Dynamic Process Simulation for the Design of Complex Large-Scale Systems with Respect to the Performance of Multiple Interdependent Production Processes

by

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Submitted to the Departments of Civil and Environmental Engineering and Mechanical Engineering in partial fulfillment of the requirements for the Interdisciplinary Degree of

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ABSTRACT

This research developed a methodology to assess the design of complex large-scale products with respect to the performance of their production processes. In complex large-scale projects, physical and functional relationships among the product systems and components, along with concurrency and co-location of their production processes, generate inter-system process dependencies that drive the relative production rates among the systems. The methodology links the complexity of the product to the complexity of the production process at the level of detail of the single component and task to model the impacts of inter-system process dependencies on production performance. This detailed focus makes the methodology highly responsive to changes in design and technology and able to capture primary, secondary and tertiary impacts of change on production performance.

Based on the methodology, a dynamic process simulation model has been developed to systematically assess different combinations of design and technology alternatives across multiple dimensions of production performance. Performance measures include project duration, costs, resource utilization and index of workers' exposure to dangerous conditions.

Simulated scenario testing based on actual data from a construction project, the renovation of Baker House (MIT building W7), demonstrates that 1) inter-system process dependencies strongly influence production performance, 2) these links build their dynamic effects on production performance at the detailed task and component level, and 3) the nature of the links and their spatial and temporal location vary as changes are introduced in the design and in the production specifications.

One important consequence is that the specification and optimization of the production processes for product systems and components as separate from one another leads to solutions that may be sub-optimal for the performance of the whole project. In addition, the specification and the representation of complex production processes at the aggregate level fails to capture important impacts of design and technology changes and, thus, leads to inconsistent duration and cost estimates.

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CHAPTER 1 : INTRODUCTION AND PROBLEM STATEMENT

1.1 Introduction

This research focuses on the design of complex large-scale products and studies how the design specifications in combination with the particular choice of production means and methods influence production performance.

Complex and large-scale are product attributes that identify a wide range of products including, for instance, ships, aircrafts, industrial plants, and occupied facilities. In these examples, complex indicates that the product is composed by multiple interdependent systems, such as structural systems, enclosure systems, plumbing systems, and electrical and communication systems, that need to fit together and ultimately function as a whole. Large-scale indicates that the size of the final product is much larger than the size of its constitutive parts and components. The design of complex large-scale products involves the detailed specification of the number and type of components and the detailed configuration of their layout for each of the product systems. A typical feature that stems from the combination of complexity and large scale is that the product systems are physically and functionally related to one another and, thus, their parts and components need to be configured together in order to meet the desired objectives of product performance in use. In the examples provided, for instance, the layout of the service systems such as electrical and communication systems, or plumbing systems is tied to the type and location of the respective usage points, which depend on the internal partition and allocation of space within the product as a whole. Location and type of the usage points drive not only the specific configuration of the respective system layouts, but also the level of coordination in space and in time that is required during their installation. Spatial accessibility and safety of the workers are examples of the requirements that limit the relative production rates in the installation of these two types of systems and, thus, make the respective installation processes interdependent. In the most general case, it is the combination of technical, logical, regulatory, and resource constraints that drives the relative production rates for the different systems of complex large-scale products. In such a sense, the realization of complex large-scale products consists of multiple interdependent processes. Aspects of project performance such as overall duration and labor costs strongly depend on the relative production rates among the systems, and, thus, make inter-system process dependencies important drivers of production performance.

This research establishes a methodology for the design of complex large-scale products that accounts for the overall performance of their multiple interdependent production processes at the early stages of design. The methodology explicitly captures the complexity of the production process and maps it to the complexity and scale of the product. While the underlying assumption for current design theories is that each subsystem or component of a product can be produced independently from the others, this research studies the reality of complex interdependent systems and processes with attention to their physical, functional and logical links.

Specifically, the physical and functional links among the product systems that are specified by the design translate into dynamic production process requirements and constraints. These process requirements and constraints, which include technical, logical and regulatory specifications, reflect the particular choice of systems included in the whole product. They are a function both of the particular combination of system types and of the choice of layout, size, and product usage. Resource availability introduces additional inter-system process requirements and constraints.

Inter-system process requirements and constraints determine the rate of progress (in space and by unit) that can be made on the production of one system based on the current progress status of other systems with respect to specific activities pertaining to their installation. For instance, a built facility can include a steel structure, panelized exterior enclosure, and a choice of service systems (including domestic plumbing, electrical and communication wiring.) The exterior enclosure, as well as the rough distribution lines for the service systems, cannot be installed on a given floor until the concrete slab has been poured on top of the decking sheets on that floor. This research examines the effects of these inter-system process dynamics building from the detailed task and component level to assess the performance of multiple interdependent production processes.

1.2 Design for the Performance of Multiple Interdependent Processes

The generation of design alternatives and the selection of one particular design among them require the ability to discriminate among alternatives on the basis of chosen measures of performance. Production performance in this work is addressed across multiple dimensions that include cost, duration, resource utilization, and workers exposure to dangerous conditions at the whole project level.

While the performance of the product in use and the feasibility of the production processes with respect to specific production capabilities can be determined based exclusively on the detailed design specifications, the performance of the production processes is determined by the combination of both the design and the production specifications for each of the constitutive systems. Aspects of performance such as project costs, duration, resource utilization, and workers exposure to dangerous conditions, in fact, are influenced not only by the design specifications for each of the product sub-systems and components, but also by the choice of production means and methods.

In complex large-scale projects, design does not automatically specify production means and methods. While the detailed specification of the design determines the general nature of the activities and tasks to be performed, it leaves production means and methods to different parties. For instance, in the realization of a large industrial or occupied facility, different portions of the production process are sub-contracted to different organizations that are responsible for completing their job within specified deadlines, but are otherwise free to choose equipment, resources and methods. Typically, the erection of the structure is contracted to a specialized organization, the installation of the electrical wiring to a different one, and the installation of the domestic plumbing, hot water heating, and fire protection systems may be contracted either to three separate organizations or, alternatively, to a single one.

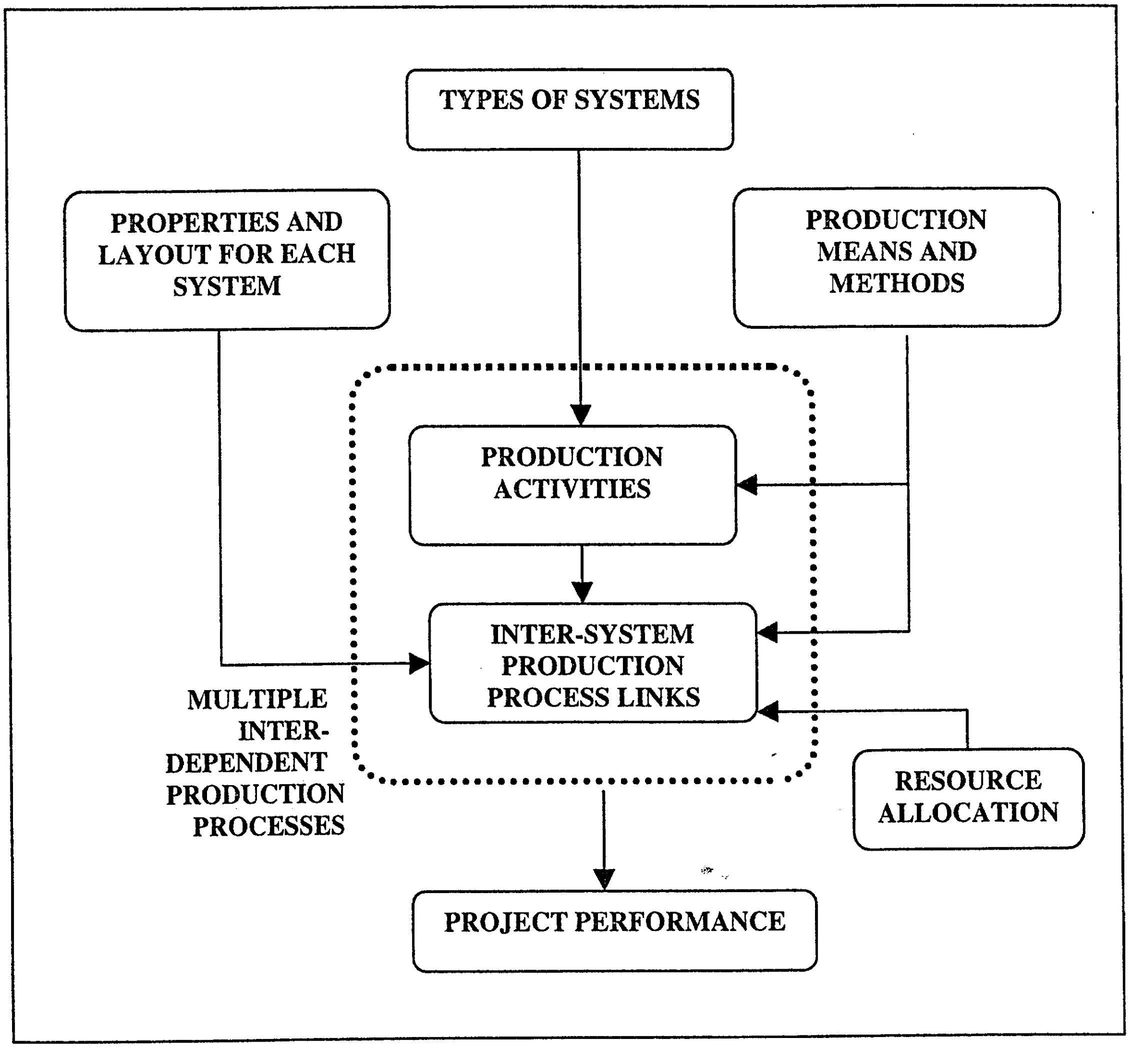


Figure 1.1 : Relationships between Project Specifications and Performance

Figure 1.1 shows that the different levels of project specifications impact project performance by influencing different aspects of the production process. The specification of the types of product systems determines the general nature of the production activities, and through them, also determines some of the logical, technical, and regulatory inter-system process links. The choice of production means and methods specifies the specific types of production activities and introduces additional inter-system process links. The detailed specification of the product systems, in terms of number and type of parts and components and system layout, introduces spatial and accessibility constraints that influence inter-system process links. Finally, the allocation of resources, in terms of number of workers and pieces of equipment per crew directly impacts project performance by constraining the production rates for each of the systems. The combination of design elements (e.g. number and types of activities), activity-types, inter-system process links, and resource allocation completely define relative project performance.

In response to the identified set of performance drivers, this research develops a systematic approach to accommodate the variability of both design specifications and production means and methods during design.

The problem of selecting among alternatives based on their performance during the production process is tied to the ability to assess the impacts of changes simultaneously with respect to both design and production means and methods. Design and production alternatives, in fact, represent variations from a standard or baseline solution, and they do represent changes, whether they are forms of "known" change (i.e.

already tested in other projects) or innovations (i.e. completely new, or never applied in the same context before).

The main hypothesis for this research is that production process performance is strongly influenced by the presence of inter-system process links. Most importantly, the nature of the links and their spatial and temporal location vary as changes are introduced in the design and in the production specifications. Therefore, the study of change in complex large-scale systems cannot neglect the presence of these links in the assessment of design and technology alternatives with respect to production process performance.

The second research hypothesis is that inter-system process links build their dynamic effects on production process performance at the level of detail of the single component and task. Since inter-system process dependencies build their effects at such level of detail, the representation of the processes either at the aggregate level (such as Critical Path Method scheduling), or on a "by-system" basis (found in systems and concurrent engineering) can be misleading and can produce, respectively, coarse estimates of performance and solutions that can be sub-optimal for the performance of the whole. As a result, only the representation of inter-system process links at the task/component level can capture the secondary and tertiary impacts of change that strongly influence overall project performance levels and would otherwise be lost by other means.

The methodology developed in this research is based upon a whole-product approach that captures complexity in its finest elements of detail and integrates these elements in time and space to determine the performance of the project as a whole. The whole-product approach focuses on inter-system process links to track primary, secondary and tertiary effects of design and technology changes across the performance of multiple interdependent processes.

The effects of changes in complex large-scale projects involving thousands of components and interdependent tasks are difficult to track across multiple systems that use different spatial units of progress without a systematic approach. This research uses dynamic process simulation to track the impacts of changes on production process dynamics and evaluate the performance of alternative combinations of design and technology for complex products.

Simulated scenario testing based on actual data from a construction project demonstrates the validity of the research hypotheses and the viability of the methodology in design and project planning applications.

1.3 Summary

This research develops a methodology to assess the design of complex large-scale systems with respect to the performance of their production processes. The methodology accounts for the variability of the design and of the production specifications to assess the production performance of different combinations of design and technology alternatives. The focus is on the detailed design elements and production activities, where inter-system process dependencies build their effects on performance. The research develops a dynamic process simulation tool to track the detailed effects of process dynamics at the system, at the inter-system, and at the whole product level (e.g. primary, secondary and tertiary impacts). Simulated scenario testing based on this tool demonstrates that 1) inter-system process dependencies strongly influence production performance in the realization of complex large-scale systems, 2) the nature of the links and their spatial and temporal location vary as changes are introduced in the design and in the production specifications, and 3) the links build their dynamic effects on production performance at the level of detail of the single component and task.

The following chapter presents the theoretical background of concurrent engineering and systems engineering, which, respectively, set the basis for the integration between the design and the production processes, and formalize the study of complexity. The chapter also includes an overview of project management tools and methodologies that are typically used in the estimate of performance measures, such as duration and cost, for complex large-scale projects. Chapter 3 describes the theoretical approach for this research that enables the systematic assessment of design and technology alternatives with respect to their performance across multiple interdependent production processes. Specifically, the chapter includes the formalization of the elements of process dynamics that drive the relative production rates in complex large-scale projects, and the development of the logic for the simulation of multiple interdependent production processes. Chapter 4 presents the research methodology. The research steps include the development of a simulation model for the representation of multiple interdependent construction processes, the definition of a set of significant performance measures, and the design of a set of experiments to analyze the impacts of inter-system process dynamics on project performance. Chapter 5 presents the analysis of 10 alternative scenarios based on actual data from a construction project, the renovation of Baker House

(MIT Building W7). The scenarios explore alternatives in process constraints, alternative in construction means and methods, and alternatives in design to establish the role of inter-system process dynamics in the presence of change. The performance measures provided by the simulation model are analyzed and compared across the different scenarios. The results clearly demonstrate that the specification and the representation of complex production processes at the aggregate level fails to capture important impacts of design and technology changes that influence project performance. The results also demonstrate that, in light of the effects of inter-system process dynamics, the specification and the optimization of the production processes for product sub-system and components, as separate from one-another, leads to solutions that may be sub-optimal for the performance of the whole project. Finally, chapter 6 summarizes the major contributions of this work and identifies opportunities for future research.

CHAPTER 2 : THEORETICAL BACKGROUND

2.1 Introduction

The accurate assessment of production performance relies on the ability to account for the complementary effects of design specifications, production means and methods, and resource allocation. In the design of complex large-scale systems for the performance of multiple interdependent processes, the assessment of different combinations of design and technology alternatives translates into three fundamental issues that need to be dealt with simultaneously. These are: 1) integration between the design and the production process, 2) complementary complexity of the product and of the production process, and 3) measurement of project performance.

Separate areas of research have addressed these issues individually. While some of their contributions may appear complementary to one another and partly overlapping the objectives of this research, major differences can be identified in the underlying assumptions, in the focus and context of application, and in the objectives. Among these, concurrent engineering integrates the conceptual definition and the detailed specification of the product design with the definition of the production capabilities and the specification of the production processes to address the feasibility and the effectiveness of the design for production.

Systems engineering, in contrast, deconstructs the system hierarchy to identify the functional and operational links among the design elements that define the performance of the product in use. Integration of the design with respect to the functional and operational links for the whole product ensures the desired levels of performance in use.

Project management tools and methods focus on the dynamic elements of production to estimate project duration and cost for a specified design and with respect to defined production means and methods.

In contrast, the proposed methodology links the complexity of the product to the complexity of the production process to analyze the impacts of design and technology changes on production performance. The approach focuses on product and process complexity at the level of detail of the single component and task to capture the elements of inter-system process dynamics that drive production performance. Integration of the production process for the whole product with respect to the elements of process dynamics provides the means to measure production performance.

2.2 Concurrent Engineering: Integration between Design and Production Process

The ability to develop new concepts and to implement them in the form of new products and technologies in the shortest possible time and at the lowest possible cost has become increasingly important for companies to establish and maintain their competitive advantage (Bower and Hout 1988; Clark and Fujimoto 1989 and 1991; Gupta and Wilemon 1990; Slade 1993; Stalk and Hought 1990; Hartley 1992). The pressure to reduce time to market and the demand for high quality products have led many different companies to adopt integrated approaches to product development. Concurrent engineering (Taguchi 1986; Clausing 1994; Pugh 1993; Yazdani 1997; Yazdani and Holmes 1999; Carter and Baker 1992; Clark and Fujimoto 1989) is the most established design theory on the integration of product life cycle considerations such as producibility, maintainability, and environmental impacts into the early stage decision making, for faster and more cost effective product development (Stalk and Hought 1990; Hartley 1992; Susman 1992; Wheelwright and Clark 1992; Liker et al. 1992). Early involvement of different functions allows designers to anticipate issues and avoid problems that may arise during the downstream stages of both development and implementation (Hartley 1992; Susman 1992; Liker et al. 1992; Hauptman and Hirji 1996; Griffin and Houser 1996; Olson and Walker 1995; Rochford and Rudelius 1992; Ragatz et al. 1997; Wolff 1988; De Meyer and Hooland 1990).

As concurrent engineering has emerged and consolidated as a design philosophy, tools and methodologies have been developed to support its implementation in different industrial contexts. Particularly, in the industrial design field, a whole family of "design for X.", or DFX, approaches has been developed, which translate the concepts of concurrent engineering into design methodologies specific to given downstream activities and costs (Huang 1996). Relevant examples are design for manufacturing (DFM), design for assembly (DFA), design for manufacturing and assembly (DFMA), design for construction (DFC), and design for quality (DFQ). Each DFX approach formalizes a design methodology, which specifically targets the aspects of a product development project which are the most relevant to the overall success of the project, and enables designers to address specific process performance objectives.

In the manufacturing industry, the concept of DFX has primarily focused on the design for the feasibility and effectiveness of the production process. This focus has led to the development of DFM, DFA and DFMA tools that support the simultaneous design and optimization of a product and of the corresponding manufacturing and assembly processes (Boothroyd et al. 1994, Yan et al. 1998).

Significant attention is drawn to "feature-based" models that describe a part or assembly in terms of combinations of standard form features and their topological relationships. Form features, including protrusions such as bosses, ribs, blocks and cylinders and depressions such as holes and slots, can be specified with information such as size, geometry, material, tolerances, and surface finishing that can be directly translated into manufacturing and assembly requirements. Topological relationships between features include adjacency, ownership and interpenetration, and these relationships geometrically constrain feasible processing sequences.

Process planning involves the translation of a part description into instructions for a feasible sequence of operations required to manufacture the part or to assemble multiple parts. Computer-aided process planning (CAPP) supports the generation of feasible production sequences, and their evaluation with respect to the overall production cost, by combining an appropriate representation of the part(s) and a reasoning scheme, in the form of rules or algorithms, for the automatic generation of manufacturing/assembly process plans. For example, the implementation of feature-based CAPP requires the availability of extensive feature information databases, of process information models, and of the appropriate software interface (Ming et al. 1998).

Feature-based models have been successfully interfaced with CAD/CAM systems to generate the set of feasible production processes for individual parts and assemblies (Yan et al. 1998; Zhang and Alting 1994). The manufacturing process can be specified to the level of detail of the tool and the tool-path, thus enabling the designer to predict duration and cost for each manufacturing step. Computer-based CAPP applications have been developed that incorporate environmental impacts of process in process planning (Srinivasan and Sheng 1998). Web-based CAPP environments have been created for the evaluation, selection and optimization of manufacturing processes (Huang et al. 1998).

Recent research in process planning uses expert systems (Tstsoulis and Kashyap 1988) and neural networks (Ming et al. 1997) to recognize part features directly from the drawings and match them to feasible manufacturing processes and corresponding resource requirements (e.g. tools, equipment, and machinery) within specified production capabilities. Appendix 1 summarizes the basic principles and computing mechanisms of expert systems and neural networks in comparison to standard computer programming.

Feature-based models in combination with CAD/CAM systems, expert systems, or neural networks allow the designer to evaluate and compare design and technology alternatives with respect to the performance of their established manufacturing and assembly processes.

One of the underlying assumption, which is valid for the vast majority of mass manufactured goods, is that the process by which each part of a product assembly is manufactured or built, is spatially and temporally independent of the processes by which the other parts are manufactured or built. In other words, the underlying assumption is that the individual parts required to build a product can be entirely manufactured as separate entities, even in different locations and at different times.

This research specifically removes this assumption and explores the case of complex large-scale systems where the complexity of the product (e.g. multiple interdependent parts and components) is matched by the complexity of the process (e.g. multiple interdependent processes and activities). In particular, this research develops an approach to link design to process for the study of production process performance across different design and technology alternatives.

Additional assumptions include that the production stages are fixed in terms of production means and methods and that the resource assignment is fixed for each production stage. These assumptions are well-suited to represent the reality of most manufacturing capabilities and processes. However, in many complex systems/process applications these assumptions do not hold. For instance, in the construction industry means and methods can vary depending on the specific properties of individual parts and components (e.g. size, rigidity, and shape) and on their specific location within the facility (e.g. height of location, and proximity to other components). In addition, individual resources within each crew are typically re-assigned to perform different tasks in different locations throughout the entire duration of the project.

Another major assumption is that design changes map directly to production changes and therefore to production performance. This research removes this assumption and shows that inter-system process dependencies alter the mapping between the design and the production processes as changes are introduced, and therefore there is no direct and predictable reflection of these changes in the measures of production performance.

In addition, significant differences in focus can be identified. While DFM, DFA, and DFMA are primarily concerned with the assessment of the feasibility and effectiveness of the production processes (specified) for a given design, the scope of this research is to analyze the impacts of design and process changes on the efficiency of the production process (not completely specified by design), measured by overall duration and cost.

Within the context of the DFX tools and methodologies, design for construction (DFC) has emerged to address the issues associated with the realization of complex large-scale systems. Along with the other DFXs, DFC specifically focuses on the feasibility for construction of a given design (O'Connor et al. 1994; O'Connor and Tucker 1986; Tatum 1990; Russel and Swiggum 1994) rather than on the performance of a design during construction. In other words, the effort is on whether the design can be constructed, rather than on how much it would cost or how long it would take to build.

While DFM, DFA, and DFMA aim at specifying the optimal production sequence within established production capabilities, DFC does not define the details of the production process. DFC focuses on learning from previous projects and on sharing all the relevant information about a complex project across specific competencies and project phases. In particular, the emphasis is on the development of 3D-CAD models that ensure consistency of design across different functions, on improved communication, and on creating common grounds among the different parties involved in the project to ease progress monitoring and project control throughout the development and implementation phases. DFC, therefore, addresses the organizational aspects of product complexity but does not explicitly consider the construction process and its performance.

2.3 Systems Engineering: Complexity of Products and Projects

The issue of complexity in the design and realization of large-scale systems is explicitly addressed by systems engineering. Systems engineering is a design theory that was developed during World War II and has been widely applied to address the complexity of large-scale systems (Jenkins 1969; Gardiner 1996; Jackson 1997). Although the applicability of systems engineering is not restricted to the development of complex large-scale systems (Gardiner 1996), its early applications, during and immediately after World War II, focused on military and space technology systems, and on industrial systems in the oil, chemical and power generation industries (Jenkins 1969).

