 Interfaces in the overall enterprise integration system



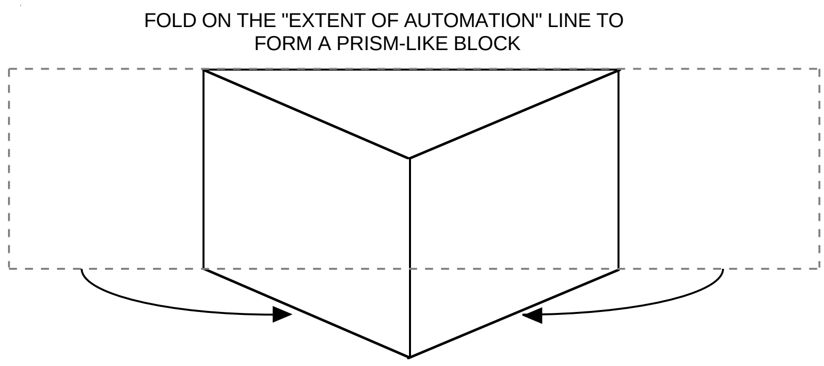


Figure 10 Development of still another method of representing each of the interfaces between the several implementation architectures

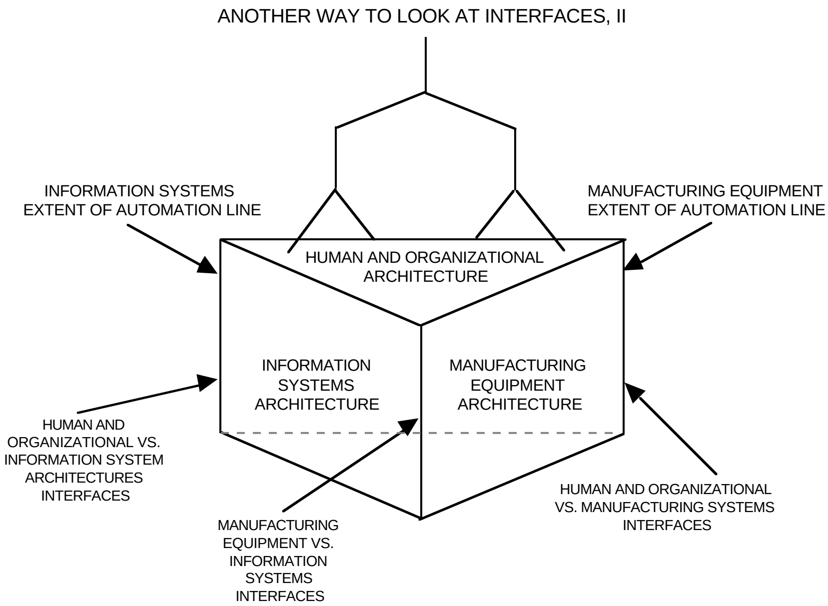


Figure 11 Use of the prism-block representation of the interfaces between the several implementation architectures

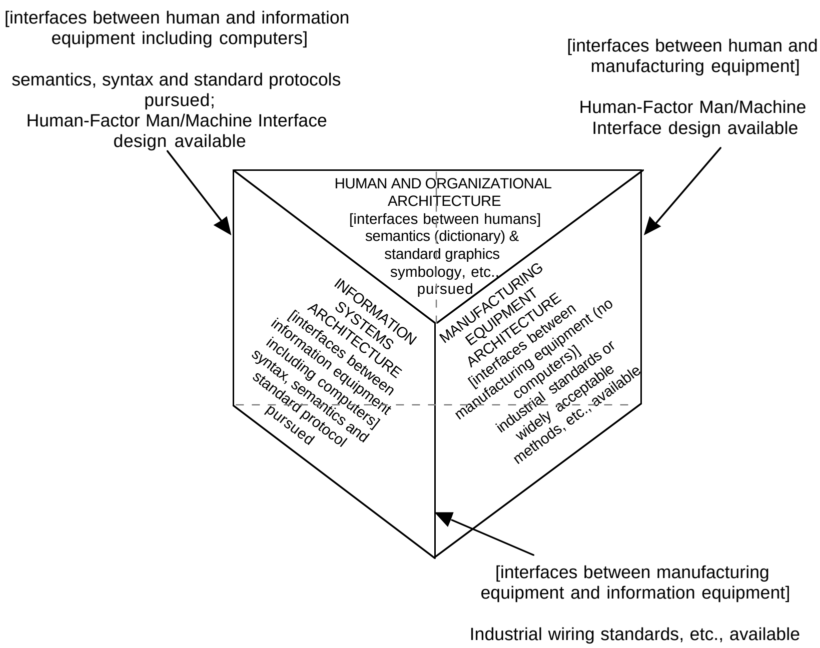


Figure 12 Representing intraarchitectural interfaces in PERA

4.2 The Use of the Architecture Diagrams for the Representation of Interfaces in Integrated Enterprises

The diagrams presented in Figures 10 to 12 can be used to represent the interarchitectural interfaces between each of the implementation architectures and either of the other two. These figures show some representations of the interfaces that must exist between the separate implementation architectures. These present the interfaces which must exist between the control system and the processes being controlled as well as the interfaces between the plant operator and both the control system and the manufacturing equipment. Figures 10 and 11 show the ideal interfaces using the functional block diagrams of the Purdue Implementation Architectures.

Figures 9 and 12 diagram the ubiquitous presence of interfaces involved Human-Machine interactions throughout the modern enterprise due to the implementation methods resulting from the major research and design work carried out on the technical and office use of computers and on plant operator interfaces (Sweeton and Crowder, 1988; Systems Group, INCOS Project, 1986). These implementations are now commonly carried out on CRTs or similar operating devices.

4.3 Further Discussion of the Assignment of Tasks to Human Execution

As noted earlier the ways in which human can be assigned tasks to carry out in the execution of an enterprise's mission can be classified in two ways: One, by whether or not these tasks are solely restricted to humans because machines are incapable of doing the task or that they can be automated but humans are doing them for economic, social and political reasons. The other is by whether the human is performing basically an information task (using their cognitive and thinking capabilities) or whether they are acting as components in the mission fulfilling equipment (and basically using their strength and physical manipulative capabilities).

Figure 13 emphasizes the second distinction above by showing that most information type tasks involve basically mental work input (the brain sketch in Figure 13) while the mission fulfillment part involves physical labor or skilled trade participation (the laborer of Figure 13).

Regardless of what type of task humans are carrying out, they must interact with other parts of the enterprise involved in the same task by means of a set of interfaces. In Figure 13, these are indicated by the CRT, Key Board, etc., for the information function and a set of tools for the physical task function on the right of the sketch. Figure 14 indicates the cooperation of the human and machine by means of a generic diagram indicating the interface involved, whatever its nature.