Systems engineering deals with the complexity of products and projects by decomposing them into subsystems and components, while keeping track of their functions towards the objectives of the whole (Sage 1977; Beam 1990; Blanchard 1991; Chestnut 19670. Systems engineering views a product, or system, as a set of interrelated components that interact with one another in an organized fashion toward a common purpose (Jenkins 1969; Jackson 1997; Shishko 1995; Hoban and Lawbaugh 1993). The functional interdependencies among subsystems and components of the whole systems are the center of attention of systems engineering. Functional interdependencies determine operational interactions among the subsystems of a product. The product architecture is viewed as a complex hierarchy of subsystems and components linked to one another by functional interdependencies. The product architecture is also referred to as "Product Breakdown Structure" (PBS) (Shishko 1995; Hoban and Lawbaugh 1993). Systems engineering views the product sub-systems and components in the perspective of the whole and in terms of the objectives of the final product/project. In such sense, systems engineering is a "holistic" approach to design. It breaks the product into components and parts to address the issue of complexity and then integrates them back into the whole to meet the system objectives.

The processes by which the product and its components are manufactured and built are also represented in the form of a hierarchy that mirrors the product breakdown structure. In this way, the production process hierarchy is product-based. A one-to-one correspondence is established between the elements of the product hierarchy and the elements of the production hierarchy, where each level in one hierarchy corresponds to the same level in the other hierarchy. Within a given level, each design element in the product hierarchy corresponds to a given task or activity in the production process hierarchy (Figure 2.1).

This type of correspondence is part of a rigorous approach to design and production that is extremely effective in dealing with the complexity of a specific product instance. However, it implies that the design is finalized when the production/realization processes are considered, and makes the correspondence static and deterministic with respect to design and technology changes. It is important to note that the classic theory of systems engineering focuses on the complexity of the product, while it gives little attention to the complexity of the production process.

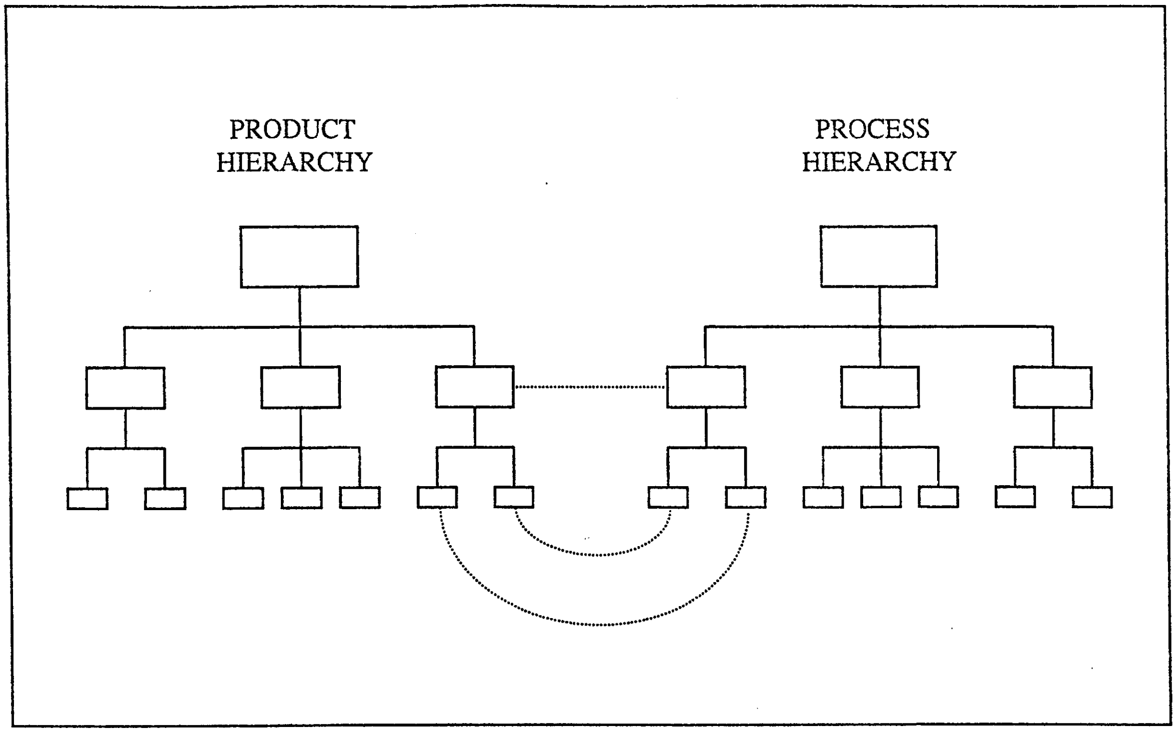


Figure 2.1 : Product and Process Hierarchies in Systems Engineering

The systems engineering approach, along with the concurrent engineering approach, assumes independence of production for each subsystem and component and, also assumes that designers have control over production means and methods. However, in many fields the designers cannot specify production means and methods and thus cannot decompose the product design and the production processes into parallel hierarchies. The systems engineering approach can lead to misunderstandings in its direct applications to the study of change. The static and deterministic nature of the mapping between the design elements and the production activities leads to assume that changes introduced in a particular level and element of the design hierarchy produce changes only in the corresponding activities and tasks at the same level of the production hierarchy. Performance estimates based on this assumption miss the ripple effects that build their impacts at that particular level in the hierarchy, but affect other systems and higher levels as well up to the level of the whole project.

2.4 Project management Theory and Tools: Evaluation of Process Performance in Terms of Overall Project Duration and Costs.

While concurrent engineering and systems engineering provide approaches to link the design to the production process, other methodologies have emerged to handle the dynamics of managing complex projects in real time. Project planning involves the choice of technology and methods, the definition of activities and tasks, the estimation of the required resources and duration for individual activities and tasks, and the identification of interactions among tasks and activities.

Estimates of project cost and duration are usually based on the experience of individual project managers and on their capability of foreseeing the implications of given technology choices for a design which is already fully specified. In the field of industrial design, an accurate project plan constitutes the basis for project budgeting and scheduling. The multiplicity of variables inherent in the realization of complex large-scale systems has led over time to the development of tools and methodologies to assist project managers' decision-making during project planning and execution.

Traditional planning tools like the Quantity Take-Off Method and the Critical Path Method (CPM) are useful for general cost and duration assessments. However, they often fail to capture the complex interactions among the key drivers of production performance such as resources, materials and the environment. In contrast, new methods, such as simulation, can accurately predict the impacts of design and technology choices by representing the actuality of the production processes and their interactions.

2.4.1 Activity Networks as Means of Project Management

Methodologies based on activity networks, such as the well known "Critical Path Method", or CPM, constitute the basis for modern computer-based scheduling and cost-estimating tools. These methods are widely used in many industries (Elmaghraby 1977; Aras and Surkis 1964). CPM, originally developed at Remington Rand and Dupont in the 1950's, is a useful tool to estimate the overall duration and cost of a project. The method arranges major processes into a precedence/sequence relationship. The duration of the individual processes is calculated to generate the overall project schedule based on the duration of the longest path sequence (i.e. critical path) (See and Baker 1974; Moder et al 1983). The specification of the resource requirements by process and of the hourly costs of these resources enables the estimate of production costs in parallel to project duration (Moder et al. 1974; Willis 1986; Mueller 1986). Figure 2.2 shows an example of a simple activity network for the construction of a built facility.

The applicability of CPM-based methods for time and cost estimating during the design of complex large-scale systems is limited by many factors. Each design alternative that the designer wishes to explore requires the complete formulation of a project plan inclusive of all the tasks that must be performed (where tasks are the basis for scheduling of activities and estimating resource requirements.)

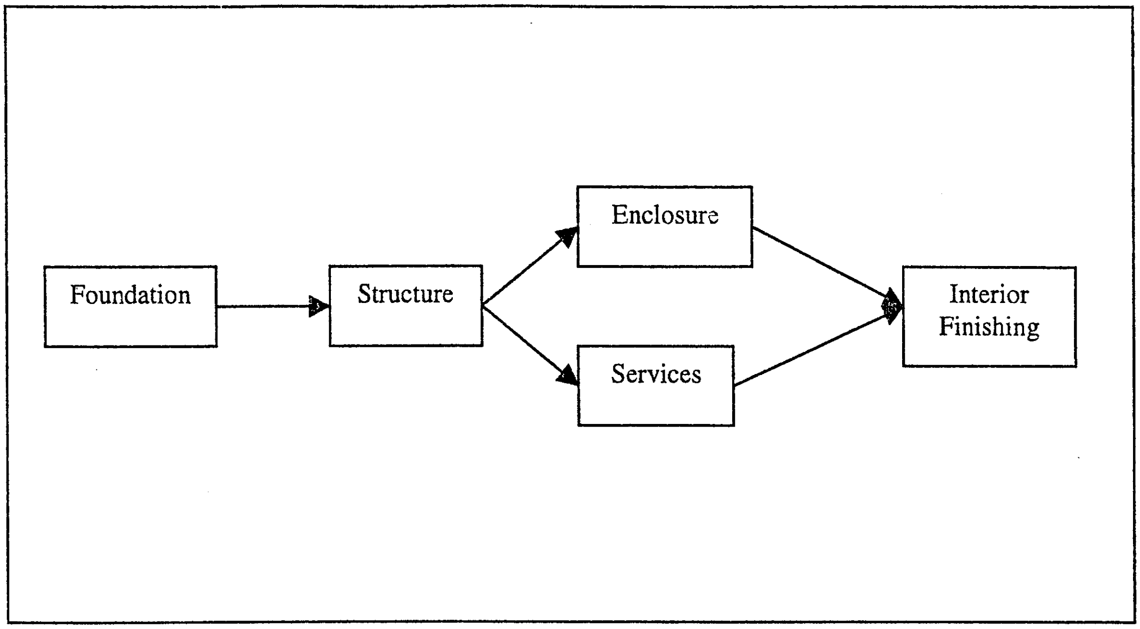


Figure 2.2 : Example of Activity Network for a Built Facility

However, the complete definition of these tasks can become extremely laborious as the complexity and the scale of the product increase (Aras and Surkis 1964; See and Baker 1974; Moder et al 1983; Willis 1986). Construction projects, for example, may involve thousands of tasks, thus making their definition costly and time consuming (Willis 1986; Mueller 1986). Processes are thus rarely split into the constitutive activities and tasks at a fine level of detail. Rather, the activity network is built upon sets of aggregated units which are representative of hierarchies of activities requiring the same type of resources (Willis 1986; Mueller 1986; Hendrickson and Au 1989). Duration and resource requirements are also assigned collectively to the hierarchies of activities rather than to the individual activities and tasks (Moder et al 1983; Mueller 1986; Hendrickson and Au 1989). This aggregated assignment often leads to coarse estimates, and these generalizations focus on primary impacts, rather than secondary and tertiary effects of design and technology choices.

Most importantly, once the activity network is built, precedence relationships among activities are fixed and, therefore, so is the schedule. This excludes any flexibility of the network to design and technology changes and makes the schedule responsive to a specific product only, which is inadequate to the study of changes in either design or production. The duration of each aggregated process is based on estimates of primary impacts. Without access to the detailed level it is impossible to establish whether the introduction of a new type of connection among steel members will change the total time required to erect a particular structure, or whether the new type of connection will have different impacts on the erection time for different structure layouts.

The major drawbacks of activity network approaches are that the project schedule is developed independent of cost estimating, and that the introduction of design and technology changes require the development of a new schedule.

Though widely used as scheduling tool, CPM is not a flexible or accurate planning tool. The deterministic and static nature of CPM presents limitations in modeling the stochastic and dynamic nature of complex large-scale projects. CPM also fails to address the concept of failure and rework, because cycling or feedback within a process is not explicitly recognized. The key assumption is that a percentage increase in the number of resources allocated directly translates in an equivalent percentage increase in production rate.

2.4.2 Process Simulation as Means of Project Management

Discrete event queuing models and graphically based models are the two major types of process simulation models can be found in the construction project management literature. Queuing models, perhaps the most established methods, are particularly useful in representing standardized systems, where activity processing times follow standard probability distributions. As in many manufacturing environments, each activity is visualized as a processing station. Parts and components either wait in a queue or get processed in a station. However, these components are assumed to remain unchanged and do not undergo any transformation as they pass through the different processing stations. In particular, activity processing times are not direct function of the parts being processed but rather are based on predetermined distributions. Queuing models principally try to answer questions regarding processing and queuing times, and mostly aim at optimizing resources allocation and production layout with respect to increasing the process throughput.

Queuing models have found vaste application both in the manufacturing and in the construction industry. Two construction queuing models, CYCLONE and MicroCYCLONE, have set the standard for queuing model simulation of construction environments. The models are incorporated into computer packages, and have been used in several applications, such as a study to identify resource inefficiencies in piping installation (Cheng and O'Connor 1993), and a study to compare the efficiencies of cranes and pumps in the placement of concrete for building slabs and columns (Alkoc and Erbatur 1997).

The CYCLONE packages are written in FORTRAN and provide an environment for the generation of queuing simulation models that are specific to the choice of design and resource allocation. However, a new model needs to be created whenever changes in design and in resource allocation are introduced.

Further improvements of the CYCLONE models have led to the Resource-Based-Modeling (RBM) environment (Shi and AbouRizk 1997), where resources and small processes are grouped into "atomic models". The appropriate processes can be selected from a library of "atomic models" to create the desired simulation model, but a new network of "atomic models" needs to be built for the representation of each particular project.

The principal concern of queuing models is resource optimization. Since the resource characteristics (e.g. number, capacity, availability) and the process flows are assumed to be fixed for a given model, the user experiments with the allocation of resources. Most importantly, the dynamic effects of site and material characteristics on process activities cannot be reflected in queuing models. Spatial and accessibility constraints, for example, do not delay or alter the duration of process activities.

In contrast, graphically-based models represent a totally different approach to the simulation of manufacturing and construction environments. While queuing models are primarily concerned with the resource usage optimization, graphically-based models focus on the spatial and geometric feasibility of a given production project. In particular, they help to identify time-space conflicts that may arise during production. In their application to the construction industry, graphically based models represent the first attempt to link construction experience and knowledge to design and project planning.

Specifically, graphically based models provide a virtual 3D environment where the user can analyze the logistical construction implications of various design alternatives and visually identify potential problems (Vanegas and Opdenbosh 1994). Computer-aided-design (CAD) was first used as interface between design and construction. In particular, the 4D-CAD and Interactive Visualizer ++ stems from a combination of CAD drawing and construction schedule, which visualizes the spatial and temporal progress of a construction project (Vanegas and Opdenbosh 1994).

Among the graphically based models for construction is the 4D-CAD system developed by Professor Martin Fisher at Stanford University, which combines "Responsive Workbench", a state of the art 3D interactive graphics system, with the concepts of graphically based simulation modeling (Fisher and Aalami 1996).

Graphically based models are specifically tied to design. Once the geometry of each element has been established, a sequence of erection/installation needs to be defined. Similarly, each of the equipment resources used on the site needs to be defined and fully characterized. In particular, data concerning geometry, degrees of mobility and production rates are specified and define the results of the simulation.

The specification of a construction sequence not only constitutes the most difficult part of this modeling approach, but it also introduces the assumption that the construction process remains fixed over the course of the project. The process is thus assumed to be independent of design, which is an underlying assumption for graphically based models.

Graphically based models attempt to identify spatial constraints during construction, but current research has only focused on large systems like steel erection and earthwork (Interactive Visualizer ++) (Vanegas and Opdenbosh 1994) and precast concrete structures for residential buildings (RUBICON) (Fisher and Aalami 1996). Programming and computing times limit the ability to combine all of the systems of a built facility in a single model. The customization of the model for a particular project requires the specification of the exact sequence of installation/erection for each part and component, and the detailed description of the spatial relationships among them at discrete points.

In contrast to queuing models, graphically based models can account for design specifications, and the design attributes can change throughout the process of construction. However, graphically based models still assume that the construction process itself is completely predefined and remains fixed throughout the project.

2.5 Summary

Concurrent engineering has introduced an integrated approach to design that simultaneously addresses the performance of the product in use and the feasibility of the production process. The applications of concurrent engineering to the manufacturing industry include tools and methodologies that considering the defined manufacturing capabilities and equipment assess the spatial/geometric feasibility of a manufacturing process for the production of each individual part and ensure that each of the single parts will fit together during assembly. The application of concurrent engineering to large-scale projects through design for construction, reflects the existence of physical and functional interdependencies among the systems that affect their spatial relationships during construction. The focus is primarily on the organizational aspects of coordination that ensure feasibility of the design and planning for construction, rather than on the actual construction process and its performance.

The major underlying assumptions for the design methodologies based on concurrent engineering include independence of the production processes for each part and component, fixed production means and methods and fixed resource assignment for each production stage, and ability to fully specify production during design.

The first formalized approach that deals with the complexity of a product in design was developed within the context of systems engineering. The specific aspect of performance addressed by systems engineering is the performance of the product in use, and consequently the requirement that the combination of product sub-systems and components function together to produce the desired performance in use. Production of each of the individual systems is also taken into account, and an established production process is associated with the realization of each type of product sub-system and component. The mapping between the design and the production hierarchy is product-based and assumes that the designers have control over production means and methods, which leads to relationships between the design elements and the production activities that are static and deterministic with respect to changes in design and in technology. The systems engineering approach assumes independence of production for each sub-system and component, the respective production processes are specified and optimized separately and no integration of activities and tasks across these production processes is explicitly established.

Concurrency and co-location of the production processes are critical aspects of the realization of complex large-scale systems that are not explicitly accounted for either in systems engineering or in concurrent engineering. In addition, by specifying the production processes for each design unit as separate from the others, both theories can lead to the optimization of production at the sub-process level. However, the summation of optimal individual production processes may be sub-optimal from the perspective of the whole project.

Project management estimating tools and methodologies, on the other hand, explicitly recognize the dynamics of the production activities but tend to aggregate systems and processes to the scale that is easily manipulated. This focus on process at the aggregate level leads to estimates that are static and deterministic with respect to changes and overall not accurate because based only on primary impacts.

Simulation provides the means to represent the detailed production processes and their interactions. Existing simulation models of construction activities include queuing models and graphically-based models. Queuing models focus on resource optimization with the objective of maximizing process throughput, however they lack the ability to capture spatial and accessibility constraints that drive production rates. In addition, process flows are fixed for a given model and, thus, the dynamic effects of site conditions and material characteristics cannot be represented. In contrast, graphically-based models capture these elements of process dynamics and their impacts on throughput, but they still assume that the construction sequences are pre-defined and remain fixed during the project.

A need is recognized to map the specificity of the systems engineering and the concurrent engineering frameworks to the dynamics of the project management methodologies. This new approach will provide a hierarchical decomposition of both the product and the process with explicit recognition of the dynamics at the detailed level of the single component and task. It will also provide integration of the production processes for the individual design units with respect to the product as a whole.

CHAPTER 3 : THEORETICAL APPROACH

3.1 Introduction

In complex large-scale projects, physical and functional relationships among the product systems and components, along with concurrency and co-location of their production processes, generate inter-system process dependencies that drive the relative production rates among the systems. The performance of multiple interdependent production processes is driven by elements of cross-system process dynamics, in the form of logical, technical, regulatory and resource constraints, that control the spatial and temporal precedence relationships among activities. The systematic assessment of design and technology alternatives with respect to the performance of multiple interdependent processes requires a methodology that characterizes each alternative in terms of the logical links among the processes and relates them to product components by spatial units of progress. Each alternative carries a set of design and production specifications that influence the nature and the location of those links. The methodology described in this chapter relates the complexity of the product to the complexity of the process at the task and component level, to identify cross-system process intersection states where a transfer of status information is required among process activities for the progress of the production project.

3.2 Structure of the Approach

The traditional approach to deal with the complexity of a problem is to break complexity into sub-problems and parts that are easier to address (are more easily addressed) alone than in the context of the whole. The famous sentence "divide et impera" best summarizes this concept that the Romans widely applied to keep control of their vast empire.

In the context of design, the concept of breaking complexity into simpler elements has been extensively used within established theories. For instance, as described in chapter 2, systems engineering follows a top-down approach to decompose the design and the production process of a complex system into matching hierarchies of sub-systems and sub-processes. The correspondence between the two hierarchies is by level and by element. Each level in the design hierarchy corresponds to a level in the production process hierarchy and at each element in the design hierarchy corresponds to an element in the process hierarchy that represents the production process, activity or task for that particular design element.

This one-to-one mapping between the design and the production hierarchies is a valid approach to develop in parallel the detailed design of a product in all of the constitutive parts and components and to specify the number and type of activities required to produce each part or aggregate of parts. In the context of this research, this is a valid approach to identify the activities required to produce a given product according to the standard industry practices. However, it leads to a static and deterministic mapping that is not suitable for the study of production performance under changing design and production specifications.

The theory developed in this research operates at the task/component level and projects the mapping between the design and the production hierarchies in time and space. It is at this level of detail that changes in the design specifications and in the production means and methods affect the production process and build their impacts on its performance. Consider, for example, the shift from bolted to welded connections between pipe segments, the change in the production process is only perceived at the task/component level, but its effects build up over time and may affect the performance of the project as a whole.

Aspects of process performance such as production costs and time are cumulative quantities that are tied to the spatial progress made over time in the production of the interdependent systems. This research assigns spatial connotations to each of the finest design elements (single parts and components) by specific units (in terms of the relevant spatial units of progress), and links them by spatial units to the corresponding production activities. These links shape the spatial sequence of activities across system boundaries starting at the task/component level. In addition, cross-system links among production activities and tasks are established that account for their logical sequence within the project. Complexity is then re-built over-time by progressive transformation and aggregation of parts and components in accordance to the spatial and logical sequencing links.

This theory defines a loop that breaks down the complexity of the product and specifies the corresponding production activities, following a top-down approach. The loop closes with a bottom up approach that rebuilds the complexity starting from the detailed production tasks and their spatial and temporal relationships with respect to the design elements and their units of progress. As the tasks are performed over time in the spatial and logical sequence determined by the links, the level of aggregation in the design hierarchy is increased till the whole product is completed. At that point the cumulative measures of performance can be extracted and compared across alternatives.

Figure 3.1 shows that spatial links tie each component type to specific tasks and activities by spatial unit of progress. The figure represents two of these links, one between component type C11 and activity A11, and one between component type C23 and activity A23. The logical links between activity A11 and activities A22 and AN2, impose that a number of components of type C11 equivalent to one spatial unit of progress for that component type be placed before any component of type C22 or CN2 can be installed. This sequence is shown in the time-space diagram at the bottom.

[During the decomposition phase (top-down process) the systems are considered as separate from one another and so are the respective production processes, in integration phase (bottom-up process) that rebuilds complexity, spatial and temporal links are established among the processes and between the systems and the respective production processes.]