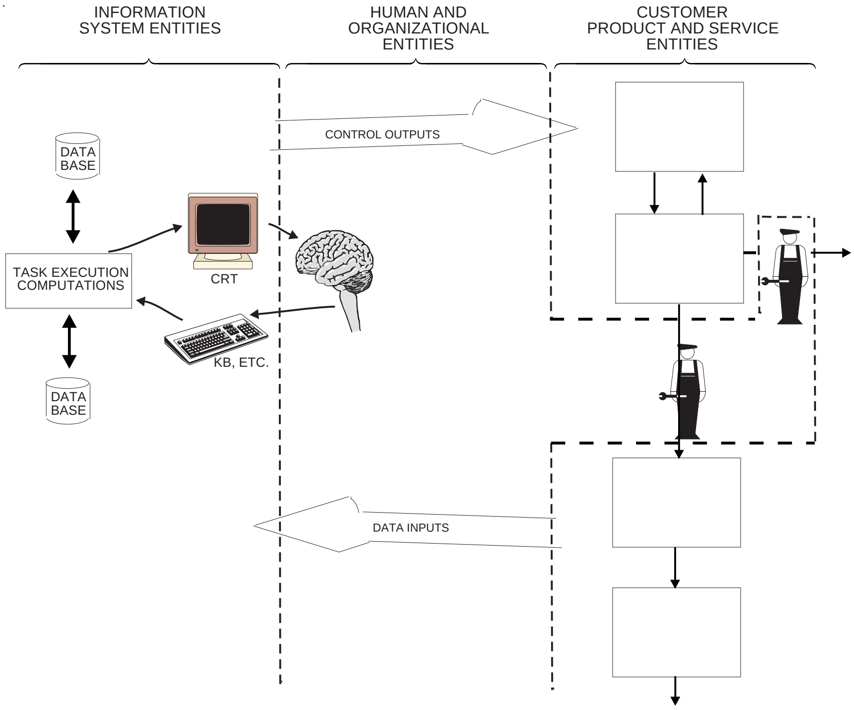


Figure 13 The place of the human in the integrated enterprise

5 A SUMMARY OF THE USE OF THE PERA DIAGRAM

Figure 15 summarizes our discussion of PERA as an example Enterprise Integration Architecture by showing the overall architectures and life cycle of the enterprise development program down to and including the operations and recycle or disposal phases. Note that the problem of analysis and disposal or renovation of the obsolete plant as shown in Figure 1 could also be included here for completeness if desired. The purpose here is to show how the architecture can be used to describe each of the tasks carried out at each phase, node and box represented in the architecture and their relationship to each other. The amount of detail shown is a function of the space available and the purpose to which a particular diagram is put. Other related presentations will be shown below.

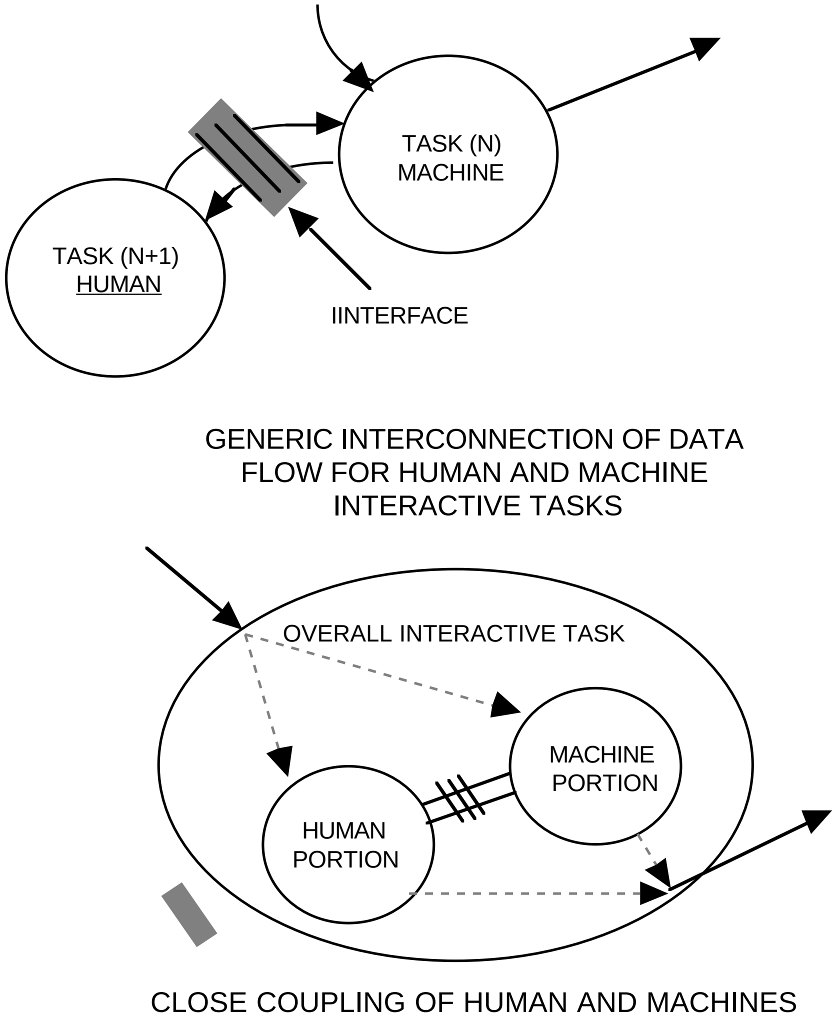


Figure 14 A Generic Interface Model Showing the Involvement of the Human in Enterprise Task Execution

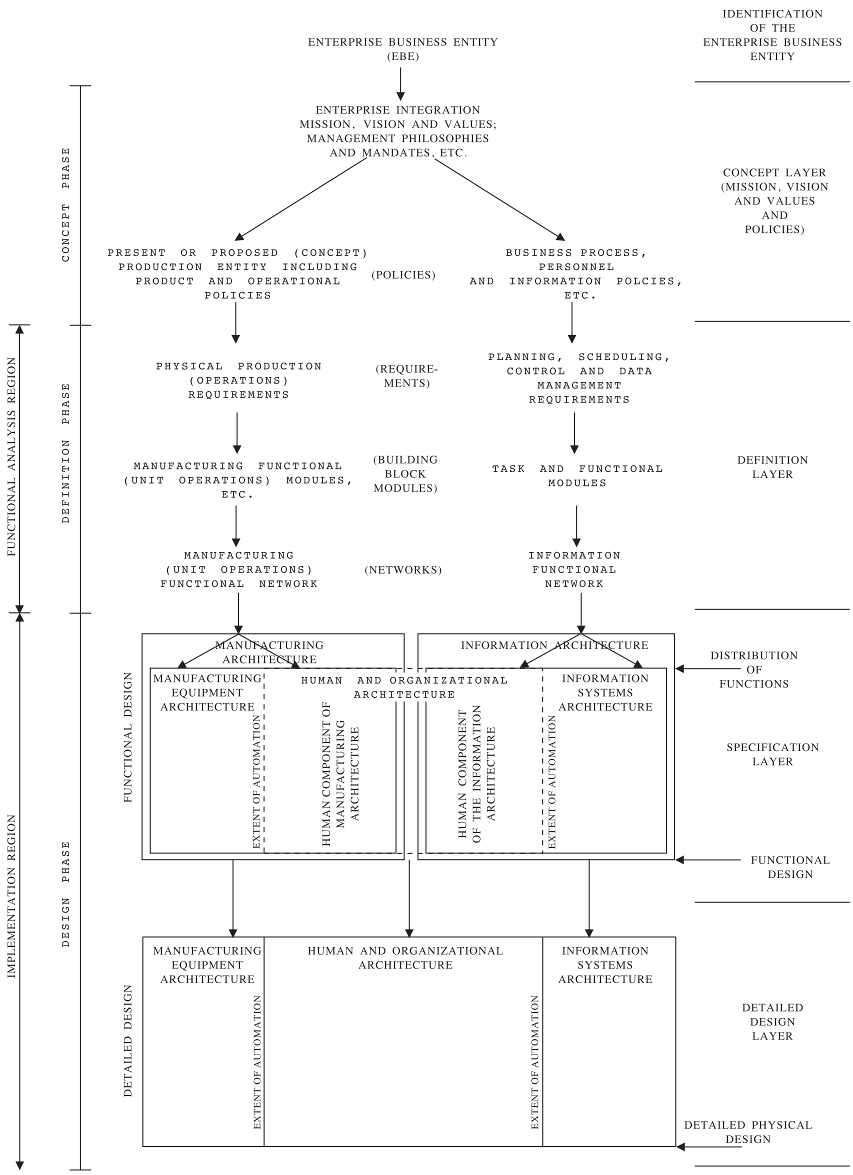


Figure 15 Development of an enterprise integration program as shown by the Purdue architecture (phases and layers of the program)

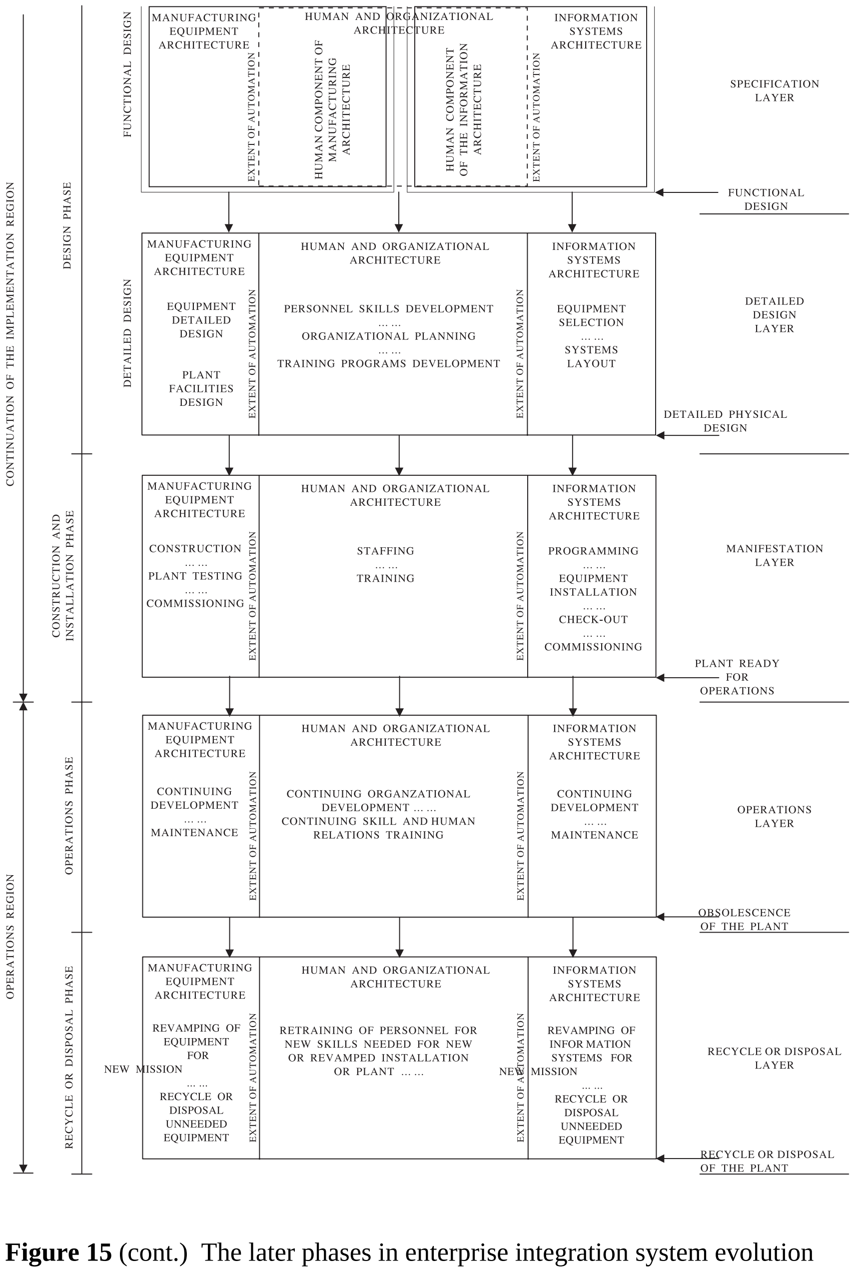


Figure 15 (cont.) The later phases in enterprise integration system evolution and their activities in relation to the Purdue architecture

6 THE METHODOLOGY OF ENTERPRISE INTEGRATION USING PERA

As has been emphasized repeatedly in this paper, the architecture is only a model or framework showing the relationship of the several steps involved in carrying out an enterprise integration program or a systems engineering project. The second and probably more important component is the associated methodology or step-by-step method of actually carrying out the project or program itself. As also noted, each of the proffered architectures must have such an associated methodology if it is to be valuable to industrial users.

The Purdue Methodology which accompanies the PERA diagram was developed by the Industry-Purdue University Consortium for CIM (Industry-University Consortium, 1992). It has been updated frequently since its initial development to increase its readability and usefulness to the industrial practitioner (Williams, 1994; Williams, et al., 1996).

6.1 The Master Plan -- Key to the Methodology

The key to the Purdue Methodology is that every program of enterprise integration or systems engineering project should start with the preparation of a master plan outlining the specifications of the proposed program or project, its schedule, its benefits, its risks, etc. The master plan should be developed as the product of carrying out steps 1–13 of the program as shown by the numerals in Figure 1 and outlined in Table III, i.e., down to and including the Specification, Functional Design, or Preliminary Engineering Level (all are synonyms for the same type of tasks).

Table III Areas of Interest on the Architecture Framework for Discussing Development and Implementation Aids for Programs and Enterprise Studies (Refer to Figure 1)

Area	Subject of Concern	Types of Aids Available
1.	Identification of Enterprise Business Entity	Feasibility studies, potential gains and benefits vs. costs of proposed business entities to undergo enterprise integration programs. Identification of chosen enterprise.
2.	Mission, Vision, and Values of the Enterprise, operational philosophies, mandates, etc.	Example sets of Mission, Vision and Values expressions from company annual reports or the basic documents themselves. These are valuable to the extent that they are generic. (continue)

Table III (continued)

Area	Subject of Concern	Types of Aids Available
3.	Operational Policies and goals related to the customer Product and Service or Manufacturing goals and objectives, etc., of the Enterprise	Example scopes of the tasks for development and operation of specific processes and plants or other corresponding Customer Product or Service Operations; if for the same process or type of plant, may be directly used or otherwise will be used as an example of types of requirements needed.)
4.	Operational policies related to the Information goals and objectives, etc., of the Enterprise	Generic lists of: Policies and requirements related to such topics as: control capabilities; degrees of performance of processes and equipment; adherence to classes of regulations and laws (environmental, human relations, safety, etc.); compliance in the above to a degree of good community behavior (good neighbor, citizen of the world, etc.); quality, productivity, and economic return goals; etc.
5.	Requirements to be fulfilled in carrying out the Customer Product and Service or Manufacturing related Policies of an Enterprise	Example sets of operational requirements for specific processes and process plants or other corresponding Customer Product or Service Operation; would include general safety requirements, fire rules, etc., that will influence plant design and process and equipment selection later in the program development; OSHA regulations and Fire Safety Underwriters rules.)
6.	Requirements to be fulfilled in carrying out the Information Policies of the Enterprise	Generic lists of requirements necessary to carry out the policies listed in Area 4, probably in the form of scopes of the macrofunctions to be listed in Area 8. (continue)

Table III (continued)