Systems engineering follows a similar approach, but the approach remains confined to the product hierarchy. In the context of systems engineering the specification of the production processes limits itself to the specification of the processes for the production of each of the systems as separate, and the bottom-up integration does not involve the production processes. However, there is a bottom-up integration across the

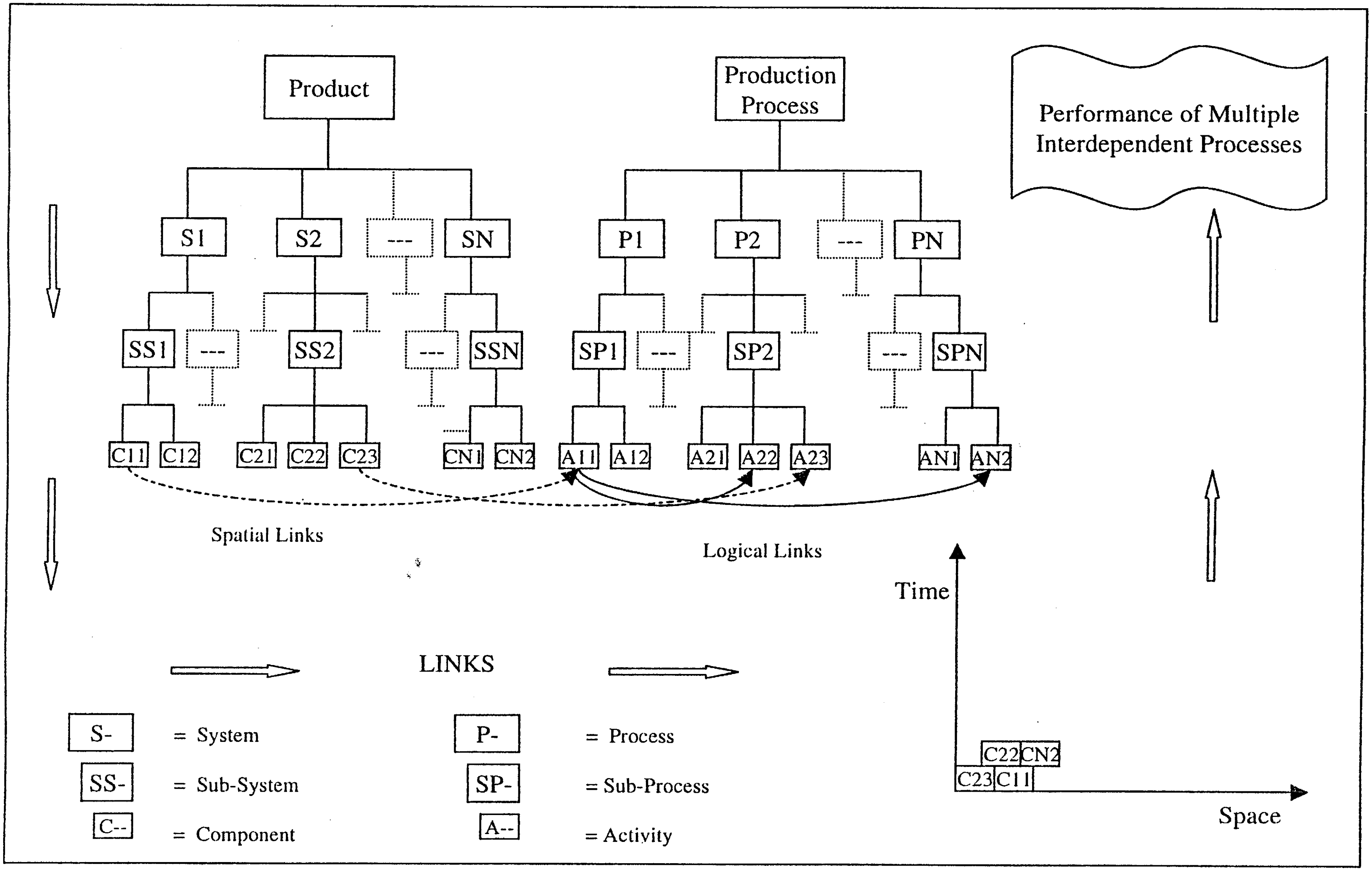


Figure 3.1 : Structure of the Theoretical Approach

levels of the product hierarchy. The detailed specification of the product hierarchy leads to the identification of functional intersection points among the systems where the systems exchange materials, information, or energy during operation. Systems engineering pays significant attention to these interface points and checks them for consistency and effectiveness across the different levels of the product hierarchy, because proper interface exchanges ensure that the whole will perform as specified by the design.

Similarly, this research identifies cross-system intersection points among the processes where information is transferred among the systems, that defines the production rate for one system relative to the others and tracks their impacts across the different levels of the design and production hierarchies to measure production performance.

Cross-system intersection points among the processes are identified by the presence of critical process stages that need to be performed before other activities pertaining to the production of other systems can start. When a specific set of parts and components corresponding to a predefined spatial unit has passed a critical process stage, information is transferred to the related processes for the whole project. In order to ensure proper information transfer among the systems, the status of the components with respect to each critical process stages needs to be monitored by spatial location within the whole, through specific status identifiers. A status identifier is associated to each critical process stage and constantly upgraded as progress is made towards the completion of the project. This research develops a dynamic multi-process simulation model that tracks the status of the critical process stages and triggers production activities accordingly. The model is built specifically for the simulation of construction processes and represents the construction of an entire facility.

3.3 Cross-System Process Intersection States: the Development of a Framework of Systems Interactions

The framework of systems interactions constitutes the basis for cross-system modeling of construction processes. The elements of process dynamics that time and route specific parts and components through process activities during the simulation of the whole construction project were first formalized within the framework of systems interactions and then implemented in the simulation model. The framework identifies cross-system process requirements and constraints (that each system imposes on all the others during construction) and translates them into elements of status information transfer among the systems.

The objective of the framework is to tie these process requirements and constraints to the status of system-specific activities, which are critical to the progress of the project with respect to the installation/erection of the other systems. The status of such activities, here named "critical" activities, defines the points, both in time and in space, where a transfer of information is required between systems. Critical activities within each material and system specific process define corresponding sets of dependent activities, which pertain to the installation/erection of other systems, and need to be held up till the critical ones have been performed by specific unit (e.g. by room, by bay, by floor). The correspondence between critical and dependent activities carries spatial and temporal connotations across systems that use different progress measures and units. For instance, the completion of one activity at a given floor may trigger activities at other locations or zones of the facility either immediately or at subsequent times, based on resource availability.

The framework of systems interactions builds off detailed flow charts of the installation/erection processes for a specific set of facility systems developed in related research (Attai 1997; Carr 1998; Eraso 1995; Maldonado 1999; Murray 1999; Murphee 1999; Pullen 1998), and maps the cross-system process intersection states that are specific to that choice of systems. At any given time, each intersection state links the status of a critical activity to the rate of progress for the corresponding dependent activities, by specific spatial unit. This correspondence specifies which piece of information needs to reach which dependent activity at a given time. The framework links such elements in a way that uniquely identifies when the information needs to be transferred and what dependent activity it needs to reach.

Figure 3.2 represents the mapping of cross-system intersection states and the respective spatial units of progress for a facility that includes structural steel, panelized curtainwall exterior enclosure, centralized service systems and sheetrock interior systems. In the picture, the solid arrows represent cross-system process interdependencies, the dotted arrows represent process interdependencies within a system. As shown in Table 3.1, for this particular choice of facility systems the critical activities in terms of cross-system process interdependencies are: decking of the structure (by floor), pouring the concrete slab (by floor), interior framing (by room), sheetrocking (by room), and room finishing (by room).

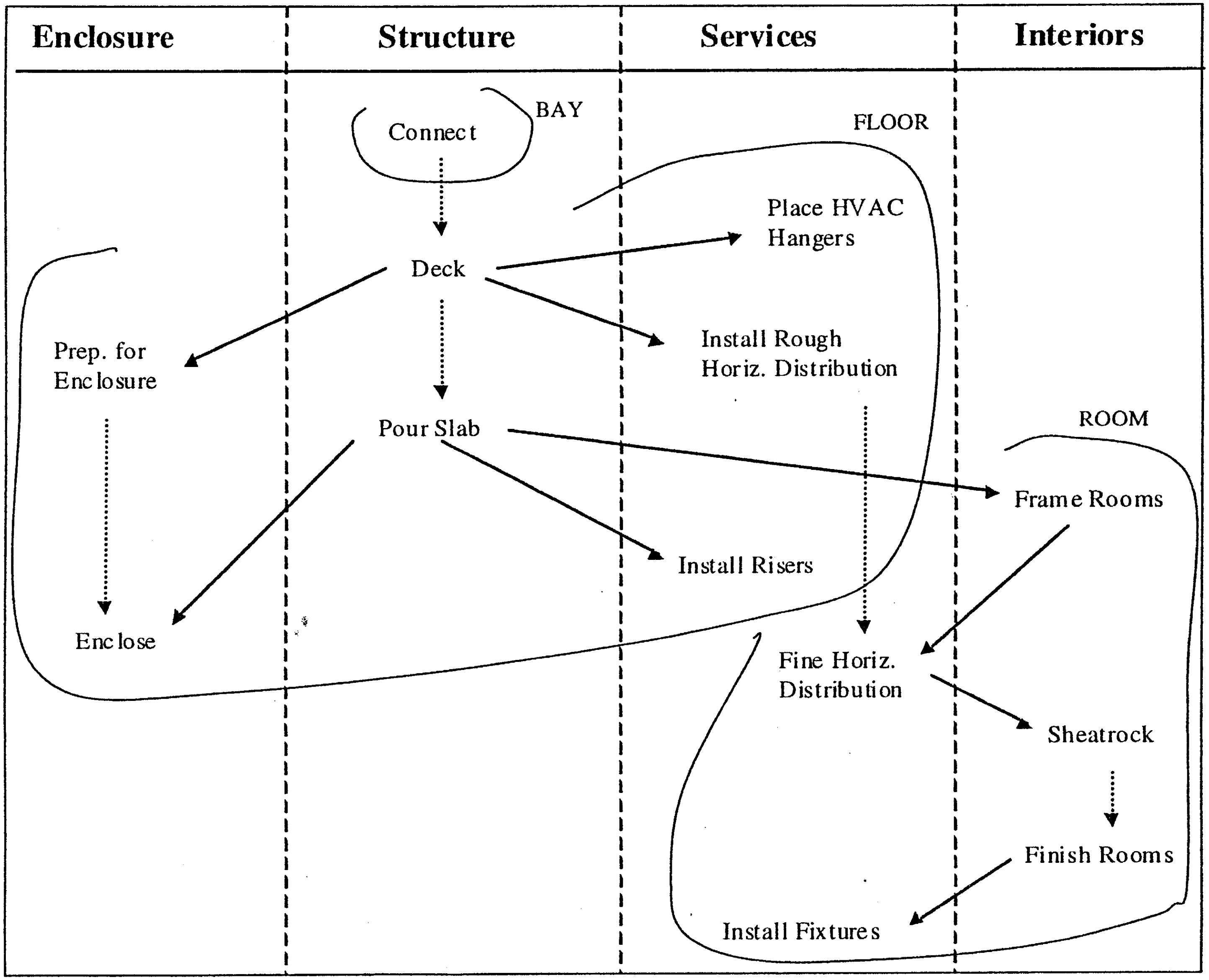


Figure 3.2: Example of Cross-System Intersection States

Critical Activity	**Dependent Activities**
Decking of Structure (by floor)	• Preparation for Enclosure (by floor) • Placement of HVAC Hangers (by floor) • Horizontal Rough In of Services (by floor)
Pouring of Concrete Slab (by floor)	• Enclosure (by floor) • Installation of Service Risers (by floor) • Interior Framing of Rooms (by room)
Interior Framing of Rooms (by room)	• Fine Horiz. Distrib. of Services (by room)
Fine Horiz. Distrib. of Services (by room)	• Interior Sheetrock (by room)
Interior Finishing (by room)	• Installation of Service Fixtures

Table 3.1: Critical and Dependent Activities for the Chosen Combination of Facility Systems

Whenever the design of a facility combines panelized exterior enclosure and structural steel, a preliminary preparation phase needs to be performed before the exterior panels can be erected. Such a phase consists of attaching joints to the structural elements, in those locations where the panels are connected to the structure (Attai 1997). Preparation activities can be undertaken before the erection of structural steel is completed for the whole building, as long as the floor where the workers are placing the joints has been decked. This process link between the structural system and the exterior enclosure system is the result of a regulatory constraint (OSHA 1994) that prevents any worker from performing any activity on a given floor while steel members are being erected until the corresponding tier has been decked. The same process constraint applies to the installation of the HVAC hangers and to the rough-in of the service systems.

Technical constraints link the placement of the exterior enclosure, the installation of the vertical risers, and the interior framing of the rooms to the pouring of the concrete slab on each floor. In fact, the lintels that hold the exterior as well as the interior studs in place need to be buried in the concrete, before the studs can be installed. Similarly, the sleeves, which the vertical risers for the different service systems run through, need to be placed in the concrete before the risers can be installed. The fine horizontal distribution of the various service systems crosses the room partitions between interior framing studs. Logical and technical constraints then require the interior studs to be in place, by room, before the fine horizontal distribution of the service systems can start in that room. Spatial accessibility, also drives the sequence of sheetrocking of the room partitions after the fine horizontal distribution has been placed in a given room. Logical and technical constraints require also that room finishing (i.e. painting and flooring) be completed before the room fixtures are installed in each room.

The inter-system process dependencies between the electrical wiring and the interior finishing for a room system can be graphically represented as shown in Figure 3.2. The grey boxes in the figure are process intersection points, and the activities that they represent are critical for the progress in the installation of other components. When a specific component has passed a critical process stage, other processes can start for different components.

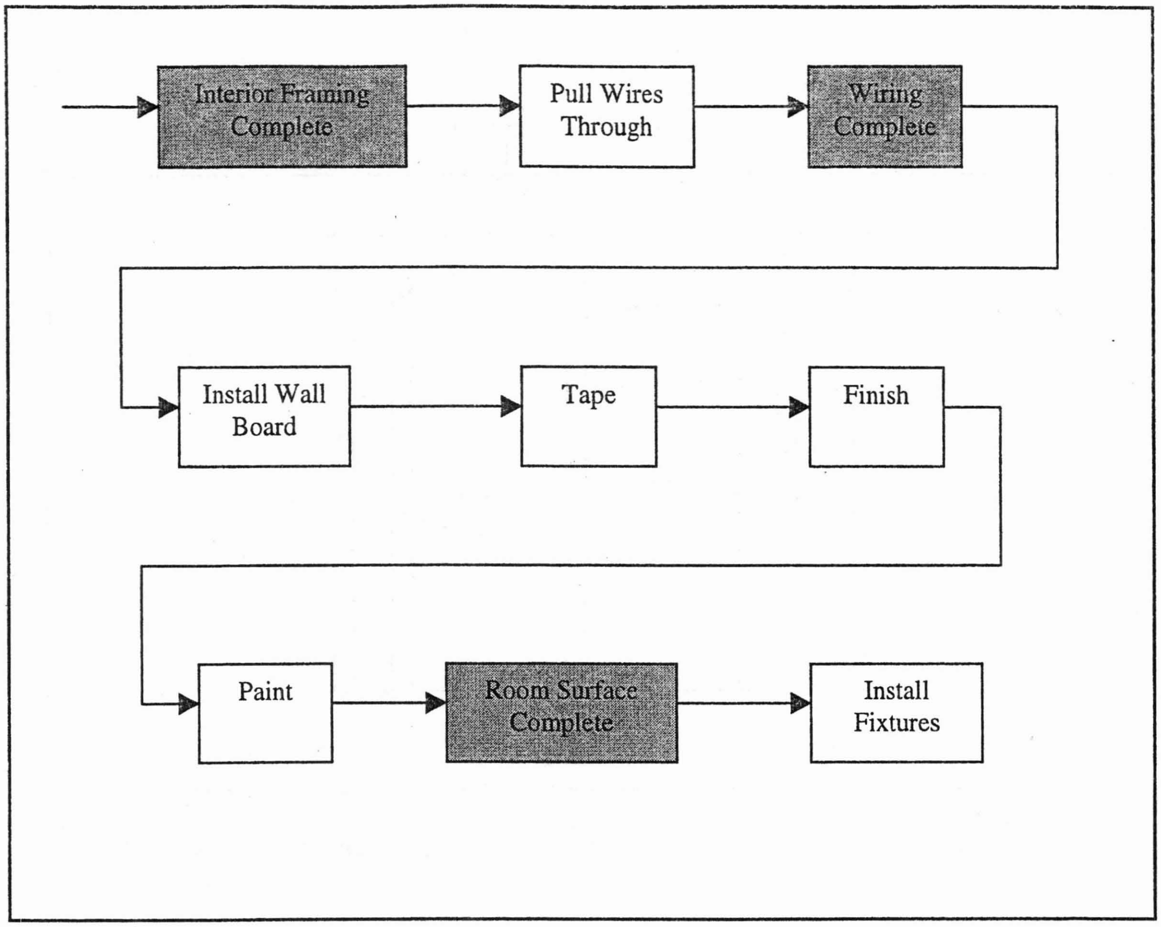


Figure 3.3: Intersection States for Electric Wiring and Interior Finishing

The installation of the electric wiring in the room waits until the framing of the room partitions has been placed. Once the wires are pulled through the interior studs the partition walls can be installed and finished, and provide the surface on which the fixtures are placed.

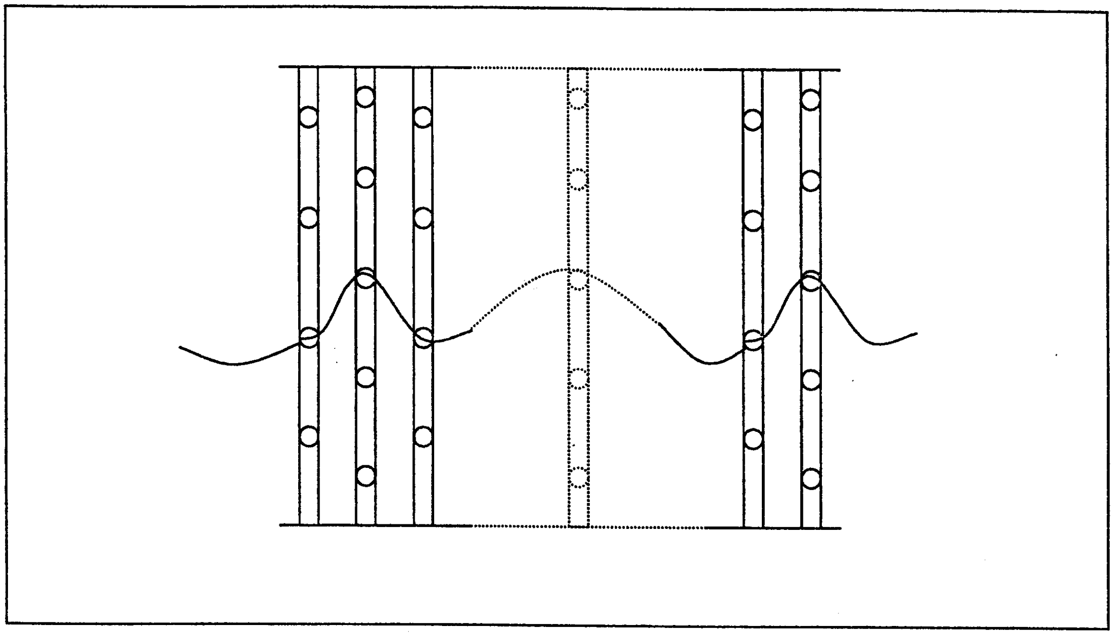


Figure 3.4: Placement of Electric Wiring through the Interior Framing Studs

The status of each component with respect to a critical activity needs to be tracked by spatial location in the facility. The completion of that activity by specific unit constitutes the element of status information transfer that needs to be conveyed to the dependent activities, where other components are waiting to be processed. Based on the framework, in fact, it is possible to determine the earliest time that a dependent activity can be performed, at a specific location within the facility, given the status of the corresponding critical activity (if any) and resource availability. This research develops a dynamic multi-process simulation model that builds upon the framework of systems interactions for the systematic assessment of what status information needs to be transferred and what activities it needs to reach, throughout the facility at any given time.

3.4 The Whole Building Metamodel

The whole building metamodel specifically oversees the transfer of information among the different systems of a built facility. In particular, the metamodel ensures that the precedence relationships in the flow of activities are respected, and that all the logical, technical, regulatory and resource constraints are actually observed, while progress is made in the project, from the perspective of different systems, at the same time.

For the purposes of this modeling work, the design of a built facility has been characterized with respect to two design domains: the design alternative and the project specifics. A design alternative identifies a whole family of buildings characterized by the same choice of systems, regardless of facility type, usage and size. The set of design and process specifications that is carried by the design alternative is common to all the facilities that include the same choice of building systems. The second design domain, designated as project specifics, characterizes a particular building within a family.

The systems of a built facility, as they are defined for this research, can be grouped in four major categories:

- Structural systems (substructure, superstructure)
- Exterior enclosure systems (walls, roof, and apertures)

- Service systems (HVAC, plumbing and sewage, electrical and communication, conveyances and fire protection systems
- Interior finishes (walls, ceilings, and apertures)

The specification of the design alternative leads to a representation of the process that is common to a whole family of buildings sharing the same types of facility systems.

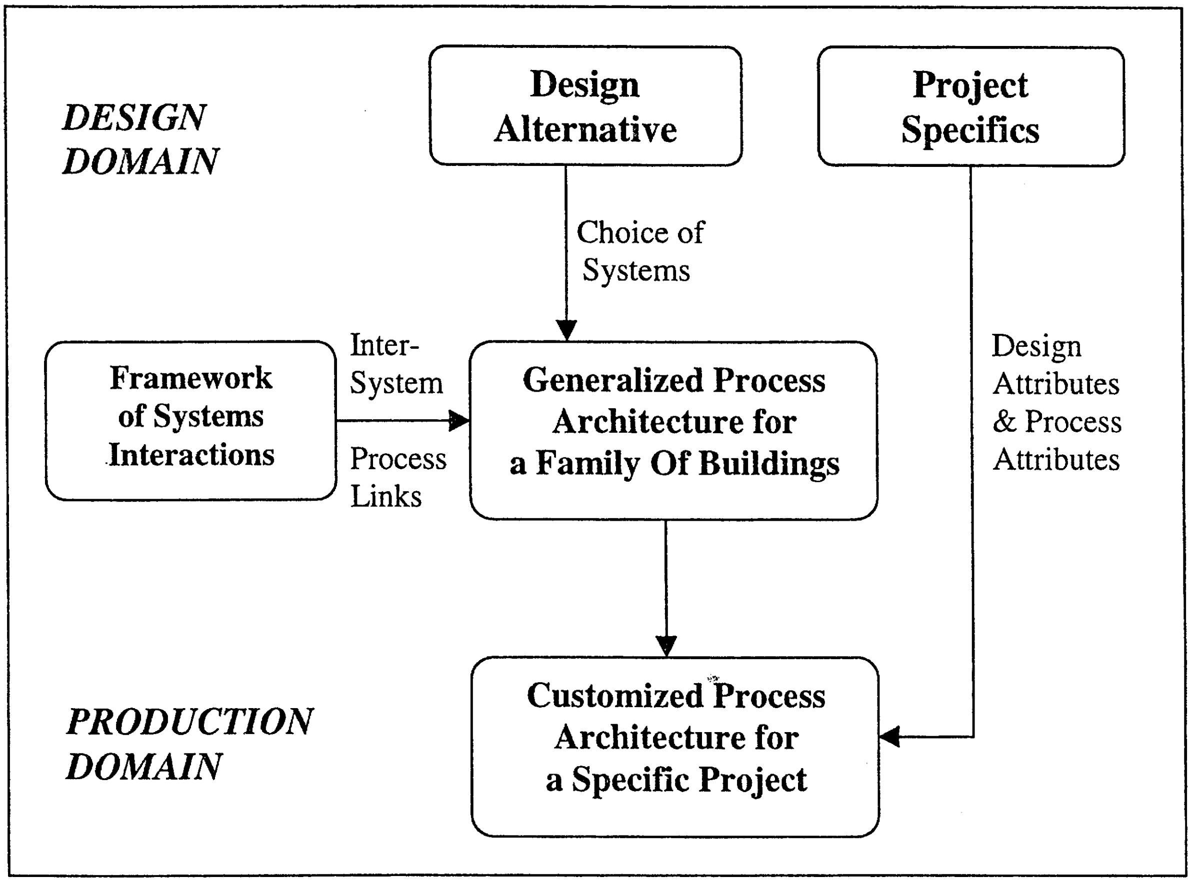


Figure 3.5: Characterization of Process Architecture based on Design Alternative and Project Specifics

This is a generalized architecture of processes, which includes all the inter-system process links for that choice of building systems. In order to particularize the model for a facility of given design, it is necessary to provide the project specifics. Project specifics include design attributes (e.g. number of floors, number and size of components etc.), spatial relations among the systems (e.g. layout), and process attributes (e.g. number and type of resources). This set of information customizes the architecture of processes for a specific project.