Area	Subject of Concern	Types of Aids Available
7.	Sets of Tasks, Function Modules and Macrofunction Modules required to carry out the Requirements of the Manufacturing or Customer Product and Service Mission of the Enterprise	Lists of generic unit process operations of chemical engineering, or, of the manufacturing features from group technology for the discrete products industry; corresponding requirements for other types of Customer Product or Service Operations.
8.	Sets of Tasks, Function Modules, and Macrofunction Modules required to carry out the Requirements of the Information or Mission Support side of the Functional Analysis	Generic lists of Control and Information Tasks, Function Modules, and Macrofunctions.
9.	Process flow diagrams showing the connectivity of the Tasks, Function Modules, and Macrofunctions of the Manufacturing or Customer Product and Service processes involved	Example of flow diagrams for commonly available processes showing material and energy balances and example process operating procedures are likely types of aids here; corresponding requirements for other types of Customer Product or Service Operations.
10.	Connectivity diagrams of the Tasks, Function Modules, and Macrofunction Modules of the Information or Mission Support Activities probably in the form of data flow diagrams or related modelling methods	Data flow diagram techniques; the generic data flow diagram of the Purdue Reference Model.
11.	Functional Design of the Human and Organizational Architecture. Establishment of the Automatability, Humanizabiltiy and Extent of Automation Lines	Example lists of generally required personnel tasks; auditing methods for skill level determination (required vs. available); methods for cultural status assessment and correction. (continue)

Table III (continued)

Area	Subject of Concern	Types of Aids Available
12.	Functional Design of the Manufacturing or Customer Product and Service Equipment Architecture	Example specifications of process equipment to be required; P and I, Ds (piping and instrumentation diagrams) indicating control systems capabilities necessary to accomplish suggested task assignments and degree of automation indicated, obtained from the current literature; computer-based process plant layout and design optimization programs available from a wide variety of vendors for almost any industry, corresponding examples from other types of Customer Product or Service Operations.
13.	Functional Design of the Information Systems Architecture	Generic representations of typical control and information systems; functional design aids; lists of sensors, actuators, control functions for particular process equipment examples; data base design techniques; entity relationship diagrams; the Purdue Scheduling and Control Hierarchy (Williams, 1988); example hardware architectures from various vendors; networked communications are also very important.
14.	Detailed Design of components, processes, and equipment of the Manufacturing or Customer Product and Service Equipment Architecture	Detailed design techniques for physical processes and equipment from the major handbooks of the various engineering fields; computerized versions of these design methods available from a wide variety of software vendors; corresponding examples from other types of Customer Product or Service Operations.
15.	Detailed Design of the task assignments, skills development training courses, and organizations of the Human and Organizational Architecture	Example lesson plans and syllabi for necessary training courses; example organizational charts for equivalent groups in terms of numbers of people, skill levels and tasks required; team building. (continue)

Table III (continued)

Area	Subject of Concern	Types of Aids Available
16.	Detailed Design of the equipment and software of the Information Systems Architecture	Computer control systems components selection aids from control system vendors; configuration software packages from these same vendors; software project management techniques.
17.	Construction, check-out, and commissioning of the equipment and processes of the Manufacturing Equipment Architecture	Project management techniques such as critical path method. These and related techniques are readily available as computerized project management aids from a wide variety of vendors.
18.	Implementation of organizational development training courses, and on-line skill practice for the Human and Organizational Architecture	Continuation of the work under Area 15 in terms of training and staffing of the members of the Human and Organizational Architecture
19.	Construction, check-out, and commissioning of the equipment and software of the Information Systems Architecture	Project management tools as noted under Area 17.
20.	Continued improvement of process and equipment operating conditions to increase quality and productivity and to reduce costs involved for the Manufacturing or Customer Product and Service Equipment Architecture	Continued improvement of the operation of the plant and its associated manufacturing system involving such techniques as Statistical Quality Control, Statistical Process Control, Total Quality Management, and other related techniques.
21.	Continued organizational development and skill and human relations development training of the Human and Organizational Architecture	Tasks here are continued improvement of workers' skills and training of replacement workers; same aids as for Areas 11, 15, and 18 prevail.
22.	Operating of the Information and Control System of the Information Systems Architecture including its continued improvement	Continued improvement of the operation of the plant and its associated control system involving such techniques and aids available as noted under Area 20 above. (continue)

Table III (continued)

Area	Subject of Concern	Types of Aids Available
23.	Review of mission for enterprise. Planning for revamping and redesign of customer product and service production equipment	Project management tools; auditing software; renovation and recycle techniques.
24.	Review of mission of enterprise. Planning for revamping and redesign of organizational architecture as mission changes; retraining of personnel as new tasks and new skills require	Same aids as for Areas 11, 15 and 18.
25.	Review of mission for enterprise. Planning for revamping and redesign of information systems; preservation and transfer of system information as needed	Project management tools; auditing software; information management tools and techniques.
26.	If decision is made to scrap Customer Product and Service Plant and Equipment, dispose of physical equipment in ways which optimize economics without major injury to environment	
27.	Dispose of Information Systems and Control equipment in ways which are benign to the environment while pursing best related economics	
28.	Take necessary legal steps to dissolve charter of former enterprise. Complete reassignment of any remaining personnel	

Figure 16 shows the relationship of the master plan to the PERA structure as noted above. It also indicates its major uses, those of: (a) a vehicle for final evaluation and approval of the overall program by management, and (b) the means for supplying the detailed design phase personnel with the data (specifications) they need for their tasks. Figure 17 indicates the types of personnel involved at each stage or phase of the life cycle's progress. The methodology manual goes into considerable detail concerning the identity, knowledge or training, tasks involved, etc., for these personnel (Industry-

University Consortium, 1992; Williams, 1994; Williams, et al., 1996). Approval of the Master Plan represents the last decision point for Management before very major monetary expenditures are made on the project such as Detailed Design, Construction, etc., will entail.

6.2 Implementation -- The Work After the Master Plan Is Approved

Once the master plan, and correspondingly the overall project, are approved by management, the major work of detailed design, construction and eventual operation of the integrated enterprise can proceed. Note that personnel numbers and project costs will increase dramatically at this point compared to work earlier in the life cycle (developing the master plan, etc.). Figure 18 indicates the types of information, tools, computer programs, other work aids, etc., available at each phase. Table III uses the numbering of Figure 1 to lay out the tasks and the respective tools and work aids at each node, phase, box, and other location in the life cycle as illustrated by the PERA diagram.

Many companies, such as Fluor Daniel (Rathwell and Williams, 1996), have developed elaborate Work Benches composed of suitable computer-aided and automated design tools, optimization programs, drafting, databases etc., to organize and automate these steps as much as possible to reduce the necessary human input. These can be readily illustrated by the architectural diagrams as noted in (Rathwell and Williams, 1996).

7 OTHER USES OF THE ARCHITECTURE

As noted in Concept 11 of Table I, the life cycle diagram applies to any enterprise and indeed any systems engineering identifiable entity. This was first pointed out by Bernus and Nemes (Bernus and Nemes, 1994a, 1994b, 1996) in their definition of GERAM, the generic enterprise reference architecture and methodology being developed by the Task Force. By definition, this must be applicable to any complete architecture. Bernus and Nemes defined four classes of life cycles to illustrate the concept. These are:

1. The Strategic Enterprise Management Process Life Cycle.
2. The Enterprise Engineering/Integration Process Life Cycle.
3. The (Manufacturing) Enterprise Life Cycle.
4. The Product Life Cycle.

They noted that Enterprise 1 develops the requirements for Enterprise 2 which plans, designs, and constructs Enterprise 3, the Manufacturing Plant in this scenario. Enterprise 3 in turn designs and produces the product which might have been the ultimate goal of Enterprise 1. Figures 19-23 use the PERA diagram to illustrate these principles. The reader should note that the life cycle diagram is here used to represent the entity or enterprise itself. Outputs or products of the enterprise are considered to emanate from the operations layer or phase. Inputs go into whichever phase needs them for its current task. Note also that the PERA diagrams in Figures 19-23 are reversed from the earlier ones, i.e., the mission is on the right and information is on the left. This allows a simpler flow of information and material between the diagrams in the figures. This makes absolutely no difference in the meanings of the PERA subdivisions involved.