A whole building metamodel is associated to each design alternative. The whole building metamodel establishes explicit links among the systems at the activity/task level, to account for the interactions among the systems during construction. Specifically, the metamodel implements the elements of process dynamics, that actively shape the interactions among the systems during construction, to determine cross-system precedence relationships among activities.

While the framework of systems interactions identifies cross-system sequences of component installation based on their spatial location in the facility and on the process constraints that apply to their installation activities by specific unit, the metamodel dynamically builds a schedule for the installation of such components based on the current spatial progress in the performance of the critical activities. In such sense the type of information provided by the framework is purely spatial, while the simulation tool adds the temporal element which is crucial to the evaluation of process performance.

The most important activities/functions that the metamodel needs to perform are "status check" and "status upgrade" at different locations and times: this leads to a double dimension of analysis, both spatial and temporal. The process constraints, which generate precedence relationships among activities at the design alternative level, allow to prompt a status check on a given system's progress or activity status. This indicates whether a given installation/erection activity (dependent activity) typical of another system can be undertaken or not. A set of critical activities is identified for each design alternative. These are the activities, which create a barrier for the progress of other systems, and, thus, require a transfer of information for dependent activities to take place. The status upgrade occurs when one of the critical activities has been performed at a specific location, and a specific progress unit has been completed (e.g. bay, floor, riser group ect). As a status upgrade occurs for one of the critical activities, all the components that were held up are released for installation. Their installation can immediately and simultaneously begin, depending on the availability of resources and on the satisfaction of other specific project conditions.

3.5 Summary

This research examines the complexity of the production processes in relation to the complexity and scale of the product for the purposes of design. The selection of a design among possible alternatives requires the ability to discriminate among alternatives on the basis of chosen measures of performance.

The research approach explicitly accounts for process interdependencies at the system and at the inter-system levels, and relates them to the design at the task-component level.

For each project, the particular combination of systems, together with the specific system layout, create interdependencies among the systems which are specific to that choice of systems and to that combination of individual system layouts. System interdependencies generate inter-system process dynamics that drive the performance of the multiple interdependent process. The elements of inter-system dynamics, namely logical, technical, regulatory and resource constraints, determine the timing of the various activities and tasks in different locations and zones of a complex large-scale system. They also define the rate of progress that can be made in the installation of one system or component, relative to the progress made on the installation of the other systems or components, by specific units. In a built facility specific units are, for example, bays and floors for the structural systems, riser units and/or floors for the rough distribution of the service systems, rooms for the fine distribution of the service systems and interior finishing, but these units can vary depending on the particular system type and layout.

The research develops a dynamic multi-process simulation model to track the detailed design elements in each system as they undergo transformation and aggregation by specific unit and location, during the different steps and levels of the production processes. The model links a set of process modules, one for each of the systems specified by design, with respect to all of the technical, logical, regulatory and resource constraints that apply for a given combination of design and technology. Model outputs include measures of process performance, specifically duration, costs, resource utilization, and workers' exposure to danger, for each system and for the project as a whole.

CHAPTER 4 : METHODOLOGY

4.1 Introduction

This chapter describes the research methodology. The steps include the development of a simulation model for the representation of multiple interdependent construction processes, the definition of a set of significant performance measures, and the design of a set of experiments to analyze the impacts of inter-system process dependencies on these measures. This research is empirically based and significant effort has been put into data collection with two principal objectives. The first one is building the logic for the simulation model and the evaluation of the performance measures, the second one is the characterization of the case study and the related set of experiments.

4.2 Data Collection

The first objective of data collection for this research is the development of the logic for the representation of multiple interdependent construction processes. With respect to this objective, information was gathered on a variety of construction projects to characterize the inter-system process links that relate the installation/erection of the different facility systems as a function of the type and nature of the systems involved, of the construction means and methods, and of the facility type and layout. The characterization of the inter-system process links involved the identification of the spatial and logical links between processes, the assessment of the level of aggregation in the respective design and production hierarchies at which they occur and build their effects, and the identification of their impacts on the spatial and temporal precedence relationships among activities across system boundaries.

The second objective of data collection was the complete characterization of a specific project, the renovation of Baker House, that was selected as example application of the theory framework analysis. Detailed data was collected on the design an on the construction means and methods for this particular project. The data provided the basis to customize the dynamic process simulation tool that was built as part of this research to evaluate project performance.

4.2.1 Characterization of Inter-System Process Links for Multiple Interdependent Construction Processes.

The characterization of the inter-system process links for multiple interdependent construction processes is the result of a combination of inductive and deductive work that fed upon actual data from the construction industry. The first level of characterization, broader in scope, aimed at identifying the type of inter-system process links and relate them to specific characteristics of the project. Repeated observation of a large number of construction projects led to a first classification of inter-system process links for major systems interactions. For instance, the DWV risers, must be placed in a specific vertical chase on a given floor before the supply risers, and both precede the electrical and communication risers in that chase. Regulatory constraints impose, for the safety of the workers, that the angles for the exterior glass curtainwall system cannot be placed on a given floor before the corresponding tier of the steel structure has been erected, plumbed, connected and decked.

Over 100 construction sites in the eastern U.S.A. were visited for this and related research from 1994 to 1999 (Attai 1997; Carr 1998; Maldonado 1999; Murray 1999; Murphee 1999; Pullen 1998). The types of facilities include office, residential, institutional, and retail buildings, and large industrial and institutional facilities. Consultation of the construction documents and follow-up interviews with industry members on each of the construction sites allowed to fully characterize the cross-system intersection states described in chapter 3.

Table 4.1 presents a list of the construction sites where the collaboration with industry members was strongest for this research. Repeated observations and subsequent in depth interviews with the different parties involved in the project, including specialty and general contractors, construction managers, and other experts in the specific systems, contributed the most to the identification and to the characterization of the cross-system intersection points among processes and activities during construction.

Project Name	Location	Facility Type
Doubletree Hotel University Park	Cambridge, MA	8 story steel framed hotel with supermarket
University Park Garage	Cambridge, MA	8 story post-tensioned CIP parking garage
75 Sidney Street	Cambridge, MA	5 story research facility
45 Sidney Street	Cambridge, MA	5 story research facility and office space
Logan Airport Hotel	Boston, MA	10 story hotel
MIT Buildings 16 and 56	Cambridge, MA	complete renovation of existing buildings
Pilot House (Lewis Wharf)	Boston, MA	renovation of 6 story office building
Two Canal Park Office	Cambridge, MA	5 story office building
Harvard Business School	Cambridge, MA	8 story extended stay hotel
Stop & Shop	Brighton, MA	2 story retail facility
Mount Auburn Hospital	Cambridge, MA	hospital renovation
Marriot Residences, Kendall Square	Cambridge, MA	14 story hotel
Polaroid Building	Cambridge, MA	renovation of 5 story office building
Suffolk Law School	Boston, MA	7 story steel framed building
Suffolk Courthouse	Boston, MA	steel framed courthouse
Federal Courthouse	Boston, MA	10 story, 2 wing courthouse
MIT Building N42	Cambridge, MA	renovation of 3 story building
World Trade Center Hotel	Boston, MA	15 story hotel and 6 story garage
Worthington Place Kendall Square	Cambridge, MA	residential building renovation
The Custom House	Boston, MA	residential building renovation
Baker House	Cambridge, MA	residential building renovation

Table 4.1: List of Most Important Construction Sites for Data Collection

The specific data collected for each project includes:

General Data on the Project:

- Nature and scope of the project (e.g. new construction or renovation)
- Construction environment (e.g. any particular site conditions and process constraint due to site location)
- Particular design alternative (e.g. type of facility systems),
- Time frame of the project (e.g. expected project duration and schedule for the installation of the different systems),
- Construction means and methods,
- Number and type of resources per crew,
- Innovations introduced in the design or construction methods compared to the standard industry practices.

Specific Data on Performance:

- Primary performance objectives for the project (e.g. cost, duration),
- Delays with respect to the schedule and causes of delay (e.g. last minute changes, rework, lack of resources, external factors such as weather conditions or local government –permits-)
- Earliest start time for specific activities and project factors influencing start time,
- Spatial units of progress for the different parts of each system in relation to the others.

Upon Project Completion: Actual project schedule and labor costs.

4.2.2 Characterization of the Baker House Project

The analysis presented in the result chapter (chapter 5) of this dissertation is based upon actual data from a construction project. Specifically, a case study was conducted on the renovation of Baker House, a student dorm located on the MIT campus. The building has six stories and hosts a total of 320 rooms. The dormitory, designed by Alvar Aalto, was built from 1947 and 1949 and underwent its first major renovation during the summer months of 1998 and 1999. The project, carried out by the firm Kennedy & Rossi, involved gutting and replacing the mechanical and electrical systems, interior flooring, and interior trim. Mechanical systems include hot water heating, fire protection, and domestic plumbing systems. The focus of this case study is on the installation of the new electrical and mechanical systems.

Because the renovation occurred during the Summer, and the building needed to be occupied by the students early in the Fall, it was critical to the design and construction management of this project to maintain an extremely tight schedule. Several measures were taken in order to maintain such a tight schedule. An unusually large number of workers per crew were allocated to this project, and several innovations were introduced to increase the rate of construction. Each floor was split into quadrants and two workers per crew were allocated to each quadrant, so that work could progress on all floors simultaneously. The project heavily relied upon off-site fabrication of components, which were delivered to the site ready for installation. For example, the plumbing supply and DWV risers with fixture stub-outs were prefabricated as a single unit for each room on each floor. Each dormitory room has a sink which is fed by independent plumbing risers. Because of the unique design of the building, with its gentle curves, (the floor plan is shown in Figure 4.1) the horizontal runs of the fire protection and hot water heating pipes would have multiple oblique angles for each set of rooms. Pipe segments were thus prefabricated in room-length sections, complete with bends where necessary.

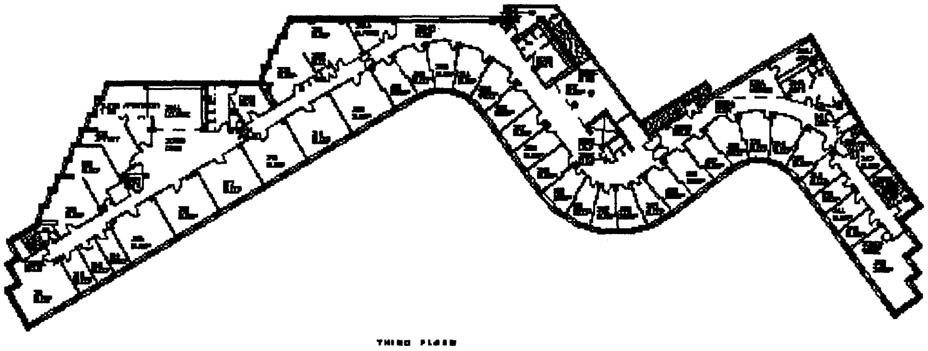


Figure 4.1 Floor Plan for Baker House Dorm (Third Floor)

The building did not include an active fire protection system prior to this rehabilitation. As part of the project, each corridor and room needed to be equipped with sprinkler heads. The installation of the fire protection system required coring through the masonry walls through each room, for the placement of the horizontal pipes. A coring rig was devised that pre-positioned the coring machine, so that it could be quickly and effectively moved and used in each room.

As mentioned before, the renovation project was completed over two Summer periods. The first phase (Summer 1998) consisted in the installation of all the major pieces of equipment including basement and roof-top units. It also included the complete renovation of the ground floor, where common areas such as a large kitchen, a fitness room and a study area are located.

The second phase (Summer 1999), was primarily concerned with the renovation of the dormitory rooms located on floors one to six. The case study focused only on this second phase of the building rehabilitation.

It is important to note that, unlike many other buildings, each room is slightly different from the others, at least in shape, number and location of pipes and number of service fixtures, and also that the number of dormitory rooms varies from floor to floor at least up to the third floor. However, a minimum number of items can be found in each single room. These are: two sprinkler heads, a wallsink, four electric outlets, an overhead light, an electric switch, a smoke detector and a radiator. Figure 4.2 shows the basic features of an average room.

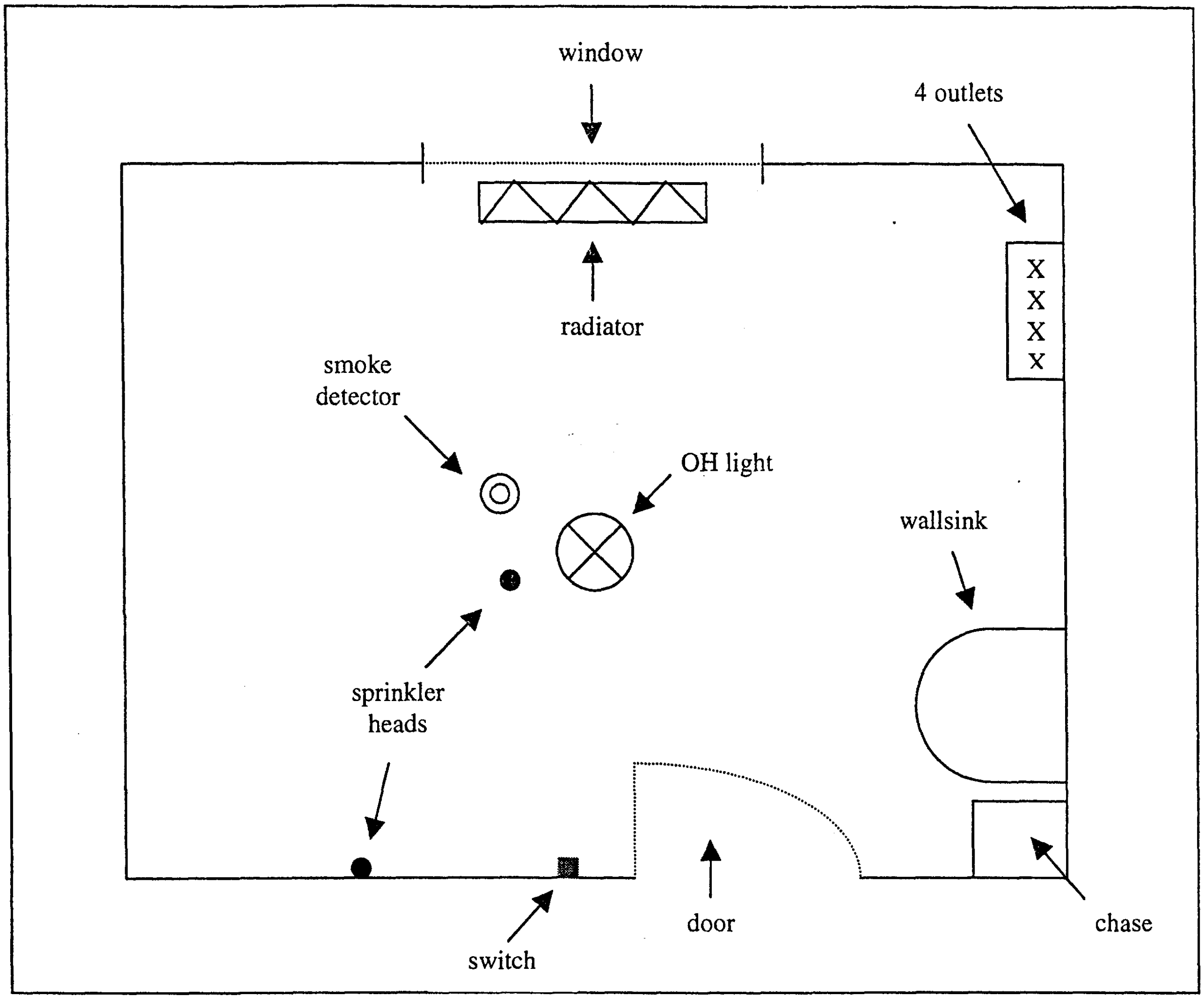


Figure 4.2 Average Room in Baker House Dorm

The study of the Baker House project and of the set of project scenarios stemming from its baseline configuration was conducted using a dynamic process simulation tool that was specifically customized to represent the construction activities involved in this particular project.

The customization of the dynamic process simulation tool required extensive data on the facility design, and construction means and methods. Data for the representation of the construction processes at the task/component level was based upon extensive study of the original floor plans, the construction specifications, the contract, and the schedule for the project. These documents were provided directly by the construction management company, Kennedy & Rossi. Interviews with the project manager and project superintendent also significantly contributed to the understanding of the design choices and means and methods of construction.

The customization of the dynamic process simulation tool based on this data involved the creation of detailed input files that contain all of the relevant information on each single component included in the design. These easily add up to thousands of items, each carrying a number of specific attributes (e.g. size, material, spatial location within the facility.)

For the purposes of the simulation experiments, the original design of the facility, as in the actual renovation project, was assumed as "baseline scenario". In the baseline configuration the layout of the heating system is spatially tied to the layout of the electrical system. The respective horizontal pipes and conduits follow the same path along the building and share the same supporting tray (Figure 4.3), which forces the heating pipes, larger in section, to be placed before the electrical conduits on each floor. This spatial link between the two systems makes the rate of installation of the electrical conduits highly dependent on the rate of installation of the heating pipes. Ten alternative scenarios were generated and analyzed in comparison to the baseline. Each scenario represents variations in the design and/or in the technology to assess the role of inter-system process dependencies in driving specific aspects of project performance. A full list of the scenarios can be found in Table 5.1, while a detailed description of the changes that each scenario entailed is provided throughout Chapter 5.

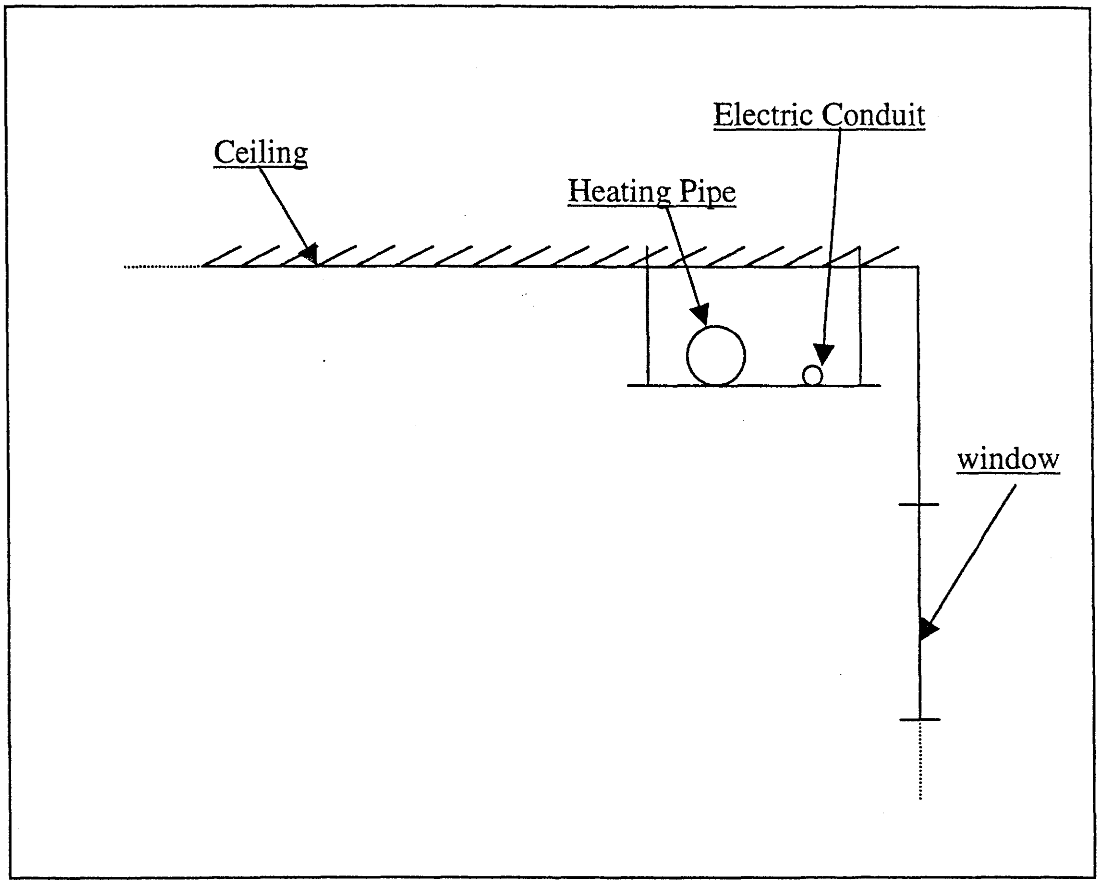


Figure 4.3 Spatial Interaction between the Hot Water Heating System and the Electrical System

4.3 The Dynamic Process Simulation Model

This research develops a dynamic process simulation model to assess and compare production process performance across alternative combinations of designs and technologies. The simulation model incorporates a complete characterization of the process at the activity/task level, as it maps to the finest design components, and the elements of process dynamics, which allow to follow the design elements as they undergo transformation, installation and assembly during construction (Slaughter 1997).

The structure of the simulation model for the whole building is modular. A library of system and material specific modules was developed. Each module is a complete simulation model, which represents the process of installation/erection for a particular system of a built facility. The modules are designed to be compatible and, thus, be able to be combined for the representation of a whole construction project. A whole building metamodel establishes explicit links among the modules to account for the interactions among the systems during construction. The metamodel is based on a framework of systems interactions which translates cross-system process constraints into cross-system information transfers. The interactions among the systems of the built facility in the form of cross-system process requirements and constraints are incorporated in a framework of systems interactions.

4.3.1 Structure of the Computer-Based Dynamic Simulation Model

The process simulation model provides a complete representation of construction processes at the activity/task level that follows the finest elements of design, the physical components, as they undergo transformation, installation and assembly during construction. Specifically, the simulation model links multiple interdependent construction processes to account for those elements of cross-system process dynamics, namely technical, logical, regulatory, and resource constraints, that generate interactions among the facility systems during construction.

As discussed in chapter 3, for the purposes of this modeling work the design of a built facility has been characterized with respect to two design domains: the design alternative and the project specifics. A design alternative identifies a whole family of buildings characterized by the same choice of facility systems. The project specifics characterize a particular building within a family. The structure of the simulation model directly reflects the presence of these two design domains in the mapping between design and process.