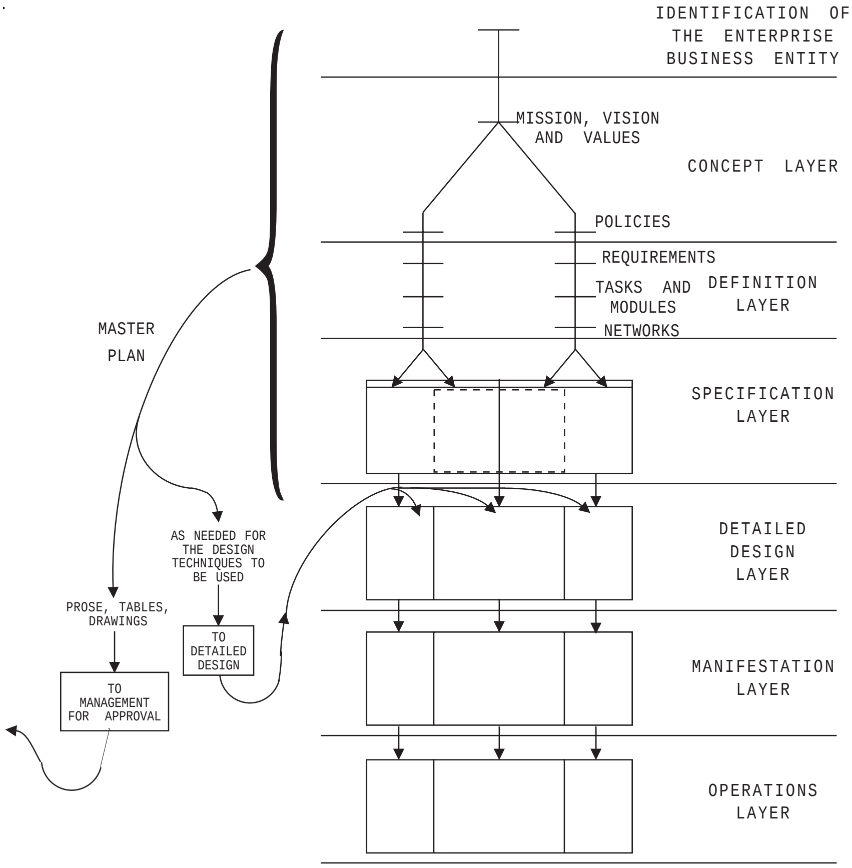


Figure 16 The place of the master plan in the PERA structure

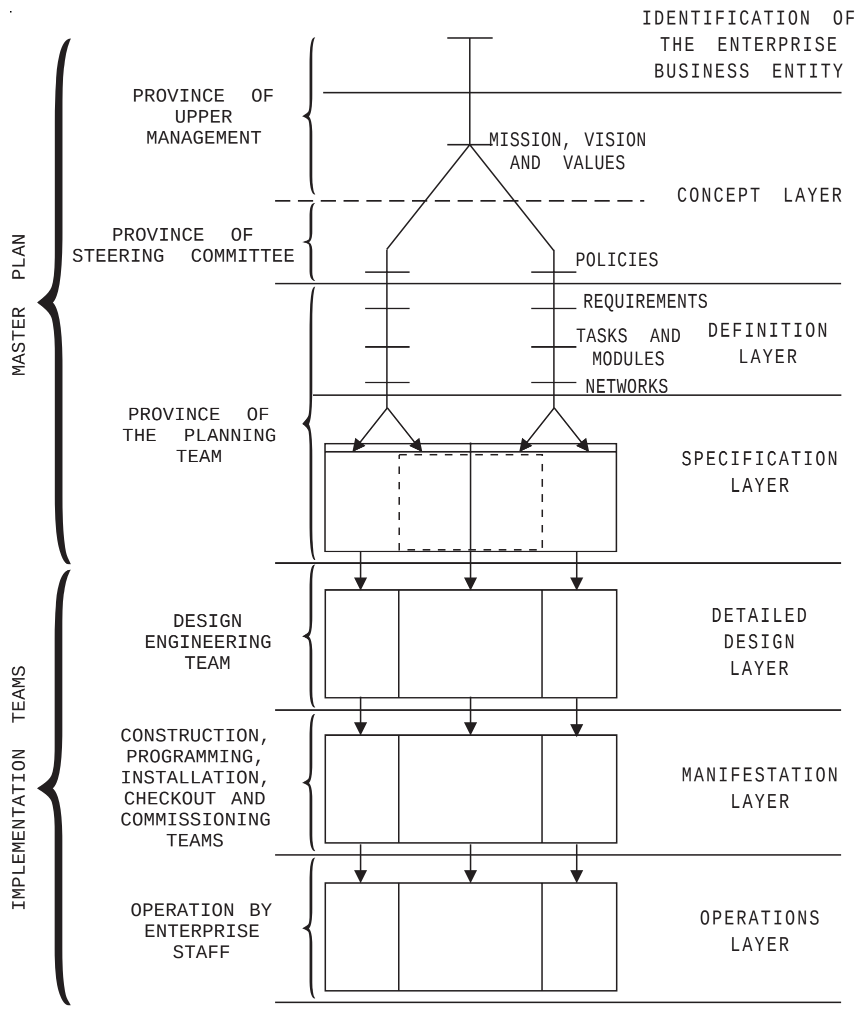


Figure 17 Who carries out the tasks involved

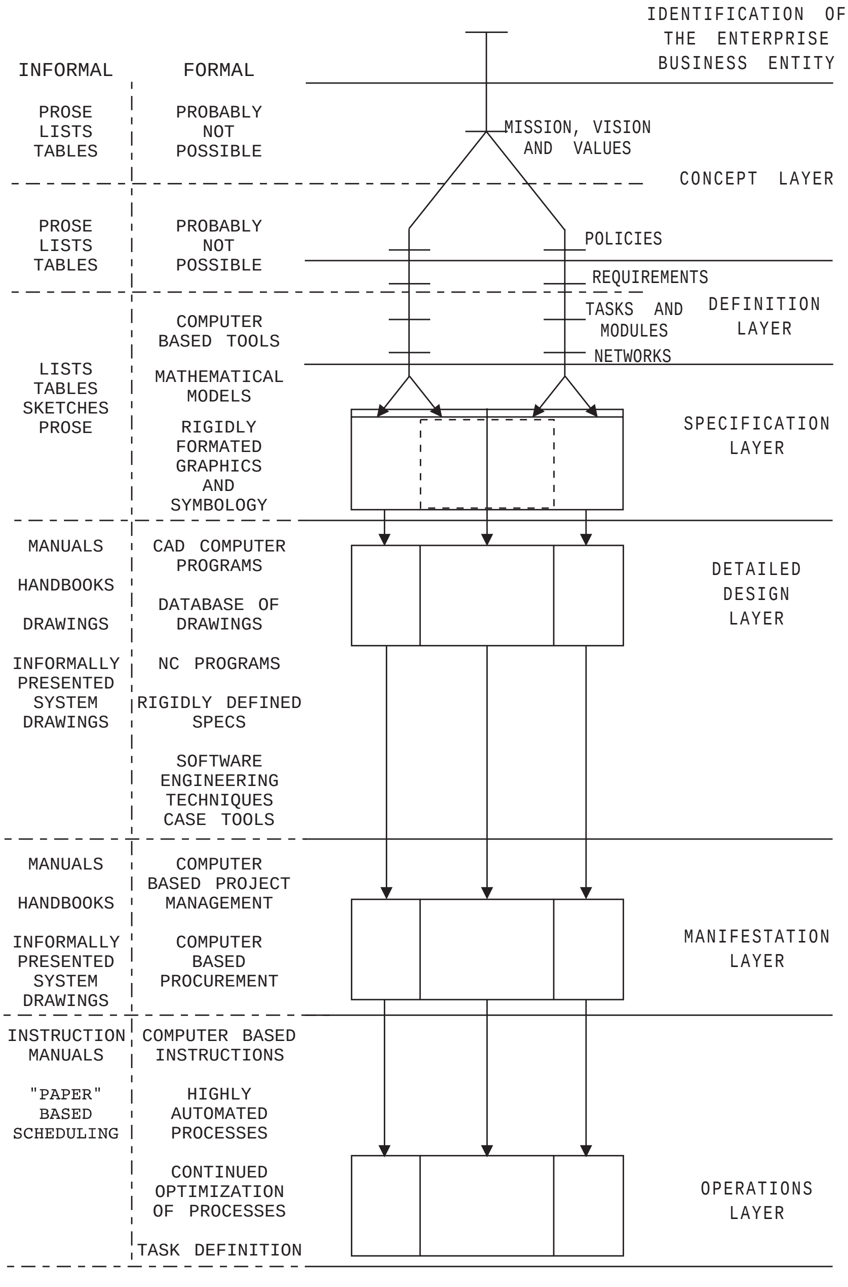


Figure 18 Types of models and tools involved at each phase of the life cycle

Figure 19 shows that the Strategic Planning Entity (Enterprise 1) produces the Mission, Vision and Values of a subsidiary enterprise as its product -- i.e., exiting from the operations layer upon request from the enterprise identification level of Enterprise 3. Figure 20 similarly shows how Enterprise 1 establishes Enterprises 2 and 3. Enterprise 2 designs and produces Enterprise 3 based on requests from Enterprise 1.

Figure 21 shows that a methodology document like the Purdue Master Planning Guide (Industry-University Consortium, 1992; Williams, 1994a; Williams, et al., 1996) is produced by a Number 2 Enterprise to help the development of the Number 3 entity.

Figure 22 shows the process of design and development of a manufactured product, here a vehicle used for freight hauling. Enterprise 3 (the Manufacturing Plant) will design and produce the vehicle (Enterprise 4) with the help of requirements from the customer who is purchasing and using the vehicle (Enterprise 5).