The structure of the simulation model for the whole building is modular. A library of system and material specific modules was developed, which includes a set of alternatives for each system type. For example, among the possible structural systems, a module for the erection of structural steel (Eraso 1995), one for Cast-In-Place-Concrete (Carr 1998), and one for wooden structures (Settlemeyer 2000) are currently available. Each module is a complete simulation model, which represents the installation/erection processes for a particular system of a built facility (e.g. structural system, exterior enclosure system, plumbing system etc.). The modules are compatible with one another and can be combined for the representation of a variety of design alternatives. A user interface, capable of reading data from input files, was developed in conjunction with related research (Murray 1999) to specify design and process attributes (project specifics) and thus to customize the models for a particular building within a family.

A whole building "metamodel" is associated to each combination of system and material specific modules. The whole building metamodel establishes explicit links among the modules at the activity, task, or subprocess level, to account for the interactions among the systems during construction. Specifically, the metamodel implements the elements of process dynamics, that actively shape the interactions among the systems during construction, to determine cross-system precedence relationships among activities. Precedence relationships among activities are dynamically established during simulation based on cross-system information transfer.

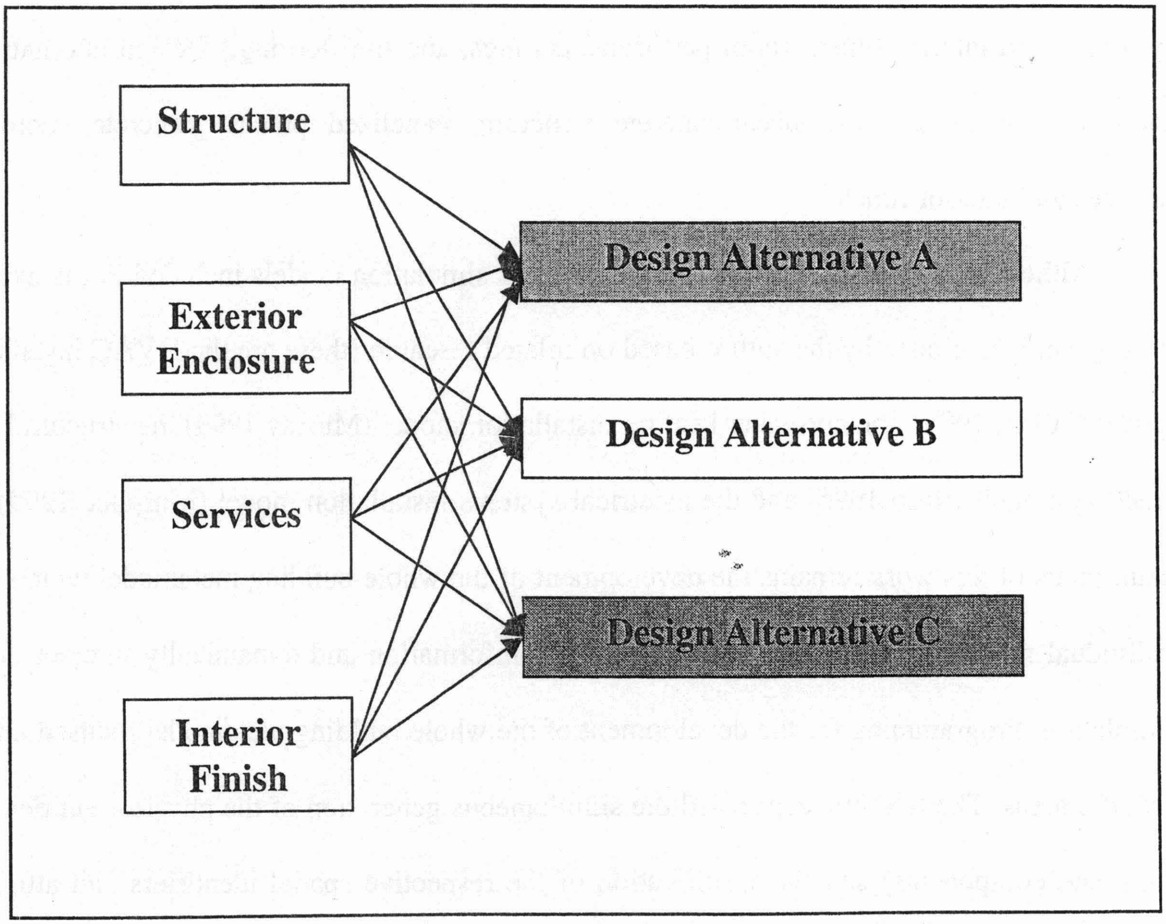


Figure 4.4: Structure of the Whole Building Simulation Model

The name "metamodel" reflects the fact that the dynamic links among the modules lie beyond the system and material specific level. Such links do not change the specific processes of installation/erection for any of the systems, but rather they impose cross-system process constraints that only affect the rate of progress for each of the systems relative to the others.

The metamodel of the whole building is, therefore, a family of relationships among the system and material specific modules and it is unique to a given design alternative, as shown in Figure 4.4. In this example, design alternative A could consists of a steel structure, glass curtainwall enclosure, services (plumbing, fire protection, HVAC, electrical and communication systems), and interior finish (room partitions, ceilings, and tile flooring.) Design alternative B could consist of a cast-in-place-concrete structure, panelized precast concrete enclosure, services and interior finish.

Although some of the system specific process simulation models included in the existing library were developed by the author based on related research (these are the HVAC installation model (Pullen 1998), the hot-water heating installation model (Murray 1999) the structural steel erection model (Eraso 1995) and the electrical systems installation model (Murphee 1999), the main focus of this work remains the development of the whole building metamodel which links individual models and enables them to exchange information and dynamically interact during simulation. Programming for the development of the whole building metamodel focused on two specific areas. The first one concerned the simultaneous generation of the physical entities (e.g. parts and components) and the specification of the respective spatial identifiers and attributes describing the individual properties of each entity, such as type, dimensions, and material. The second one concerned the transfer of status information among the facility systems during construction and specifically involved the development of a system to track, store, and make status information available throughout the simulation of a construction project. The two areas are strongly connected to one another because, based on the specific attributes and spatial identifiers associated to each entity, spatial progress can be tracked with respect to the critical process stages and accounted for in the generation of a dynamic cross-system project schedule.

The initialization of the physical entities, which includes their generation and the simultaneous specification of the respective attributes and spatial identifiers, is handled within a specific block of the program at the very beginning of the simulation. The initialization block was specifically designed for flexibility of representation and for ease of customization, where flexibility of representation is intended as ability to simulate the construction of a variety of facility designs and to specify different construction means and methods for each of the systems.

The system and material specific modules were originally developed to represent the installation/erection of the different facility systems for a prototype building of given design and layout with respect to the industry standard construction means and methods. In the original version of the modules, the detailed specification of the number and type of components and of their attributes for each system was deeply embedded in the simulation program, and thus not immediately accessible for customization purposes. The first step in the development of the initialization block for the whole building metamodel was to pull these specifications out of the simulation program by enabling the program to read this information from external input files. The input files are plain text files that can be edited in any commercial spreadsheet or word processor. The simulation environment, in which the whole building model is built, generates a specified number of physical entities per entity type at the beginning of the simulation, and routs them through the respective process activities based on individual entity attributes, such as type, material, and size. The initialization block reads the number and type of physical entities to be generated from separate input files (one for each entity type in each facility system), which also contain the specific attributes of each entity. Most importantly the entities are generated in a chain that reflects their physical, functional, and spatial dependencies. The generation of entities in a chain allows the program to transfer some of the attributes from the entities generated upstream to the ones generated downstream in the chain and, thus, helps keeping the input files as lean as possible.

Consider, for instance, a generic plumbing system. The major entity types included in the design of this system (besides large pieces of equipment) are vertical risers, horizontal pipes, and fixture groups. Each floor, by design, includes a number of vertical risers that feed a number of main horizontal runs. The horizontal runs feed the different floor fixtures through a number of separate branches. Each riser belongs to a continuous vertical unit, called riser unit that can span across a number of facility floors. A riser unit, together with the set of horizontal pipes and fixtures that are fed by it, constitute a riser group. In this example, the chain of entity generation would start from a number of facility floors that is read directly from a first input file. As each floor is generated at the beginning of the simulation, a line is read from a corresponding input file, which contains all the attributes associated to that floor. The set of attributes for each floor include the corresponding number of risers and a spatial identifier, in the form of a numerical value, called "entity.floornumber", which specifies the location of the floor within the facility. The next step involves the generation of the risers in the number specified for that floor. Each riser carries the same numerical value for the identifier "entity.floornumber", which is directly inherited from the floor and is common to all the entities belonging to that particular floor. As each riser is generated, a line is read from another input file that specifies the number of horizontal runs and fixture groups associated with that riser, specific properties of the riser (i.e. size, material, and type of connection) and two spatial identifiers called respectively "entity.riserunit" and "entity.risergroup". These identifiers are numerical attributes that specify respectively the riser unit and the riser group, which that particular riser belongs to. The value of such attributes along with the floor number are automatically transferred to all the entities that are generated in the next steps including horizontal runs, branches, fixture groups, and individual fixtures within a group. The generation of the facility floors is common to all the system and material specific modules included in the model and triggers a separate generation chain, by entity type, within each module.

Programming for the transfer of information status between system and material specific modules involved the definition of model attributes to record the spatial progress with respect to the critical process stages throughout the simulation. Model attributes, unlike entity attributes, describe properties that are common to the facility as a whole, and carry information can be accessed by any of the modules at any stage of the simulation run. The spatial identifiers associated to each entity allow the program to track the completion of a critical process stage by specific unit of progress, such as floor, riser unit, and room for each system. The model attribute associated to a critical process stage is incremented every time a spatial unit of progress has been completed. As a new entity gets ready to be processed through one of the dependent activities, its spatial identifier is compared to the current value of the corresponding model attribute to decide whether that entity can be processed right away or needs to wait. The value of the model attribute is continuously checked for the entities that are put on hold. These entities are released for processing as soon as the model attribute indicates that sufficient spatial progress has been made. The continuous upgrade of the model attributes, simultaneously for all of the critical process stages, as progress is being made in the installation of the facility systems creates the conditions for the automatic generation of a dynamic project schedule where the next step is always based on the current progress status.

The simulation model for the whole building can easily be customized to represent a specific project. The type, number, and location of each component in each system can be derived either from the detailed drawings or from the cost estimating documents (quantity take-off) and directly entered in the input files. Data on the nature of the specific tasks, their duration and sequencing, and the required resources for standard construction processes are embedded in the system and material specific modules. The links among the processes with respect to standard construction means and methods are unique to each design alternative and thus only depend on the particular combination of facility system and on their spatial relationships. These links are included in the metamodel. Alternative designs and technologies can be tested by changing the type or quantities of components and systems, the nature or level of the resources and their production rates. Changes in the processes themselves can also be explored by altering specific tasks and/or their sequences.

Outputs to the whole building simulation model are duration, activity-based cost, duration-based cost, index of worker exposure to dangerous conditions. Each of these outputs can be tracked at different levels ranging from the sub-process level to the system level to the whole facility level. This flexibility in the level of detail at which the results can be provided depends on the detailed level of representation (component/task level) that is built into the system and material specific modules and the corresponding links.

4.3.2 The Whole Building Meta-Model

The whole building metamodel dynamically builds the cross-system schedule of construction activities for a specified project. In particular, the metamodel ensures that precedence relationships in the flow of activities are respected, and that all logical, technical, regulatory and resource constraints are actually observed, while progress is made in the installation/erection of the different systems.

The most important activities/functions that the metamodel needs to perform are "status check" and "status upgrade" at different facility locations and times. Spatial progress in the performance of the critical process stages is tracked and recorded throughout the simulation. Critical process stages, as defined in chapter 3, are activities, specific to the particular design alternative, which create a barrier for the progress in the installation of other systems with respect to specific dependent activities. In the metamodel a transfer of status information from the critical to the dependent activities is required for the dependent activities to be undertaken on specific spatial units of parts and components. A variable, called “model attribute” is associated to each critical activity to track and record spatial progress, and the value of this attribute is shared among the systems. The presence of inter-system process links between critical and dependent activities prompts a status check on a critical activity whenever new components get ready to be processed through any of the corresponding dependent activities. Based on the current value of the model attribute associated with that critical activity, these new components are either processed or held up.

A status upgrade, reflected in an increment of corresponding model attribute, occurs whenever a set of parts equivalent to a spatial unit of progress has been processed through a critical activity. As a status upgrade occurs for one of the critical activities, all the components that were held up are released for installation. Their installation can immediately and simultaneously begin, depending on the availability of resources and on the satisfaction of other specific project conditions.

4.3.3 The Dynamic Process Simulation Environment

The primary objective of this modeling effort was the translation of the contents of the framework of systems interactions into a logic for the dynamic sequencing of activities in the representation of construction projects.

Based on the framework, in fact, it is possible to determine the earliest time that a dependent activity can be performed, at a specific location (within the facility), given the status of the corresponding critical activity and resource availability. In order to expedite the systematic assessment of what information needs to be transferred and what activities that specific information needs to reach, it seemed convenient to translate the contents of the framework into a model, specifically a computer based dynamic process simulation model.

Dynamic process simulation was first developed for use in the design of chemical processing facilities (Glasscock and Hale 1994). This and related research (Attai 1997; Carr 1998; Murray 1999) represent the first application of dynamic simulation to the modeling of construction activities. This departure from the standard queuing and graphically based models described in chapter 2 highly improves the accuracy of representation. Dynamic process simulation is the most responsive to the changing conditions of a typical construction site, and, thus, offers a representation of construction processes which is the closest to the reality of the industry (Slaughter 1997; Attai 1997; Carr 1998; Murray 1999).

Dynamic process simulation takes a substantially different approach from queuing and graphically based models. While queuing models follow the cyclical flow of resources from one activity to the next one, dynamic process models follow the flow of parts and components and their transformation from one activity to the next. The overall process is looked at from the perspective of the changes which the entities undergo as they are being worked on, rather than from the perspective of a cyclical flow of resources.

The focus of dynamic models is on the dynamic nature of the process. Parts and components are transformed as they are being processed, and dynamic simulation accounts for that by allowing their attributes to change, as activities are performed on them. The most interesting feature of dynamic models is that these attributes are capable of affecting activity processing times and even entire processes. Output from earlier activities can have an impact on later ones. Decision branches and alternative processing paths allow to dynamically route parts and components through process activities, thus breaking the assumption of a deterministic sequence and a fixed process which is typical of queuing and graphically based models.

Another aspect of entity transformation allowed by dynamic simulation is the aggregation of the design elements into more complex units. For example, in the erection of structural steel beams and columns are aggregated into bays, bays into floors and floors into a whole building structure.

Dynamic process simulation handles resources quite differently from the other types of models. Each activity has a set of resource requirements. As an entity (e.g. part or component) reaches a particular activity, a check is performed in a pool of resources for the availability of those required by that activity. If such resources are available, they are automatically allocated to that activity and made unavailable to other activities for the entire entity processing time. The resources are then returned to the pool once the entity has been processed, and made again available for use in other activities. Resources are not specific to a process step. The same resource can be reassigned to multiple different tasks, sub-processes, and even entire processes (e.g. a crane).

In summary, dynamic process simulation allows for:

- Transformation of materials and components
- Aggregation into completed facility
- Simultaneous performance of processes
- Shared and re-assignable resources

This simulation environment was built using a commercial computer simulation programming tool called SIMPROCESS. This tool, developed by CACI Product Company, integrates project mapping, object oriented simulation, and activity based costing, for process modeling and analysis (Attai 1997; Carr 1998; Murray 1999; Simprocess 1999).

The specific process simulation modules that were used in this research for the purposes of the experimental analysis on the Baker House project are:

- ***Plumbing Installation Module***: developed by J. W. Murray based on process flow characterization by J. W. Murray (Murray 1999)
- ***Fire Protection Installation Module***: developed by J. W. Murray based on process flow characterization by J. W. Murray (Murray 1999).
- ***Hot Water Heating Installation Module***: developed by J. W. Murray and A. Orsoni based on process flow characterization by J. W. Murray (Murray 1999).
- ***HVAC Installation Module***: developed by A. Orsoni based on process flow characterization by M. Pullen (Pullen 1998).
- ***Electrical Installation Module***: developed by A. Orsoni based on process flow characterization by W. L. Murphee III (Murphee 1999).

4.4 The Process Performance Measures

Complex large-scale projects involve interests of several parties, such as the owner, the general contractor, and the different specialty contractors. Each party, depending on the type of contract, has different objectives within the project. This diversification and fragmentation of tasks and goals, which is typical of complex large-scale projects, makes it quite difficult to establish an absolute "optimum" for the project and makes it even more difficult to express it in terms of a single performance measure. Depending on the particular project and party of perspective, one aspect of performance may become critical to the success of the project, but in general the level of success achieved in a project can only be measured across multiple dimensions of performance.

The objective of this research is to analyze the impacts of change on the performance of multiple interdependent processes, and to highlight the impacts that are generated by inter-system process dependencies across a set of project scenarios. These impacts, as will be shown in the results chapter, can be difficult to predict and can manifest their effects in unexpected forms.

This research proposes a set of performance measures that covers the different aspects of performance that may be relevant to complex large-scale projects. The idea behind these performance measures is to provide multiple dimensions of performance without proposing an "optimal" solution, given that all of these measures are relevant, and one or the other can become more or less important depending on the nature of the project and on the party of perspective.

The set of performance measures selected for this research consists of project duration, duration-based cost, cost of utilized resources, percentage resource utilization, and an index of workers' exposure to dangerous conditions (or danger index). The significance of each performance measure, and the way it was calculated is explained in detail in the following sections.

4.4.1 Project Duration

Project duration is defined as the total number of workdays required to complete the project. In this context, a workday consists of eight consecutive working hours. Duration is the primary output of the dynamic process simulation model that was built for this research. The model itself provides duration both for the installation of the individual systems and for the project as a whole.

4.4.2 Duration-Based Cost

Duration-based cost is the total labor and equipment cost of the project. Costs per resource vary among different locations and companies. The costs assumed for the purposes of the case study presented in this dissertation were derived from interviews with contractors in Massachusetts. The costs for each crewmember are based on local 1998-1999 wages for plumbers and electricians in Boston. The costs include direct labor costs and workmen's compensation costs (which is 26% of direct labor wages for these 2 crews). Sprinkler and hot water heating systems installers are assumed to cost the same as plumbers in the Boston area. This assumption is based on the fact that many plumbing contractors perform these activities as well. For simplicity, the same hourly costs were extended to the crews of electricians, since the industry average values, in the Boston area, based on interviews with specialty contractors as well as general contractors, seemed to converge to the same costs identified for the plumbers.

Table 4.2 shows the key resources and their associated costs for plumbing and electrical installation. As the table shows, the total crew for both system types, in the Baker House renovation project, consists of 12 foremen/inspectors, 24 journeymen, and 12 apprentices. The crew remains consistent throughout the entire project. Journeymen perform the majority of the installation tasks in two-person teams, and the apprentice helps out with simple tasks as needed. The foreman performs some installation tasks, but spends the majority of his/her time supervising.

Both plumbers and electricians perform the majority of their installation tasks with their own set of hand tools. However, larger equipment may be necessary, for example, for the placement of heavier or thicker sections of pipe. For vertical piping, stack installation requires a hoist to lift and place the heavy pipe, but supply piping can be installed by hand. Also, large equipment or palletized loads of pipe or conduit sections are assumed to be delivered via forklift or crane to the desired location. The model assumes that the General Contractor provides these forklifts or cranes, and that they will be available whenever the sub-contractors need them. Since the use of larger pieces of equipment is only occasional in the installation of plumbing and electrical systems, these costs are not included for the purposes of this research. In order to account for these additional costs, a flat daily rate could be added for each of these pieces of equipment.

Resource Type	**Direct Labor**	**Workmen Comp (26%)**	**O&P (29%)**	**Cost per Hour**	**# per Crew**	**Total Cost/ Resource CrewHour**
Foreman	$ 39.15	$ 10.18	$ 11.35	$ 60.68	12	$ 728.16
Journeyman	$ 37.42	$ 9.73	$ 10.85	$ 58.00	24	$ 1,392
Apprentice	$ 33.95	$ 8.83	$ 9.85	$ 52.62	12	$ 631.44
		TOTAL	**CREW**	**Cost/Hour**	**=**	**$ 2,751.6**

Table 4.2: Key Resources and Associated Costs for Baker House Project

Duration-based cost is the sum of the duration-based costs for the installation of each system. The duration-based costs for the installation of each system is calculated as the product of the specific duration times the hourly cost of each type of worker/equipment in that crew, times the number of workers of each type present on the site. Duration-based cost can be expressed as

$$C^D_{Tot} = \Sigma_{i=1}^{N} \Sigma_{j=1}^{Mi} (R_{ij} C_{Rij} T_i)$$

where: C^D_{Tot} = total duration-based cost,

N = total number of systems in the facility,

M_i = total number of resource types in the crew allocated to the installation of system "i",

R_{ij} = total number of resources of type "j" in the crew allocated to the installation of system "i",

C_{Rij} = hourly cost of resource type "j" in the installation of system "i"

Ti = installation time for system "i".

4.4.3 Cost of Utilized Resources

The cost of utilized resources is the bare cost of performing the total number of activities required to complete the entire project, without considering resource idle time due to inter-system process dependencies.

The cost of utilized resources for a system is based on the total number of man hours, by labor category, required to perform each activity pertaining to the installation/placement of each entity type (e.g. part or component). The total number of man hours for each category of laborer are first multiplied by the average hourly cost of that particular type of laborer and then summed across the different categories of laborers. The cost for the whole project is obtained as the sum of the costs of utilized resources for each of the systems. The cost of utilized resources can be expressed as follows:

$$C^{UR}_{Tot} = \Sigma_{i=1}^{N} \Sigma_{j=1}^{Mi} C_{Rij} \{\Sigma_{k=1}^{Pi} [n_{ik} \Sigma_{q=1}^{Ak} (r_{jkq} T_{ikq})]\}$$

where: C^{UR}_{Tot} = total cost of utilized resources for the project

$\Sigma_{k=1}^{Pi} [n_{ik} \Sigma_{q=1}^{Ak} (r_{jkq} T_{ikq})] =$ total number of man hours required of laborers of type "j" in the installation of system "i".

$\Sigma_{q=1}^{Ak} (r_{jkq} T_{ikq}) =$ total number of man hours required of laborers of type "j" to perform activity "q" in the installation of one part of type "k".

Specifically, Pi = total number of part types in system "i",

n_{ik} = total number of parts of type "k" in system "i",

A_k = total number of activities for the installation of part "k",

r_{jkq} = total number of resources of type "j" required in activity "q' for the installation of part type "k",

$T_{ikq} =$ duration of activity "q" in the installation of part "k" in system "i"

The definition of the other variables remains the same as in section 4.4.2.

4.4.4 Percentage Resource Utilization

The percentage of resource utilization is measured as the ratio of the cost of utilized resources to the duration-based cost. This ratio measures the fraction of the dollar value of the time in which the resources were actually working on the project, as opposed to being idle. Resource utilization for the whole project is defined as

$$RU_{Tot}^{\%} = C^{UR}{}_{Tot} / C^{D}{}_{Tot}$$

for each of the systems it is defined as

$$RU_i^{\%} = C_i^{UR} / C_i^{D} \qquad i = 1,\ldots,N$$

Where N = total number of systems in the facility,

$C_i^{UR} = \Sigma_{j=1}^{Mi} C_{Rij} \{\Sigma_{k=1}^{Pi} [n_{ik} \Sigma_{q=1}^{Ak} (r_{jkq} T_{ikq})]\}$, as defined in section 4.4.3, and

$C_i^{D} = \Sigma_{j=1}^{Mi} (R_{ij} C_{Rij} T_i)$, as defined in section 4.4.2

4.4.5 Index of Worker Exposure to Dangerous Conditions

The index of worker exposure to dangerous condition, danger index in short, is a cumulative index that accounts for the frequency of occurrence of injuries during the performance of specific tasks and activities. Worker exposure to dangerous conditions during the installation/erection activities can be measured through a relative danger index. The danger index is based on Table 4.3, which lists the incidence rates of causes of injury in the construction industry (OSHA 1992).