Figure 23 shows a genealogical tree of enterprises. Note the interactions between the several enterprises. Note also that the type of customer interaction discussed in Figure 22 could also arise here but is not shown in the interests of clarity of the diagram.

The architectural diagram has also been used to illustrate many other aspects of the enterprise such as interfaces in the development processes and in the enterprise itself (Williams, 1988; Williams, et al., 1991; Li, et al., 1994; Williams and Li, 1995), the dynamics and stability of the design process (Rathwell and Williams, 1996), to compare and evaluate architectural proposals (Task Force, 1993; Williams and Li, 1995; Bernus and Nemes, 1996), enterprise planning and market studies (Rathwell and Williams, 1996), among many others.

8 STANDARDIZATION OF ARCHITECTURES

The Task Force on Architectures for Enterprise Integration early in its work decided that the standardization of a single architecture would be impossible due to the proliferation of them in the literature, their varying forms and the fact that these different forms can show different aspects of the enterprise and thus give new insights into the enterprise engineering process.

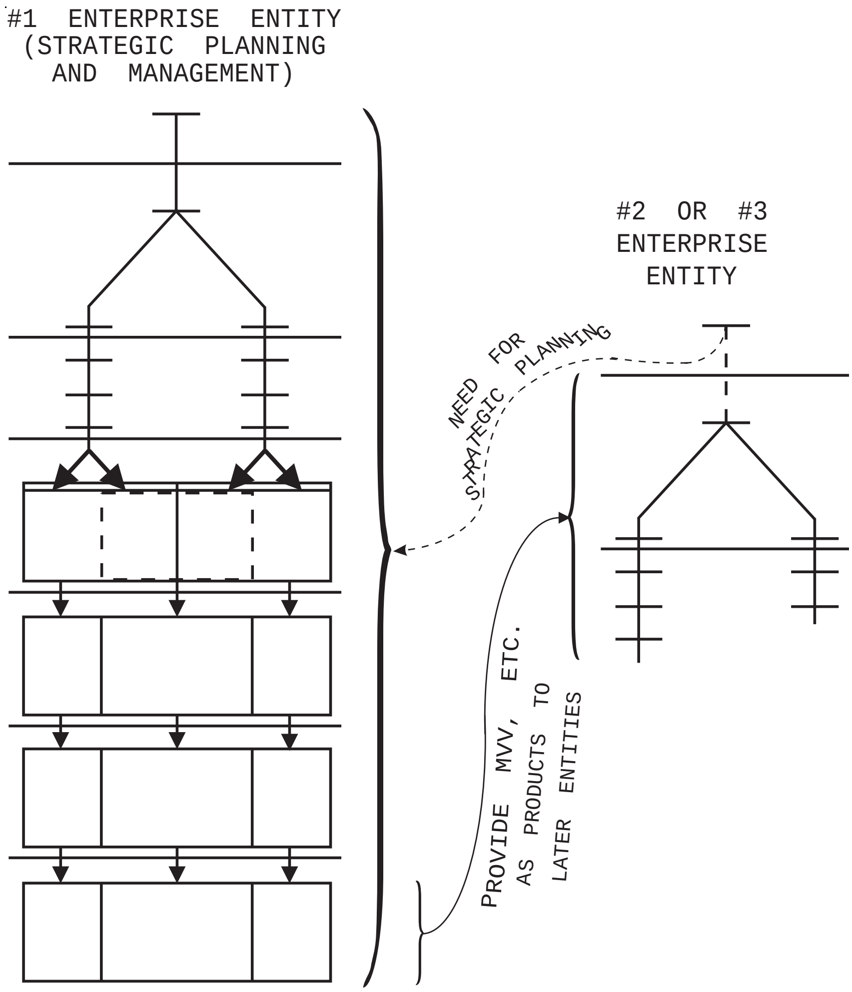


Figure 19 Relationships between the strategic management enterprise entity and the engineering or manufacturing enterprise entities

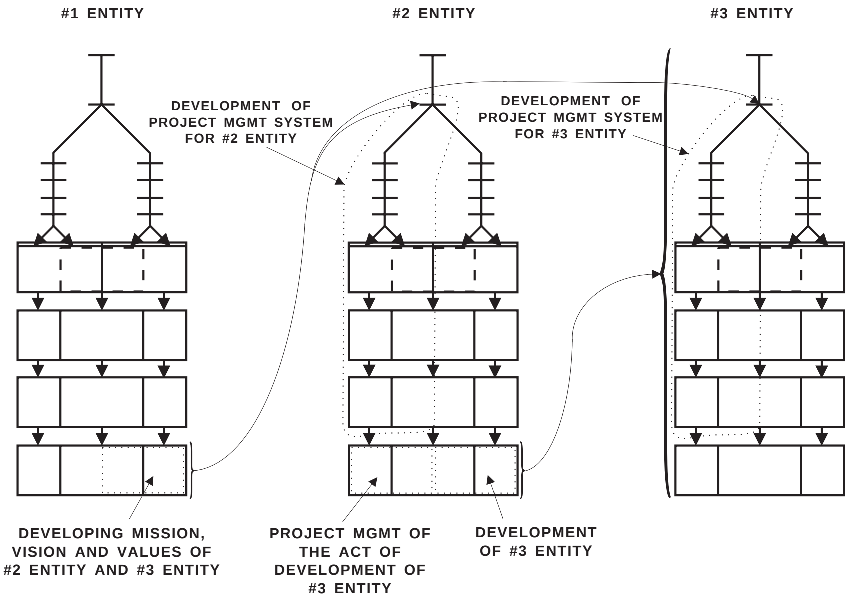


Figure 20 Development duties of #1 and #2 enterprise entities

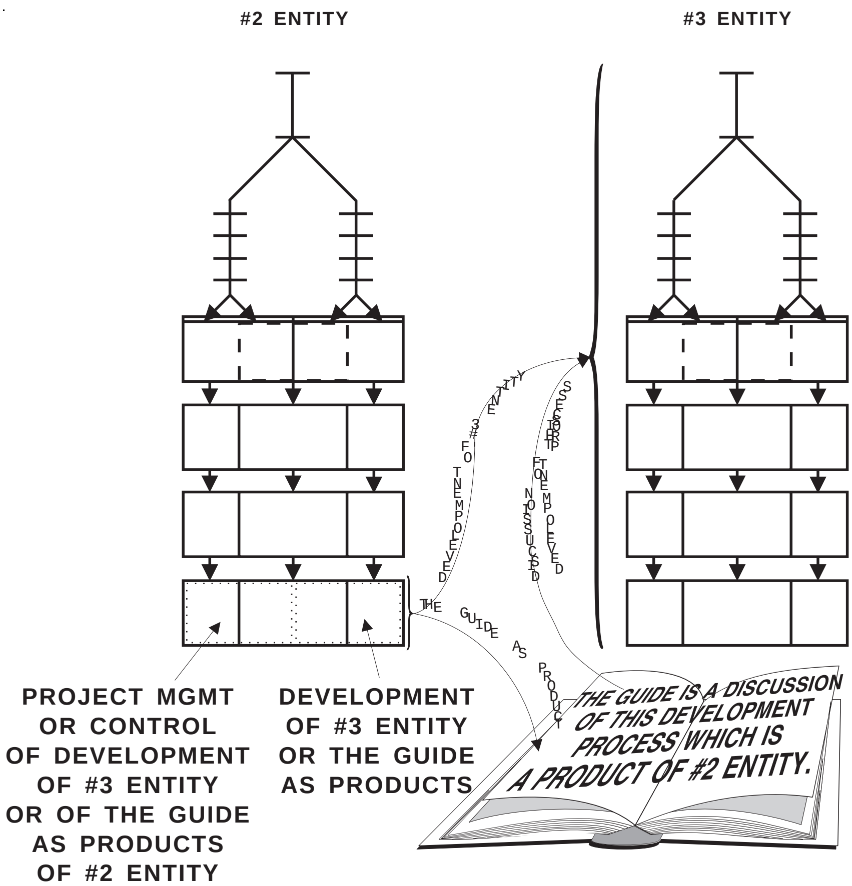


Figure 21 The Purdue Guide as a product of #2 enterprise entity

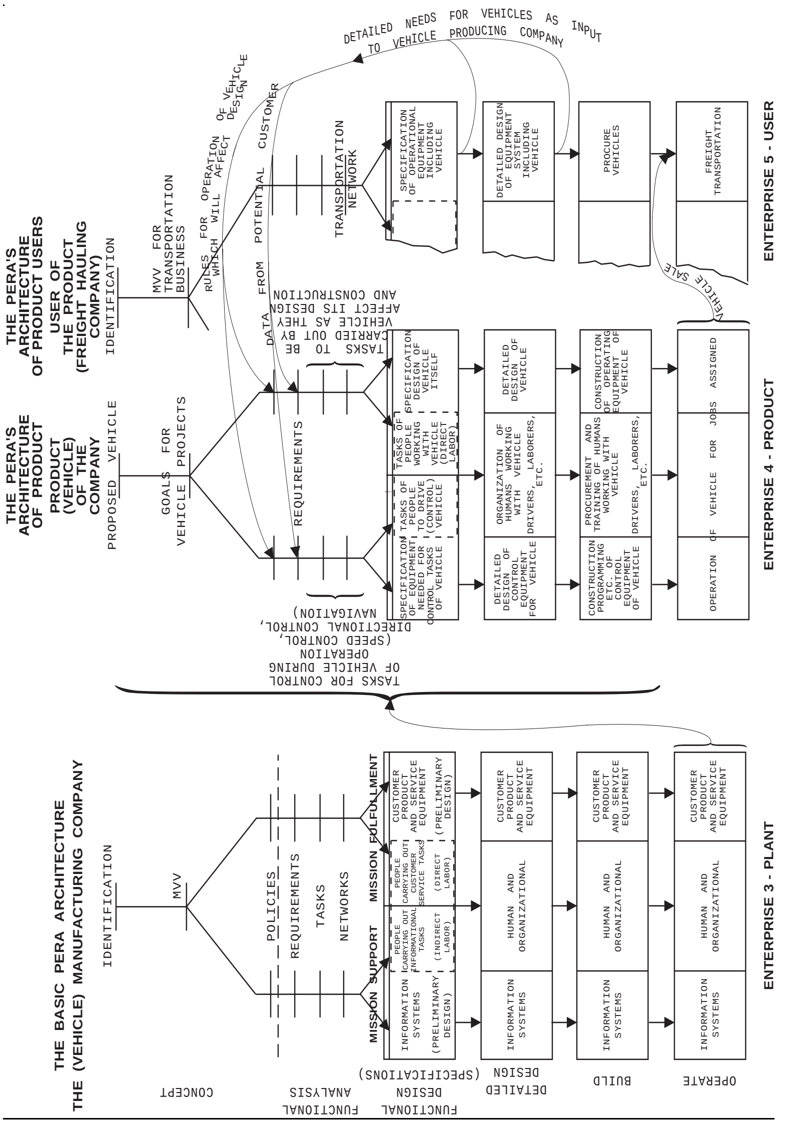


Figure 22 Users' input to a product development process carried out by the manufacturer of the product