Causes of injury in the Construction Industry	**Percentage**
Struck Against	8.0%
Struck By	21.0%
Caught in or Between	4.1%
Rubbed, Abraded or Penetrated	3.5%
Fall of Person (different level)	14.9%
Fall of Person (same level)	7.0%
Bodily Reaction	31.6%
Other (temperature, Radiation, Electrical Shock)	9.9%
TOTAL	**100%**

Table 4.3: Incidence Rates of Causes of Injury in the Construction Industry

The danger index for a particular installation activity is the sum of all the incidence rates associated with that activity multiplied by the total time that workers spend performing that activity. The danger index for the overall installation process of a system is the sum of all the danger indices associated with each of the activities within the process. The danger index for the whole facility is the sum of the danger indices of all the systems included in the facility.

As an example, the following table shows how the incidence rates associated to the different activities involved in the installation of the above-ground portion of the plumbing systems are calculated.

	Prepare Pipe	**Connect Pipe**	**Install Hangers**	**Install DWV Stacks**	**Install Supply Risers**	**Install Fixtures**	**Install Equip-Ment**
Struck Against							8.0%
Struck By		21%	21%	21%			
Caught in or between	4.1%			4.1%	4.1%		4.1%
Rubbed, Abraded	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Fall of Person (diff. level)		14.9%	14.9%				
Fall of Person (same level)		7.0%		7.0%	7.0%		
Bodily Reaction		31.6%	31.6%		31.6%	31.6%	31.6%
Other							
INCIDENCE RATE (%)	**7.6%**	**71%**	**71%**	**35.6%**	**42.6%**	**35.1%**	**47.2%**

Table 4.4: Incidence rates of injuries for the installation of plumbing systems (Murray 1999)

The danger index for the installation of a specific system is then calculated as the product of the incidence rate associated to each of the activities required to complete the installation of that system, times the total number of entities that require the performance of such activities, times that number of man hours required to perform one of such activities for one entity.

The index for the building as a whole is the sum of the indices associated with each of the systems, and can be expressed as follows:

$$D_{Tot} = \Sigma_{i=1}{}^{N} \Sigma_{k=1}{}^{Pi} [n_{ik} \Sigma_{q=1}{}^{Ak} (d_q \, r_{kq} \, \delta T_{ikq})]$$

Where: D_{Tot} = Index of workers exposure to dangerous conditions for the whole facility,

d_q = incidence rate for the performance of activity "q",

r_{kq} = number of resources required to perform activity "q" in the installation of part "k".

All other variables remain the same as defined in section 4.4.3.

The calculations of the different performance measures for the Baker House project (baseline) as well as for the alternative scenarios described in the result chapter are included in Appendix 2.

4.5 Validity, Reliability and Accuracy and Replicability of the Research Methodology

The scope of the research is the assessment of the role of process interdependencies on the performance of complex large-scale projects. The significance of the results heavily relies on the development of an effective methodology for the systematic assessment of process performance across multiple interdependent processes. Validity of the methodology establishes the ability of the methodology to measure process performance across multiple interdependent processes. The steps that led to a valid measurement of process performance include the appropriate definition of performance, the identification of process interdependencies and the characterization of their impacts on process, and the development of a tool for the measurement of performance. The impacts of process interdependencies can be highly unpredictable and can manifest their effects in unexpected forms. In order to capture all of these effects, performance was defined across multiple dimensions to ensure that all of the aspects of a project that are relevant to its success or failure would be captured.

The identification and the characterization of intersystem process dependencies was entirely based on empirical data gathered from actual construction projects. Repeated observations of over 100 construction projects were the basis for the identification of the types of process dependencies for different facility types and designs. To ensure variety of the sample, all kinds of occupied facility types and sizes were included in the observations. Interviews with specialty and general contractors, construction managers, architects and other experts allowed to tie the process interdependencies previously identified to the particular choice of facility systems and/or to the particular selection of construction means and methods. Detailed review of the construction documents, and particularly of the construction schedule for the different projects located the specific level in the design and process hierarchies where process interdependencies build their impacts on the project schedule. In particular empirical evidence showed that process interdependencies build their effects at the task/component level rather than at the aggregated level.

The ability to fully appreciate the impacts of intersystem process dependencies appeared clearly to depend on the availability of a tool that can represent the multiple processes involved in the construction of a built facility at such level of detail. Thousands of components and parts are involved in the realization of projects of high complexity and large scale, such as construction projects. Therefore computer-based simulation appeared to be the best approach to the detailed representation of multiple interdependent construction processes. This choice was strongly supported by the results of prior research. Computer-based dynamic simulation was effectively used to develop system and material specific models of construction activities for individual facility systems, as isolated from the others (Attai 1995; Carr 1998; Murray 1999). This research extends the modeling effort to the representation of such processes as simultaneous and mutually interconnected.

While the dynamic process simulation of construction activities produced accurate and reliable measures of process performance at the system and material specific level, additional verification was necessary to establish the same level of accuracy and reliability at the whole building level. Detailed design and construction data from an actual project, the renovation of Baker House, was collected through consultation of the construction documents and observation of the project during construction. A whole building metamodel was then built and customized with the data gathered from the project to simulate the simultaneous and co-located installation of the corresponding facility systems. The simulation results in terms of project duration, costs, and rate of progress for each of the systems as well as for the facility as a whole were compared to the actual project values to ensure consistency of representation. The duration for the whole project as provided by the simulation tool was 52.2 workdays which is well representative of the two and half months that took for the project to reach completion. The rates of progress obtained for the facility systems also mapped to the actual rates of progress observed on the site. The whole building simulation model was then validated with respect to accuracy and reliability for the baseline configuration of this project, and could be used for effective scenario testing.

This methodology for the assessment of the performance of multiple interdependent production processes is highly replicable and can be applied in similar contexts as long as a sufficiently large amount of empirical data is available for the identification and the characterization of the relevant inter-system process links. Modeling choices can vary, but the use of dynamic process simulation makes it the easiest to track, both in space and in time, the progress of interdependent processes at the detailed level of tasks and components. The availability of complete information on the design and production for a particular project can be used to check the accuracy and the reliability of the simulation model in terms of the relevant performance measures.

4.6 Summary

The methodology presented in this chapter develops a dynamic process simulation model to assess and compare production process performance across alternative combinations of designs and technologies. Data is collected from a large number of construction sites to characterize the elements of inter-system process dynamics that drive the spatial rate of progress for the different systems of a built facility during construction. The elements of process dynamics are organized within a framework of systems interactions that defines the spatial and logical links between construction activities at the detailed task and component level. These links identify the points in time and space where a status information transfer is required among activities. The completion of a critical process stage by specific spatial unit of progress is the status information that needs to be transferred to the corresponding dependent activities. A process simulation tool is developed that dynamically builds the cross-system project schedule based on the logic formalized within the framework. [Dynamic process simulation captures the dynamic nature of construction processes as opposed to static and deterministic representations of queuing and graphically based models.] The simulation tool includes a library of system and material specific modules. Modules can be linked to generate process architrectures that represent the construction of a whole facility. For each design alternative a whole building metamodel links the specified modules and tracks the status of critical process stages to ensures that the cross-system precedence relationships among activities are respected. A set of performance measures is defined to capture the relevant impacts of design and technology changes. Data from an actual construction project, the renovation of the Baker House dorm on the MIT campus, is used to customize the simulation model for an example application of the theory framework with respect to 10 project scenarios. The model is first validated with respect to the actual performance measures for the project (baseline scenario) and then used for the experimental analysis on the selected set of alternative scenarios.

CHAPTER 5 : RESULTS

5.1 Introduction

The introduction of design and technology changes impacts project performance at three levels: system, inter-system, and project level. This research demonstrates that the impacts of change in complex large-scale systems can be accurately tracked at all three levels, across multiple dimensions of performance. Specifically, the system level observes the effects of change within the system of introduction. The inter-system level tracks the effects as they ripple out to systems other than the one of first introduction. The whole project level captures the impacts on the performance of the overall project

This research analyzes 10 different project scenarios, including alternatives in design, technology and process constraints, and compares each scenario to the actual baseline design. Five performance measures reveal the different cost, duration and safety impacts at the system, inter-system and project levels. The measures are: 1) project duration, 2) duration-based cost, 3) cost of utilized resources, 4) percentage of resource utilization, and 5) worker exposure to dangerous conditions. As described in the methodology chapter, the duration-based cost represents the total cost of the project, assuming that all of the resources are present on the site for the entire duration of the project. The cost of utilized resources is the bare cost of performing all of the project activities and tasks, excluding resource costs of delays and wait times introduced by process interdependencies (both at the system level and at the inter-system level). The percentage of resource utilization is the ratio of these two costs. Worker exposure to dangerous condition is measured through an index that builds upon tabulated values of occurrence of injuries during the performance of specific construction tasks over the entire duration of the project. It is important to note that the choice of performance measures targets the assessment of the impacts of inter-system process dependencies. Measures such as duration and duration-based cost in fact are “dynamic” measures of performance, meaning that they account for the actuality of the duration and cost of the construction process because they reflect inter-system process dynamics. Measures of performance such as cost of utilized resources and worker’s exposure to dangerous conditions, as defined in chapter 4, are not dynamic in such sense. They are direct functions of the bare number of man hours required to complete the project without considering resource idle time due to inter-system process dynamics. Any discrepancies in the simulated results for these two sets of performance measures in this study is entirely determined by the effects of inter-system process links. The simulation of plumbing and electrical installation does not account for the impacts of resource downtimes (such as failure, maintenance and repair). The installation of plumbing pipes and electric conduits, in fact, is labor intensive and requires minimal use of large pieces of equipment (Murray 1999; Murphee 1999). Plumbers and electricians typically use their own sets of handtools to perform their job, therefore no significant impacts of resource downtime can be appreciated in those processes. This is not the case for example in the representation of mass manufacturing processes where machine failure, maintenance, and repair contribute to the gaps between the predictions of dynamic and non-dynamic measures of performance. Manpower shortage is the only effect similar to resource downtime that can be experienced in plumbing and electrical installation processes. The effects of manpower shortage are actually examined in the first alternative scenario, "reduced resources", presented in this study. As shown by the results for this scenario project duration is obviously stretched by the lack of manpower, but the difference between duration-based cost and cost of utilized resources is still driven by inter-system process dependencies.

In the following section a set of scenarios that are relevant to the Baker House renovation project are presented and examined with respect to the difference in prediction between dynamic and non-dynamic performance measures to assess the impacts of inter-system process dynamics. Resource utilization is also a measure of process dynamics since it is the ratio between cost of utilized resources and duration-based cost. Increases in resource utilization may reflect loose inter-system dependencies (little resource idle time due to inter-system process constraints) or excess resource allocation. Decreases in resource utilization reflect tight constraints among process activities and presence of bottlenecks, where the critical process stage constitutes a bottleneck for the performance of the corresponding dependent activities, or again shortage of manpower.

Table 5.1 presents the list of scenarios and highlights the major changes that each scenario entails as compared to the baseline configuration. Table 5.2 presents the simulation results of each scenario for the whole project. Tables 5.3 through 5.6 present the simulation results for each of the systems (i.e. fire protection, heating, plumbing and electrical).

Figures 5.1 and 5.2 present the simulated results obtained for the baseline design. The actual values of the 5 performance measures are shown for the project as a whole (indicated as "Total" in the figures) and for each of the facility systems. Throughout this chapter the values of the performance measures for the baseline scenario are used as the basis of comparison to assess the impacts of the changes introduced in the alternative scenarios.

	Plumbing	**Fire Prot**	**Heating**	**Electrical**
	• Risers: Prefabricated • Fixtures: Prefabricated	Horiz. Distr. : Prefabricated	Horiz. Distr. : Prefabricated	Reuse of Conduits
	• Risers: Prefabricated • Fixtures: Prefabricated • ***½ Resources***	• Horiz. Distr. : Prefabricated • ***½ Resources***	• Horiz. Distr. : Prefabricated • ***½ Rresources***	• Reuse of Conduits • ***½ Resources***
	• Risers: Prefabricated • Fixtures: Prefabricated • ***Shared Resources***	• Horiz. Distr. : Prefabricated • ***Shared Resources***	• Horiz. Distr. : Prefabricated • ***Shared Resources***	• Reuse of Conduits
	• Risers: Prefabricated • Fixtures: Prefabricated	Horiz. Distr. : Prefabricated	Horiz. Distr. : Prefabricated	***Replacement of Conduit***
	• Risers: Prefabricated • Fixtures: Prefabricated	***Horiz. Distr. : In situ***	Horiz. Distr. : Prefabricated	Reuse of Conduits
	• Risers: Prefabricated • Fixtures: Prefabricated	Horiz. Distr. : Prefabricated	***Horiz. Distr. : In situ***	Reuse of Conduits
ng	• ***Risers: In situ*** • Fixtures: Prefabricated	Horiz. Distr. : Prefabricated	Horiz. Distr. : Prefabricated	Reuse of Conduits

Scen 2-2-4 In situ Plumbing Fixtures	• Risers: Prefabriacted • ***Fixtures: In situ***	Horiz. Distr. : Prefabricated	Horiz. Distr. : Prefabricated	Reuse of Conduits
Scen. 3-1 Centralized	• Risers: Prefabricated • Fixtures: Prefabricated • ***Centralized***	• Horiz. Distr. : Prefabricated • ***Centralized***	• Horiz. Distr. : Prefabricated • ***Centralized***	Reuse of Conduits
Scen 3-2 Flexible Plumbing Horiz	• Risers: Prefabricated • Fixtures: Prefabricated • ***Centralized*** • ***Horiz. Distr: Flexible***	• Horiz. Distr. : Prefabricated • ***Centralized***	• Horiz. Distr. : Prefabricated • ***Centralized***	Reuse of Conduits
Scen 3-3 HVAC	• Risers: Prefabricated • Fixtures: Prefabricated	Horiz. Distr. : Prefabricated	• Horiz. Distr. : Prefabricated • ***System Type: HVAC***	Reuse of Conduits
Scen 4 Worst Case	• ***Risers: In situ*** • ***Fixtures: In situ***	***Horiz. Distr. : In situ***	***Horiz. Distr. : In situ***	***Replacement of Conduits***

TABLE 5.2 : SUMMARY OF RESULTS FOR THE WHOLE PROJECT

Design Alternative	Duration [days]	Duration-Based Cost [$]	Cost of Utiliz. Resources [$]	% Res. Utilization	Danger Index
Scenario 0 *Baseline Design*	52.2	2,977,829	2, 660,717	89.4	17,278
Scenario 1-1 *Reduced Resources*	95.9	2,962,284	2, 660,717	89.8	17,278
Scenario 1-2 *Shared Resources*	49.4	2,741,196	2, 660,648	97	17,278
Scenario 2-1 *Replacement of Electric*	54.4	3,002,880	2,731,629	91	17, 910
Scenario 2-2-1 *In-Situ Fire Protection*	52.2	3,002,513	2,774,251	92.4	17,434
Scenario 2-2-2 *In-Situ Heating*	57.9	3,211,205	2,793,125	87	17,460
Scenario 2-2-3 *In-Situ Plumb. Risers*	63.9	3,233,645	2,993,411	92.6	19,802
Scenario 2-2-4 *In-Situ Plumb. Fixt.*	53.8	3,067,854	2,853,987	93	17,544
Scenario 3-1 *Centralized*	84.6	3,870,288	2,449,299	63.3	15,867
Scenario 3-2 *Centralized & Flexible*	48.5	2,935,560	2, 336,293	79.6	15,062
Scenario 3-3 *Air-Based Heating*	48.3	2,913,817	2, 673,107	92	17,351
Scenario 4 *Worst Case Scenario*	75.6	3,682,669	3,503,625	95	20406

TABLE 5.3 : SUMMARY OF RESULTS FOR FIRE PROTECTION

Design Alternative	Duration [days]	Duration-Based Cost [$]	Cost of Utiliz. Resources [$]	% Res. Utilization	Danger Index
Scenario 0 *Baseline Design*	40.4	660,960	555,359	84	4,279
Scenario 1-1 *Reduced Resources*	80.3	655,860	555,359	84.7	4,279
Scenario 1-2 *Shared Resources*	----	----	-----	-----	-----
Scenario 2-1 *Replacement of Electric*	40.4	660,960	555,359	84.02	4,279
Scenario 2-2-1 *In-Situ Fire Protection*	42	685,644	668,894	97.6	4,435
Scenario 2-2-2 *In-Situ Heating*	40.4	660,960	555,359	84	4,279
Scenario 2-2-3 *In-Situ Plumb. Risers*	40.4	660,960	555,359	84	4,279
Scenario 2-2-4 *In-Situ Plumb. Fixt.*	40.4	660,960	555,359	84	4,279
Scenario 3-1 *Centralized*	84.6	1,380,264	555,359	40.2	4,279
Scenario 3-2 *Centralized & Flexible*	44.5	726,240	555,359	76.5	4,279
Scenario 3-3 *Air-Based Heating*	40.4	660,960	555,359	84	4,279
Scenario 4 *Worst Case Scenario*	42	685,644	668,894	97.6	4,435

TABLE 5.4 : SUMMARY OF RESULTS FOR HEATING

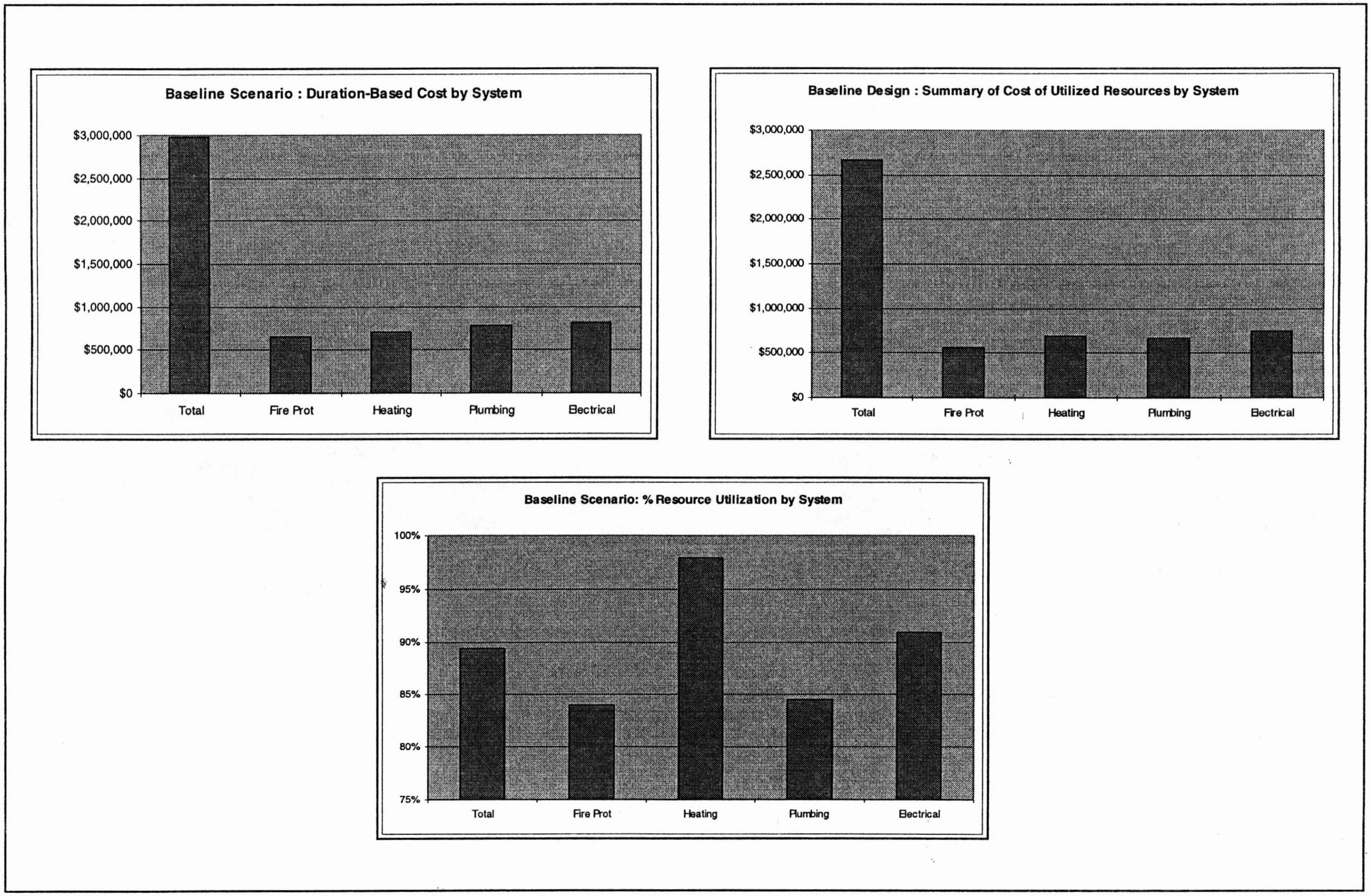
Design Alternative	Duration [days]	Duration-Based Cost [$]	Cost of Utiliz. Resources [$]	% Res. Utilization	Danger Index
Scenario 0 *Baseline Design*	43.3	707,880	693,419	98	4,885.6
Scenario 1-1 *Reduced Resources*	93.3	761,940	693,419	91	4,885.6
Scenario 1-2 *Shared Resources*	----	----	-----	-----	-----
Scenario 2-1 *Replacement of Electric*	43.3	707,880	693,419	98	4,885.6
Scenario 2-2-1 *In-Situ Fire Protection*	43.3	707,880	693,419	98	4,885.6
Scenario 2-2-2 *In-Situ Heating*	52	849,660	825,828	97.2	5067.6
Scenario 2-2-3 *In-Situ Plumb. Risers*	43.3	707,880	693,419	98	4,885.6
Scenario 2-2-4 *In-Situ Plumb. Fixt.*	43.3	707,880	693,419	98	4,885.6
Scenario 3-1 *Centralized*	48	785,400	385,432	49.1	2,861.5
Scenario 3-2 *Centralized & Flexible*	48	785,400	385,432	49.1	2,861.5
Scenario 3-3 *Air-Based Heating*	43.4	710,335	705,809	99.4	4,958.4
Scenario 4 *Worst Case Scenario*	52	849,660	825,828	97.2	5067.6

TABLE 5.5 : SUMMARY OF RESULTS FOR PLUMBING

Design Alternative	Duration [days]	Duration-Based Cost [$]	Cost of Utiliz. Resources [$]	% Res. Utilization	Danger Index
Scenario 0 *Baseline Design*	48.3	787,440	665,322.8	84.5	4,297.6
Scenario 1-1 *Reduced Resources*	95.3	782,340	665,322.8	85	4,297.6
Scenario 1-2 *Shared Resources*	43.4	1,936,620	1,914,101	98.8	17,278
Scenario 2-1 *Replacement of Electric*	48.3	787,440	665,322.8	84.5	4,297.6
Scenario 2-2-1 *In-Situ Fire Protection*	48.3	787,440	665,323	84.5	4,297.6
Scenario 2-2-2 *In-Situ Heating*	48.3	787,440	665,323	84.5	4,297.6
Scenario 2-2-3 *In-Situ Plumb. Risers*	63.9	1,043,256	998,017.5	95.7	6,821.6
Scenario 2-2-4 *In-Situ Plumb. Fixt.*	53.8	877,465.2	858,593	97.8	4,563
Scenario 3-1 *Centralized*	57.8	942,480	761,893	80.8	4,910.4
Scenario 3-2 *Centralized & Flexible*	40.5	661,776	648,886	98	4,105.4
Scenario 3-3 *Air-Based Heating*	48.3	787,440	665,323	84.5	4,298
Scenario 4 *Worst Case Scenario*	75.6	1,234,200	1,191,287	96.5	7087