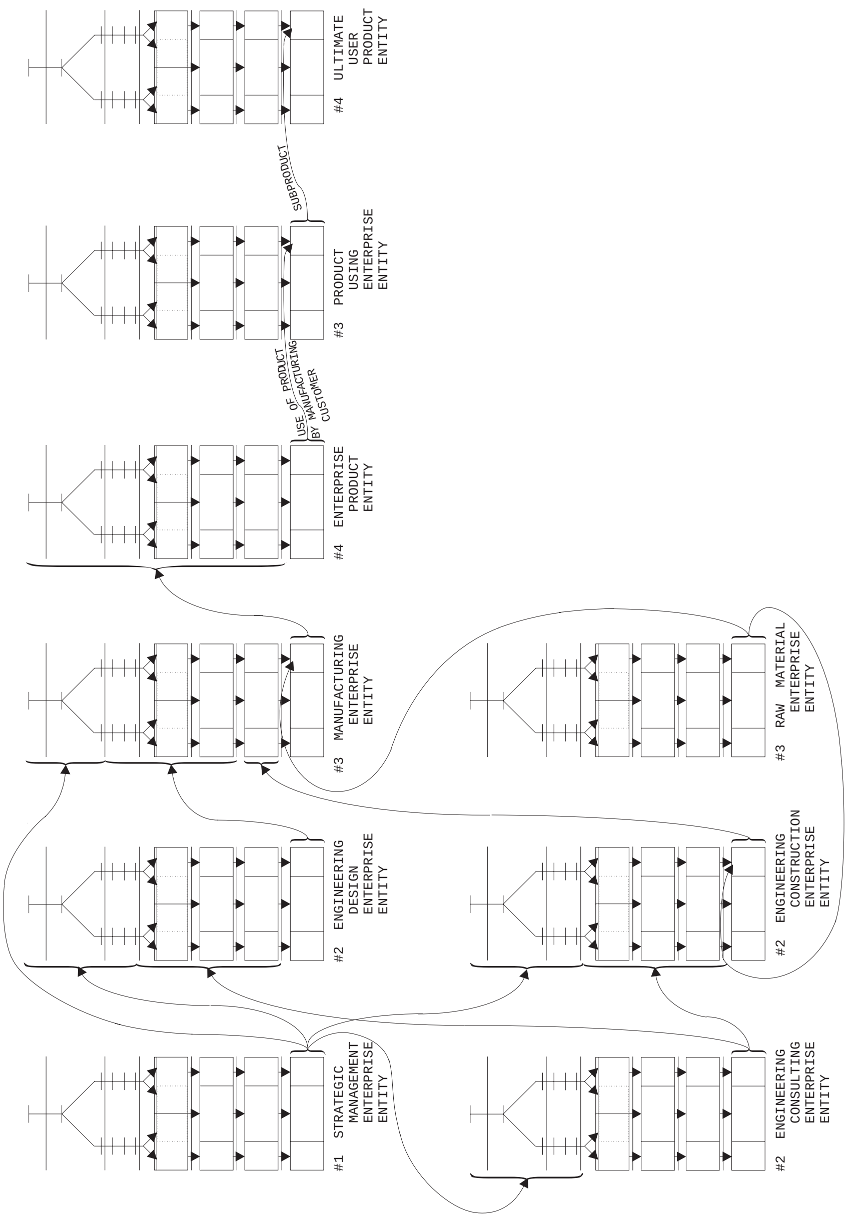


Figure 23 A genealogical tree of enterprise entities

Instead, the Task Force has cooperated with ISO/TC184/SC5/WG1, which has a similar mission to that of the Task Force, to develop a set of requirements for the generic enterprise reference architecture (GERAM) as a class. In other words, any architecture now developed or which may appear in the future could claim the status of a GERAM if it fulfilled the given requirements for capabilities, etc. This proposal has (September 1996) been accepted by ISO for study toward its acceptance as a standard. Table IV presents the proposed requirements list (ISO, May 1996).

9 CONCLUSIONS

As has been shown here, the field of architectures for development of enterprise reference systems has developed very rapidly in the past few years. It has branched out from the relatively restricted view of discrete manufacturing to encompass the whole world of systems engineering projects of which CIM and even enterprise integration engineering are only a very small part.

These architectures have also shown their capabilities for illustrating many aspects of and answering numerous questions about enterprises in general which were not even dreamed of by the early practitioners of CIM.

Industrial personnel who have made extensive use of the Purdue Enterprise Reference Architecture and the Purdue Methodology (PERA) believe it to be important for the following reasons:

1. It provides a full "life cycle" for the facilities being developed in the company's projects.
2. It provides a means for handling human and organizational factors inherent in these projects and in the company's approach to these projects.
3. It presents a "phased" approach to reduce rework in carrying out projects.
4. It provides an understanding of the dynamic interfaces between the many disciplines of engineering and management working on a particular project.
5. It provides informational models of each phase to improve understanding and to monitor the work in progress.
6. Perhaps best of all, the PERA diagram looks intuitively correct and presents the life history in a way which follows the conception which most engineers in industry have of their plants and companies.

Each of these capabilities were more successful than the corresponding ones available from previous methods or were entirely missing from those earlier methodologies.

Such capabilities would be shown by any Enterprise Reference Architecture which fulfilled the GERAM Requirements listed under the Standards section just above.

In common with all areas of technology today, it is certain that this field also will continue to develop with new applications and new uses for the technology as it matures.

Table IV Statement of Requirements for Enterprise Reference Architectures

Requirements (as envisaged by the IFAC/IFIP Task Force) which must be fulfilled by a candidate enterprise reference architecture and methodology for it to be considered as a GERAM compliant architecture.

I. Important definitions related to these requirements for the GERAM class of Enterprise Reference Architectures:
   1. GERAM (The Generalized Enterprise Reference Architecture Methodology) is a class of enterprise architectures and their associated methodologies as developed by the IFAC/IFIP Task Force on Architectures for Enterprise Integration in their work during the period 1990-1996.
   2. An Enterprise can be any entity for which a definite mission can be defined. This term must include such related terms as extended enterprise, virtual enterprise or any other relevant terms.
   3. An architecture can be defined as a definition (model) of the structure of a physical or conceptual object or entity. Thus there are two and only two types of architectures which deal with enterprise integration. These are:
      a. A type 1 architecture deals with the structural arrangement (design) of a physical system such as the computer control system part of an overall enterprise integration system; and
      b. A type 2 architecture deals with the structural arrangement (organization) of the development and implementation of a project or program such as an enterprise integration of other enterprise development program.

These requirements will deal only with type 2 architectures.

II. A candidate enterprise reference architecture and methodology for consideration as a GERAM (herein to be termed candidate architecture)must be a complete architecture and methodology, it must cover all of the details of the life cycle of any enterprise, entity or system from its initial concept throughout all aspects of its life history until and including its operation and final disposal. In this statement, completeness means that human factors requirement VII), customer product and services (requirement III) and information systems all must be considered.

(continue)

Table IV (continued)

III. The candidate architecture must not be confined to any specific class or type of systems (discrete manufacture, information systems, CIM, etc.), e.g., it should be capable of handling the description and development of any conceivable enterprise, entity or system.

IV. The candidate architecture must be able to incorporate, present and utilize all of the useful capabilities of any and all pertinent type 2 architectures. Thus, it should contain the total capability of all type 2 architectures proposed by the Task Force and others.

V. The methodology associated with the candidate architecture must be able to provide all the necessary guidelines and management techniques for the initiation and pursuit of a project or program of development and operation of an enterprise or entity.

Members of the GERAM class of enterprise reference architectures and methodologies need not be based on any one single methodology and its accompanying architecture or framework. There are potentially many different methodologies and/or frameworks which might be used for it. The primary consideration should be total applicability and total capability in relation to these requirements.

Other necessities may require that any combinations of suitable frameworks and methodologies adequately presenting the capabilities of a GERAM may be used by different user groups. CIMOSA, GRAI-GIM, and PERA (for example) may suitable modify their current architectures (frameworks) and methodologies to satisfy the requirements of GERAM.

VI. The framework or overall graphical form of any member of the GERAM class of enterprise reference architectures and methodologies should be able to assist users in the interpretation and use of the associated methodologies of that candidate architecture. It is recommended that this be done by showing graphically the place and relative applicability of:

1. Computer-based tools of all types helpful to the user;
2. Modeling languages applicable in all areas of the life cycle;
3. Generic and partial models of the subject enterprises;
4. Generic modules (standardized implementation components -- software and hardware) which might find wide use in implementation in many industries and other application areas;
5. Ontologies which can describe the overall requirements for these systems. Ontologies should be described in text form and informal representations;
6. Project and task interfaces, i.e., intraphases relationships;
7. All of the life cycle tasks of the enterprise (concept, design, development, manifestation, operation and disposal is one such list) including interphase relationships.

(continue)

Table IV (continued)

VII.	The candidate architecture for consideration as a GERAM must be able to show the place of the human in all aspects of their involvement in the enterprise; in terms of the tasks carried out wholly or initially by humans; in terms of their interaction with information systems or mission fulfillment components of the enterprise; in terms of necessary skills and other requirements for task execution, the skills themselves, training, working conditions, safety, compensation and benefits, social factors, etc.; human organizational structures; and all other factors vital to the well-being of the enterprise and its human staff.
VIII.	The candidate architecture for GERAM should present a standardized glossary for use in enterprise integration engineering and other systems engineering efforts and provide a semantics and syntax to promote overall understanding in projects and other cooperative efforts in this area or provide reference to another suitable glossary to which it complies.

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