TABLE 5.6 : SUMMARY OF RESULTS FOR ELECTRICAL

Design Alternative	Duration [days]	Duration-Based Cost [$]	Cost of Utiliz. Resources [$]	% Res. Utilization	Danger Index
Scenario 0 *Baseline Design*	52.2	821,549	746,615	90.9	3,816
Scenario 1-1 *Reduced Resources*	95.6	762,144	746,615	98	3,816
Scenario 1-2 *Shared Resources*	49.4	804,576	746,615	93	3,816
Scenario 2-1 *Replacement of Electric*	54.4	846,660	817,528	97	4,448
Scenario 2-2-1 *In-Situ Fire Protection*	52.2	821,549	746,615	90.9	3,816
Scenario 2-2-2 *In-Situ Heating*	57.9	913,145	746,615	81.8	3,816
Scenario 2-2-3 *In-Situ Plumb. Risers*	52.2	821,549	746,615	90.9	3,816
Scenario 2-2-4 *In-Situ Plumb. Fixt.*	52.2	821,549	746,615	90.9	3,816
Scenario 3-1 *Centralized*	48.6	762,144	746,615	97.6	3,816
Scenario 3-2 *Centralized & Flexible*	48.6	762,144	746,615	97.6	3,816
Scenario 3-3 *Air-Based Heating*	48	755,082	746,615	98.9	3,816
Scenario 4 *Worst Case Scenario*	58.5	953,944	817,528	85.7	4,448



Baseline Scenario : Duration-Based Cost by System

Baseline Design : Summary of Cost of Utilized Resources by System

Baseline Scenario: % Resource Utilization by System

Figure 5.1 : Summary of Results for the Baseline Scenario

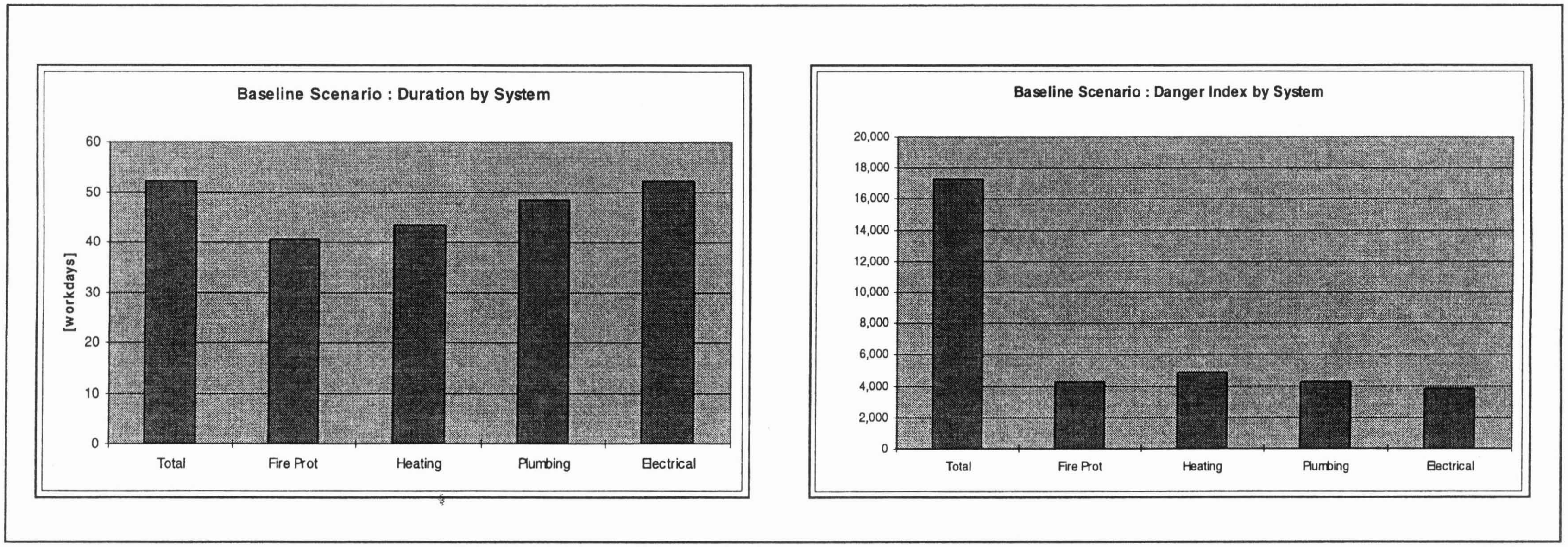


Figure 5.2 : Summary of Results for Scenario Baseline Scenario (continued)

5.2 Project Scenarios

Three major sets of scenarios corresponding to three distinct levels of change were analyzed with respect to the actual design of Baker House as the baseline configuration. These three sets include changes in process constraints, changes in design alternative, and changes in technology alternative, to cover all the possible types of changes that impact production performance. Design changes range from changes in the design alternative (system types), to changes in individual parts and components, to changes in system layout. Process changes vary the nature and/or the number of activities to be performed, while changes in process constraints directly affect the nature and the location of the links among production activities. These changes are not independent of one another, in fact design changes affect the number and types of production activities, and both design and process changes influence the nature and the location (in space and time) of the links among production activities.

The specific types of changes that are tested within each of the three sets are chosen to be relevant to the Baker House Project. The scenarios and simulated experiments primarily target the innovations introduced in the actual project, such as extensive prefabrication of parts and components (process change in number and type of activities). For these experiments, the scenarios assess the impacts of lack of innovation (e.g. lack of prefabrication) as represented by the standard industry practices (e.g. in-situ fabrication of parts and components). Other scenarios explore alternative solutions that may have been considered at the design and project planning stages. Among these are the adoption of a completely centralized layout for the plumbing systems (design change in layout), the use of flexible plumbing pipes in combination with a centralized layout (design change in materials and components), the installation of HVAC rather than hot water heating systems (design change in system type), and the allocation of a single pool of resources (e.g. plumbers) to the installation of the three water-based service systems: fire protection, hot water heating and domestic plumbing (change in process constraints: resource allocation and system definition).

A total number of 10 project scenarios are presented in this chapter. The results from each scenario are analyzed in comparison to the baseline. [For each scenario] charts are presented that compare the absolute values of each performance measure to the corresponding ones in the baseline. Summary tables also provide the percentage change for each performance measure with respect to the baseline at the whole project level. Similar tables are built for the results at the system and inter-system levels whenever relevant impacts at such levels are observed.

5.2.1 Impacts of Process Constraints

In the realization of complex large-scale systems, process constraints (namely technical, logical, resource and regulatory constraints) determine process dynamics. Process constraints actively shape the nature and the timing of the precedence relationships among processes and activities during construction, and thus significantly impact project schedule, cost and safety. While logical, technical, and regulatory constraints are fixed once the project is specified and cannot be changed in order to better meet project objectives, resource constraints can be controlled at any time during a project, by varying the type and the number of resources allocated. Resource allocation assumes the highest importance in the construction industry where labor costs account for almost half of the total cost of a project (Means 1998). As part of this case study, two scenarios were analyzed which involve changes in resource allocation with respect to the actual project plan. The first scenario reduces the number of resources at the crew level compared to the number of resources originally planned to be on site for each trade. The second scenario combines the crews assigned to the installation of the water distribution systems (domestic plumbing, hot water heating and fire protection systems) into a single pool of resources.

No change of the input files was required to test these two scenarios since resource definition and allocation is a function that is built into the simulation environment and can easily be customized for each simulation run. Most importantly, no changes needed to be made in the process flow or interdependencies. Therefore, the structure of the metamodel (i.e. the logical interdependencies among the processes at the detailed component and spatial level) remains unchanged for these two scenarios.

5.2.1.1 Scenario 1-1: Reduced Resources

Given the short completion times that the contractor was given to complete this project, an unusually large number of resources per trade was allocated to the installation of each system, on each floor. Each floor was split into quadrants and two workers per trade were assigned to each quadrant. A total of 48 workers per trade were scheduled to be present on the site at all times. Under such conditions, the possibility of resources being a constraint on this project was minimal. The original project plan represents a scenario with minimal resource constraints. A new scenario was then created, where the impacts of resource constraints could be evaluated. Specifically, the size of each crew was reduced by 50%. Process performance was tested under the new conditions and compared to that of the original resource allocation plan. The new scenario represents a form of sensitivity test, to examine where and how the shortage of resources could create bottlenecks in the project. (As a matter of fact, a shortage of manpower was experienced during project execution since the planned number of resources was never available on the site. On average the number of resources available for each crew was 50% or less than planned at all times. Significant overtime work was necessary to keep the project on schedule due to such manpower shortage). Therefore, this scenario is representative of the actuality of the project as compared to the initial plan, and shows how much longer the project would have taken to complete if the crews had not worked overtime.

Changes in the Metamodel

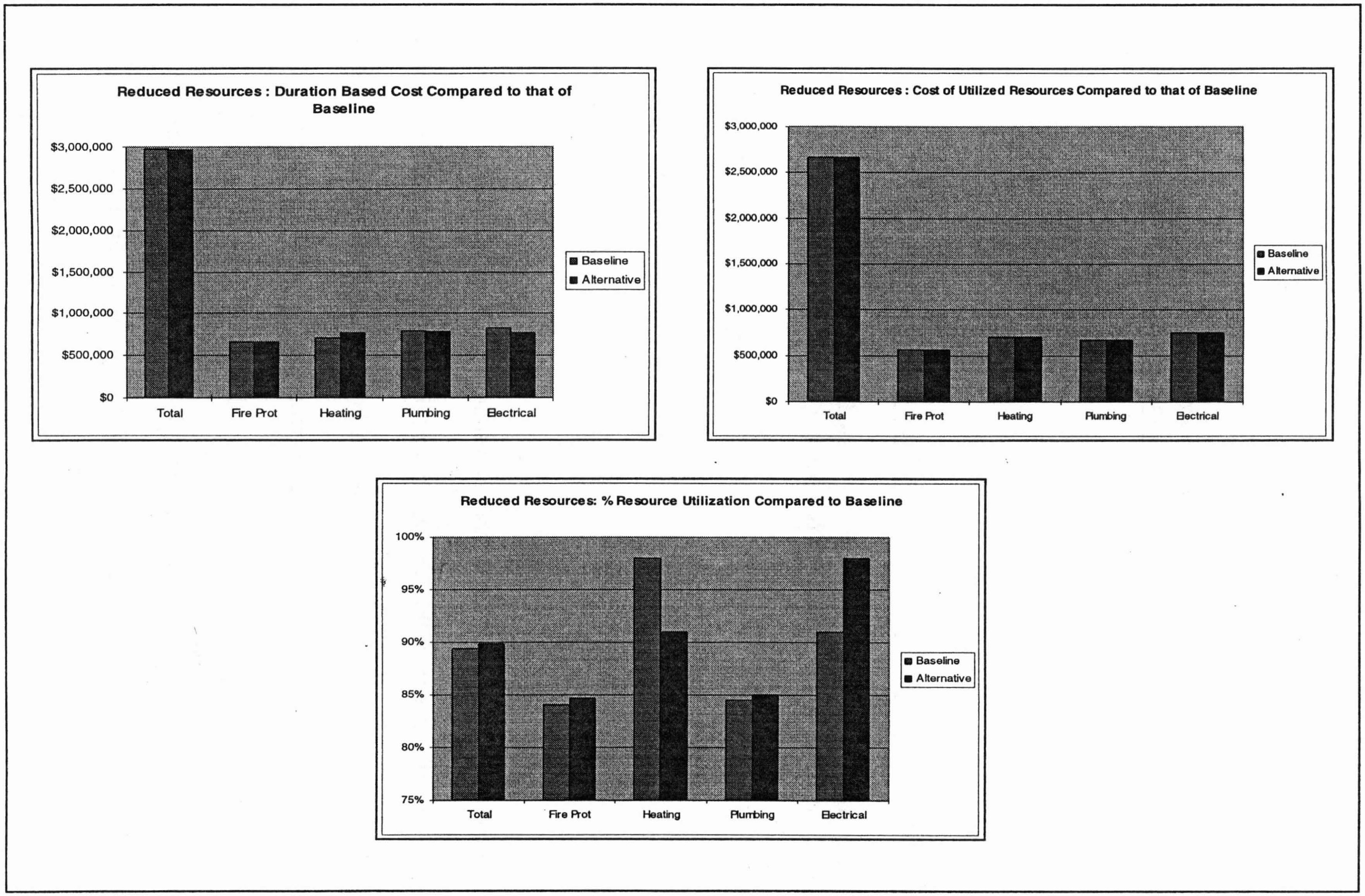
The study of process with limited resources does not entail any significant change in the process models or in the input files. The facility design remains unchanged and so do the construction means and methods. The logical interdependencies among the processes are also unchanged. The difference is only in the number of resources available for each crew. As shown in Table 5.7, the total number of foremen, journeymen and apprentices for each trade and subcontractor involved in the project is reduced by half.

Type Of Resources	Original Number Of Resources	New Number Of Resources
Foremen	6	3
Journeymen	24	12
Apprentices	12	6
Inspectors	6	3

Table 5.7 : Distribution of Resources at the Crew Level for Scenario 1-1 compared to Baseline

Results

As shown in Table 5.2, reducing the number of resources by 50% at the crew level nearly doubles the overall duration of the project, from 52 days in the baseline configuration to 96 days. Interestingly, the duration-based cost remains virtually unchanged as compared to the baseline, proving that the major impact of reducing the number of resources is to stretch the duration of the project over a longer period of time. Consistently, both the cost of utilized resources and the danger index are exactly the same as those calculated for the baseline configuration, since no changes in design or construction methods were introduced in this scenario. In fact, no changes in the design implies that the number of

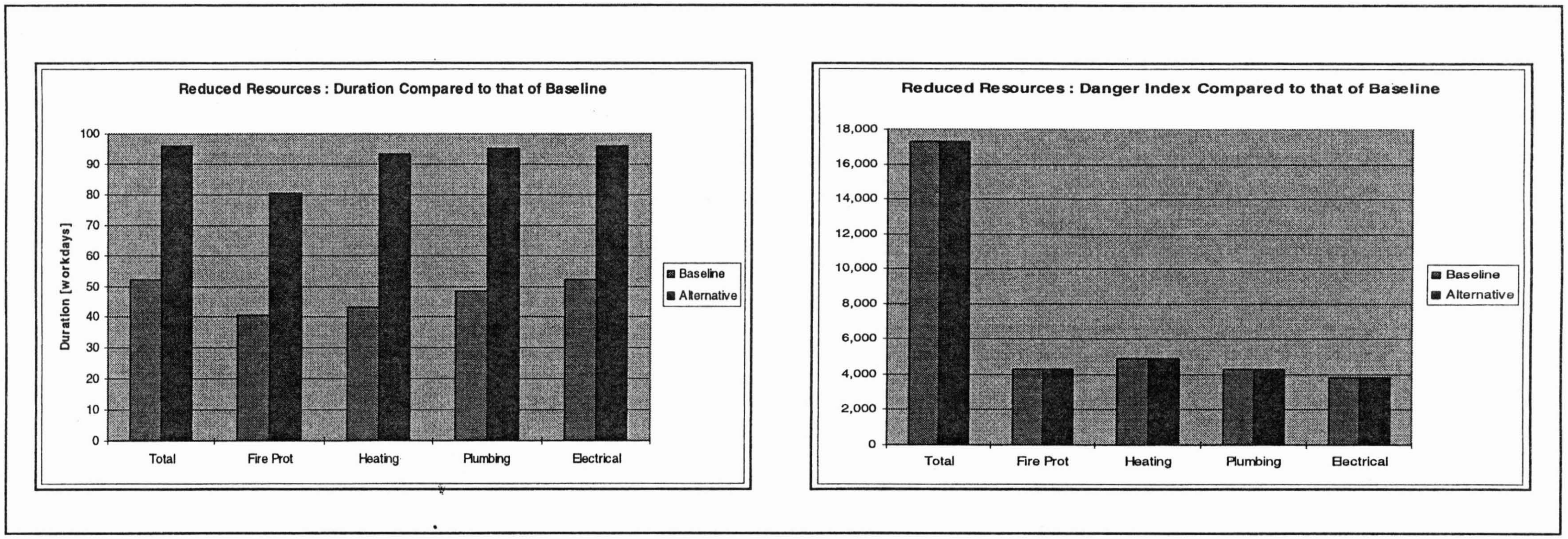


Reduced Resources : Duration Based Cost Compared to that of Baseline

Reduced Resources : Cost of Utilized Resources Compared to that of Baseline

Reduced Resources: % Resource Utilization Compared to Baseline

Figure 5.3 : Summary of Results for Scenario 1-1 (Reduced Resources) Compared to Baseline



Reduced Resources : Duration Compared to that of Baseline

Reduced Resources : Danger Index Compared to that of Baseline

Figure 5.4 : Summary of Results for Scenario 1-1 (Reduced Resources) Compared to Baseline (continued)

parts and components to be installed is the same. No changes in the construction methods implies that the number and types of activities to be performed is exactly the same as in the baseline scenario. Consequently, the number of man-hours required to complete the project does not change, and project duration is only a function of resource availability.

Performance Measure	% Change
Duration	+ 84%
Duration-Based Cost	- 0.5%
Cost of Utilized Resources	No Change
% Resource Utilization	+ 0.5 %
Danger Index	No Change

Table 5.8: Impacts at the Whole Project Level for Scenario 1-1

The same discussion applies to each of the systems individually, since this particular scenario does not introduce additional process interdependencies. However, project duration in this case is driven by the installation of the plumbing system.

5.2.1.2. Scenario 1-2 : Shared Resources

This scenario combines the crews assigned to the installation of the water distribution systems (domestic plumbing, hot water heating and fire protection systems) into a single pool of resources to assess the benefits of shared and re-assignable resources. In the actual project, separate sub-contractors were in charge of the installation of each of the water distribution systems: domestic plumbing, fire protection, and heating. A new scenario was created were a single sub-contractor would be in charge of the installation of the three water distribution systems. At a first glance, this change seems to be merely an organizational alternative since the number of resources (namely plumbers) allocated to the job remains unchanged. However, its implications in terms of the process dynamics reach far beyond pure administrative grounds. In particular, this scenario shows how the optimal resource allocation within the scope of installation of each individual system may be sub-optimal for the performance of the project as a whole.

Changes in the Meta-Model

As mentioned above, the scenario with shared and re-assignable plumbing resources does not entail any significant change in the process models, in the input files, or in the logical interdependence of the processes. The facility design remains unchanged and so do the construction means and methods. The change only nominally affects the type of resources [and do not alter either the process flow, the construction methods (and thus the structure of the Meta-Model) or the design (and thus the input files)]. Table 5.9 shows the change in resource that was introduced to study this scenario.

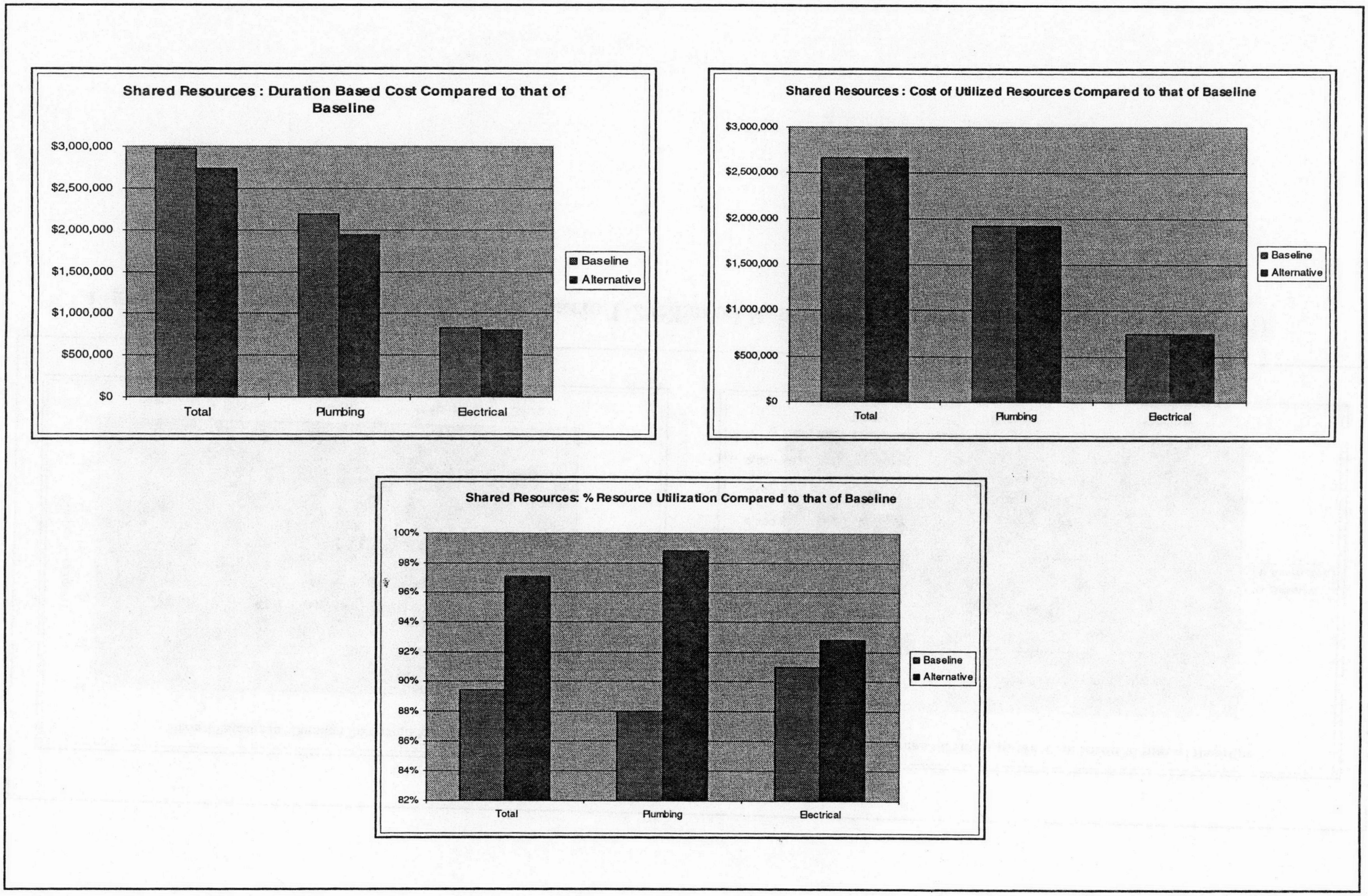
Type Of Resources	Original Number Of Resources Per Crew *	New Number Of Resources To be shared
Foremen	6	18
Journeymen	24	72
Apprentices	12	36
Inspectors	6	18

* For the 3 crews (plumbing, fire protection and heating)

Table 5.9 : Distribution of Resources for the Shared Crews in Scenario 1-2

Results

At the whole project level, significant benefits of shared and reassignable resources can be observed. As shown in Table 5.10, the reduction in project duration and duration-based cost increase the percentage of resource utilization. Again, both the cost of utilized


Shared Resources : Duration Based Cost Compared to that of Baseline

Shared Resources : Cost of Utilized Resources Compared to that of Baseline

Shared Resources: % Resource Utilization Compared to that of Baseline

Figure 5.5 : Summary of Results for Scenario 1-2 (Shared Resources) Compared to Baseline

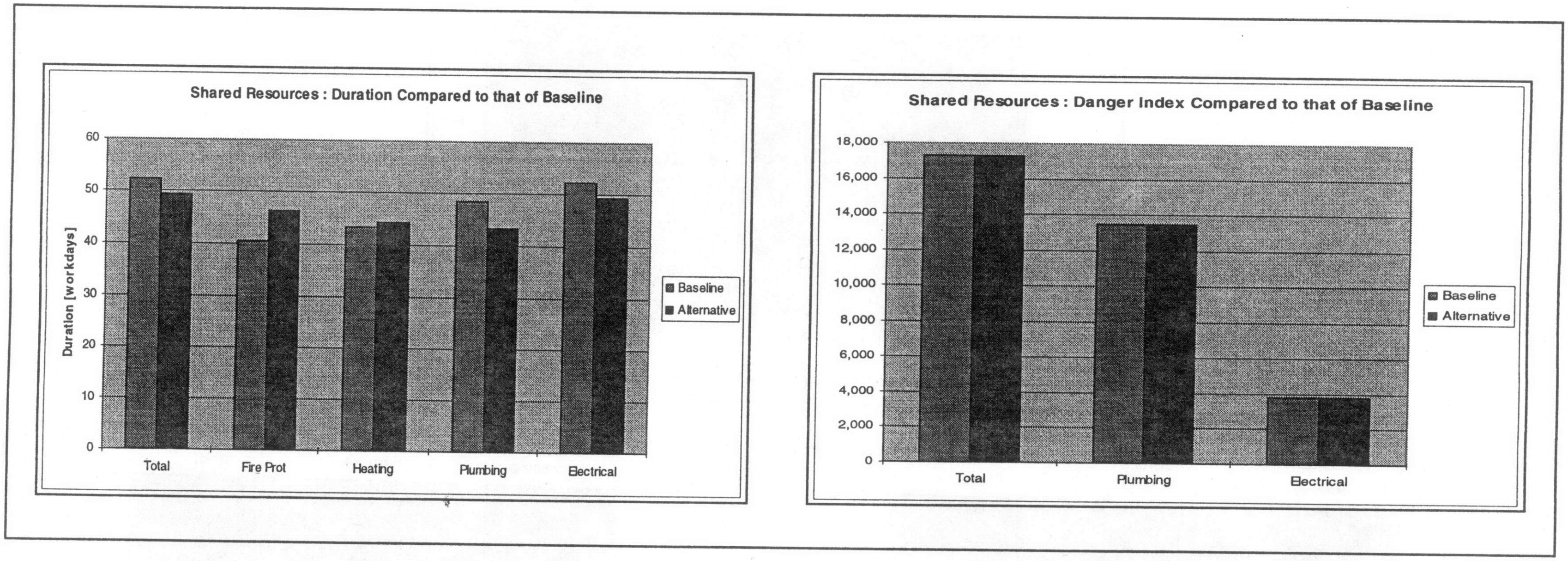


Figure 5.6 : Summary of Results for Scenario 1-2 (Shared Resources) Compared to Baseline (continued)

resources and the danger index for the project remain the same as in the baseline configuration, since this scenario does not introduce changes in either the design or the construction methods.

Performance Measure	**% Change**
Duration	- 5 %
Duration-Based Cost	- 8 %
Cost of Utilized Resources	No Change
% Resource Utilization	+ 9 %
Danger Index	No Change

Table 5.10: Impacts at the Whole Project Level for Scenario 1-2

The duration for the fire protection and heating systems increases, but it decreases for the plumbing system. The installation of the plumbing system, which has the largest number of parts and components to be placed, absorbs most of the resources at the beginning of the project, thus pushing forward the start times for the installation of fire protection and heating. Towards the end of the project, most of the plumbing resources are allocated to the installation of heating and fire protection. On average this distribution of resources over time results into a shorter completion schedule for the combination of the three water distribution systems and, thus, leads to lower duration-based cost (10% lower than in the baseline for the combination of the 3 systems). Lower duration-based cost leads to significantly higher resource utilization (17% higher), since the cost of utilized resource, as explained above, does not change.

Performance Measure	**% Change**
Duration	- 10 %
Duration-Based Cost	- 10 %
Cost of Utilized Resources	No Change
% Resource Utilization	+ 17 %
Danger Index	No Change

Table 5.11: Impacts on the Combined Water-Based Systems for Scenario 1-2

Interesting impacts can be observed at the intersystem level. The installation of the electrical system also benefits from the flexibility in resource allocation among the water distribution systems. As in the baseline configuration, there is an important process link between the heating and the electrical systems. Spatial requirements impose that the horizontal distribution of heating pipes be in place on a given floor before the installation of the horizontal conduits for the electrical system can start on that same floor. The availability of more plumbing resources for the installation of the heating conduits towards the end of the project speeds up the placement of these horizontal pipes, thus reducing idle time for the crews of electricians during the installation of the horizontal conduits. Shorter idle time results in faster installation, reduced duration-based cost and higher resource utilization for the electrical system as well.

Performance Measure	% Change
Duration	- 5 %
Duration-Based Cost	- 2 %
Cost of Utilized Resources	No Change
% Resource Utilization	+ 2 %
Danger Index	No Change

Table 5.12: Impacts at the Inter-System Level for Scenario 1-2 (Electrical)

At the system level the presence of a single sub-contractor allows for optimal resource allocation among the three water distribution systems, which minimizes the overall installation time and cost for the combination of the three systems. Process interdependencies between the heating and the electrical system allow the benefits from the flexibility in resource allocation in the water-based systems to improve process performance for the electrical system. In particular, the reduction in the installation time for the electrical system directly impacts the performance of the project as a whole. In this scenario, the duration of the whole project is driven by the installation of the electrical system, so any reduction in installation time for the electrical system translates into an equivalent reduction in project duration (5% in this case).

5.2.2 Impacts of Process Alternatives

Process alternatives are defined as changes in the means and methods by which a facility is constructed compared to the standard industry practices.

Two significant process alternatives were introduced by the contractor on the Baker House project. Both alternatives were used as objects of scenario testing and compared to the standard practices. The first process alternative is the re-use of existing conduits for the distribution of electrical wiring, as opposed to the full replacement of both conduits and wiring. The second one is the extensive use of prefabricated units for the water distribution systems, both vertical components (i.e. risers) and horizontal distribution (i.e. fixtures) for the plumbing system, and horizontal distribution (i.e. pipe segments) for the hot water heating and the fire protection systems.

5.2.2.1. Scenario 2-1: Reuse vs. Replacement of Existing Electrical Conduits

The first process alternative that was tested is the replacement versus the re-use of the existing electrical conduits. According to the standard procedures for the installation of the electrical systems, the conduits are placed first and then the electric wires are pulled through (Murphee 1999). The process alternative introduced for the realization of this project, skips the activities associated with the placement of new conduits and simply pulls the wires through the existing ones.

According to the facility design, each room includes a total of four distinct electrical fixture groups, and each of them needs to be fed by one or more branches. Specifically, each room includes four outlets, one smoke detector, two overhead lights and one main switch. In addition, there are electrical installations in the corridors, in the bathrooms, in the laundry facilities and in all the other administrative and common areas. The total number of branches equals 1,928.

Given the large number of branches involved in the horizontal distribution of the electrical service, significant time and cost savings could be expected from the re-use of the existing conduits. Simulated results for this scenario show that inter-system process dependencies actually absorb most of the projected benefits from changes introduced at the system level. In this case, the process link between the heating system and the electrical system absorbs the effects of faster installation for the electric conduits, and thus only minor benefits can be appreciated in the performance of the whole project.

Changes in the Meta-Model

The installation of the horizontal distribution for the electrical service involves two major sets of activities that can be performed in parallel. The first one is the installation of the fixtures, and the second one is the installation of the conduits, runs and branches respectively.

The process by which the horizontal conduits are installed varies depending on the type and rigidity of the material of which they are made. The electrical module of the metamodel is set up to distinguish among different types of conduits and route them into different processes accordingly.

Specifically, the four types of conduits which are represented in the metamodel are: flexible, semi-rigid (or wiremold), rigid and pull-only (Murphee 1999).

While the conduits are by design of the rigid type, and, thus would require installation before the inner wires can be pulled through them, in the actual project the existing conduits were not stripped off and replaced, thus leaving wire pulling as the only process required for the horizontal installation.

In the metamodel, the only change required for the testing of this scenario was at the input file level: the routing attribute for each branch was set to "rigid", and the "place conduit" sub-process was included

Results

As anticipated during the design stage, the placement of new conduits leads to larger electrical installation time and costs. However, given the large number of fixtures and, thus, the large number of branches to be installed, the magnitude of the impacts from the placement of new conduits, both at the whole project level and at the system level, does not reflect the actual increase in the number of activities to be performed.

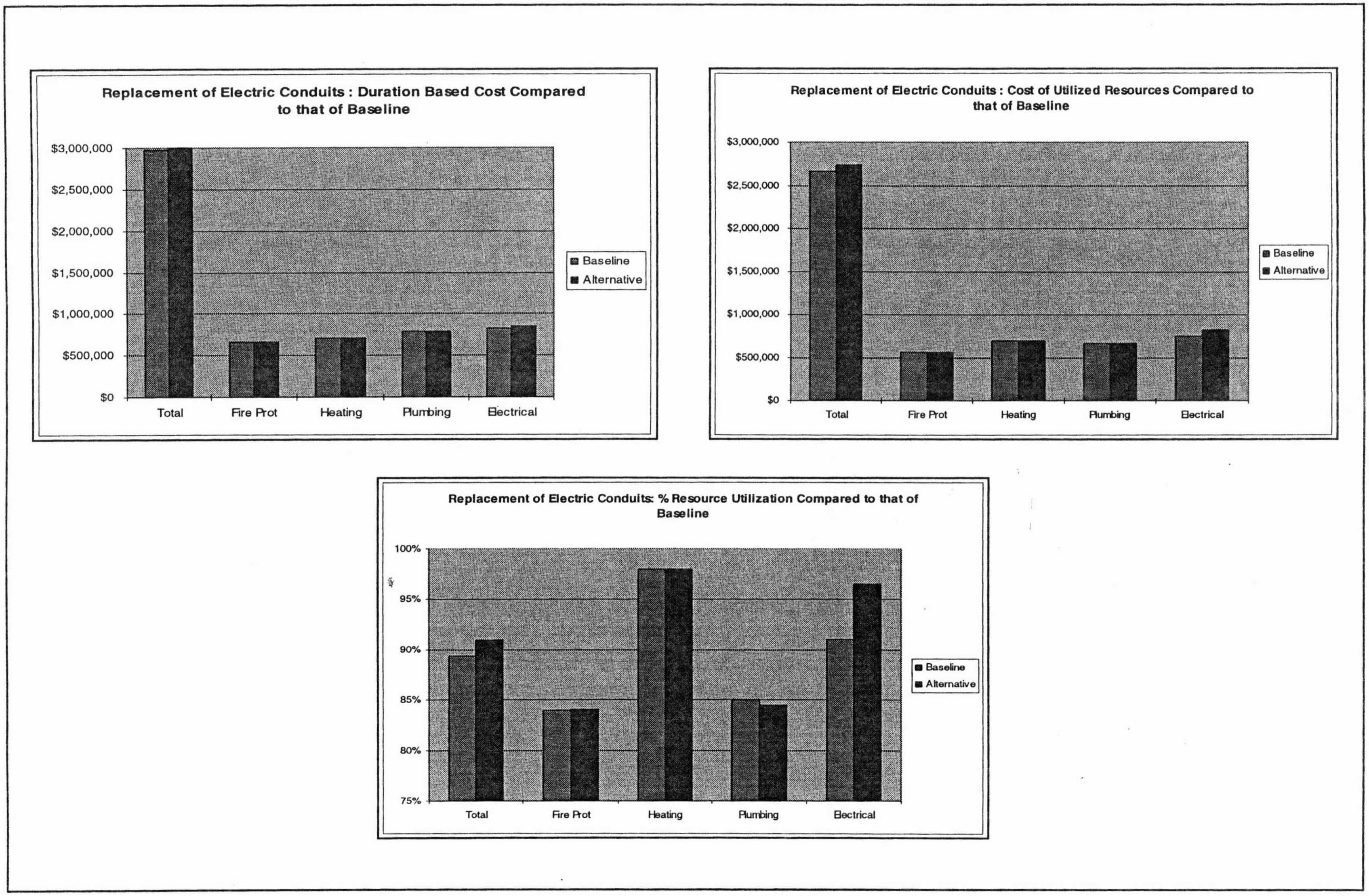
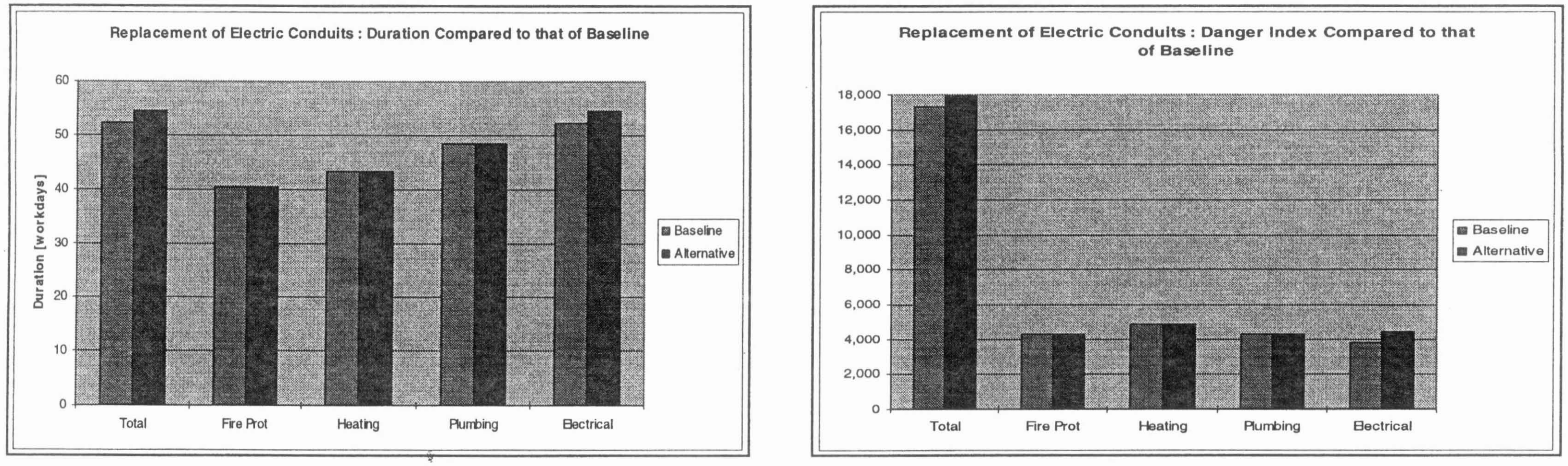


Figure 5.7 : Summary of Results for Scenario 2-1 (Replacement of Electric Conduits) Compared to Baseline



Replacement of Electric Conduits : Duration Compared to that of Baseline

Replacement of Electric Conduits : Danger Index Compared to that of Baseline

Figure 5.8 : Summary of Results for Scenario 2-1 (Replacement of Electric Conduits) Compared to Baseline (continued)

In this scenario, the installation of the electrical system drives the duration and cost of the whole project, therefore the increase in installation time for the system is directly reflected in an equivalent increase in project duration.

Table 5.13 and Table 5.14 summarize, respectively, the impacts at the whole project level and the impacts at the system level on each of the performance measures with respect to the baseline scenario.

Performance Measure	**% Change**
Duration	+ 4%
Duration-Based Cost	+ 0.8%
Cost of Utilized Resources	+ 2.7 %
% Resource Utilization	+ 1.8 %
Danger Index	+ 3.6 %

Table 5.13: Impacts at the Whole Project Level for Scenario 2-1

A high increase in cost of utilized resources reveals, as expected, an increase in the number of man hours required to complete the installation of the electrical system. The increase in the cost of utilized resources, both for the whole project and for the electrical system, is significantly (approximately three times) higher than the increase in duration-based cost. This difference shows that the performance of additional activities for the placement of new electric conduits does not add directly to project duration and duration-based cost, but takes up some of the resource idle time that was experienced in the baseline scenario. A reduction in resource idle time is actually reflected by the increase in percentage resource utilization both at the system level and at the whole project level. The increase in worker's exposure to danger is also a result of the increased number of activities to be performed to complete the project/system installation, each carrying a specified danger index per man hour.

Performance Measure	**% Change**
Duration	+ 4%
Duration-Based Cost	+ 3%
Cost of Utilized Resources	+ 9.5%
% Resource Utilization	+ 6 %
Danger Index	+ 16.5%

Table 5.14: Impacts at the System Level for Scenario 2-1

At the intersystem level, changes in the electrical installation do not affect the performance of any other system. However, as observed before, the presence of an inter-system process link between the heating system and the electrical system causes the effects of this process change increases duration, cost and worker exposure to dangerous conditions, both at the system level and at the whole project level.

The second set of process alternatives includes four different scenarios corresponding to the four types of units which were fabricated off-site in this project. Respectively the horizontal water distribution pipes for the heating and fire protection systems and the vertical risers and the fixture groups for the plumbing system. The impacts of prefabrication were studied separately for each system and unit type.

The availability of prefabricated elements, which are delivered to the site ready for installation, has an impact on project duration and labor cost. Avoiding on-site preparation and assembly can save time and reduce worker's exposure to danger and potential injuries. Simulated results for the different scenarios show how the impact of prefabrication highly depends on the extent of prefabrication (e.g. percentage of the whole that is fabricated off-site) and on the inter-system process dependencies that link the system of introduction to the other systems.

5.2.2.2. Scenario 2-2-1: In-situ Fabrication vs. Prefabrication of Fire Protection Pipes.

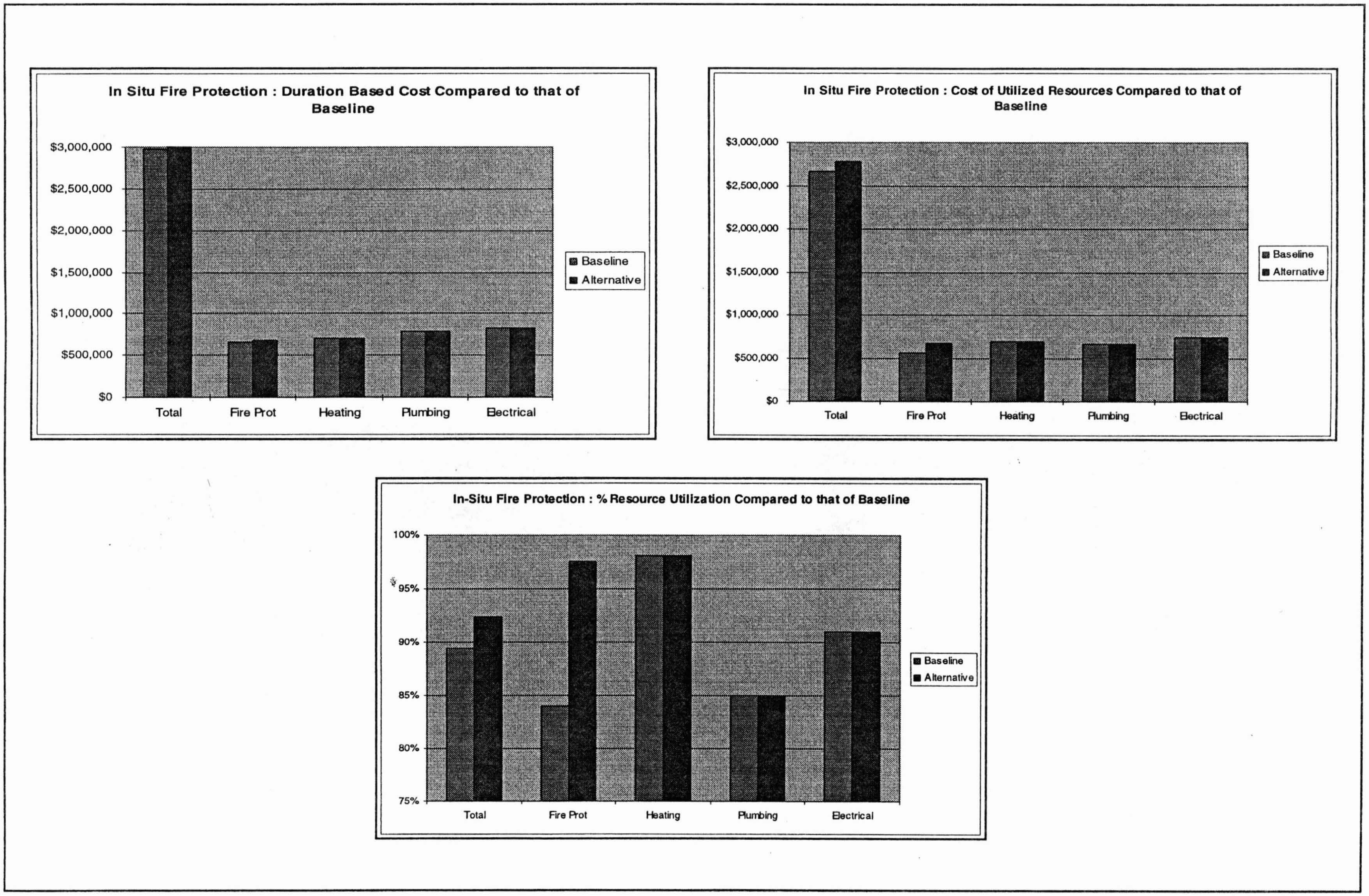
The layout of the fire protection system is fairly centralized and the horizontal distribution follows the shape of the building along the length of the main corridor, crossing through the room partitions. In the baseline configuration, the segments of the horizontal distribution pipes are prefabricated to the length of each room and already include the required bends. All of the segments are prefabricated (100% extent of prefabrication) and do not require any preparation work before installation. This scenario assesses the impacts of in-situ fabrication versus prefabrication of the fire protection horizontal pipes.

Changes in the Meta-Model

Pipe preparation, including cutting, bending and threading, is a sub-process of pipe installation which can be performed in parallel with the placement of the hangers and the coring activities. While the standard version of the metamodel includes by default the preparation stage in the installation process, for the purposes of this scenario, an alternative path was built which excludes the preparation phase. A value of the variable "Prefabrication" can be set for each branch in the corresponding input file. By switching from "yes" to "no" it is possible to represent the in-situ fabrication of the horizontal units.

Results

The impacts of in-situ fabrication at the whole project level are not particularly high. The project completion time is still driven by the installation of the electrical system, thus there is no change in overall project duration. Minimal impacts can be observed on duration-based cost and percentage of resource utilization. Moderate ones can be observed on cost of utilized resources and on danger index.


In Situ Fire Protection : Duration Based Cost Compared to that of Baseline

In Situ Fire Protection : Cost of Utilized Resources Compared to that of Baseline

In-Situ Fire Protection : % Resource Utilization Compared to that of Baseline

Figure 5.9 : Summary of Results for Scenario 2-2-1 (In-Situ Fire Protection) Compared to Baseline

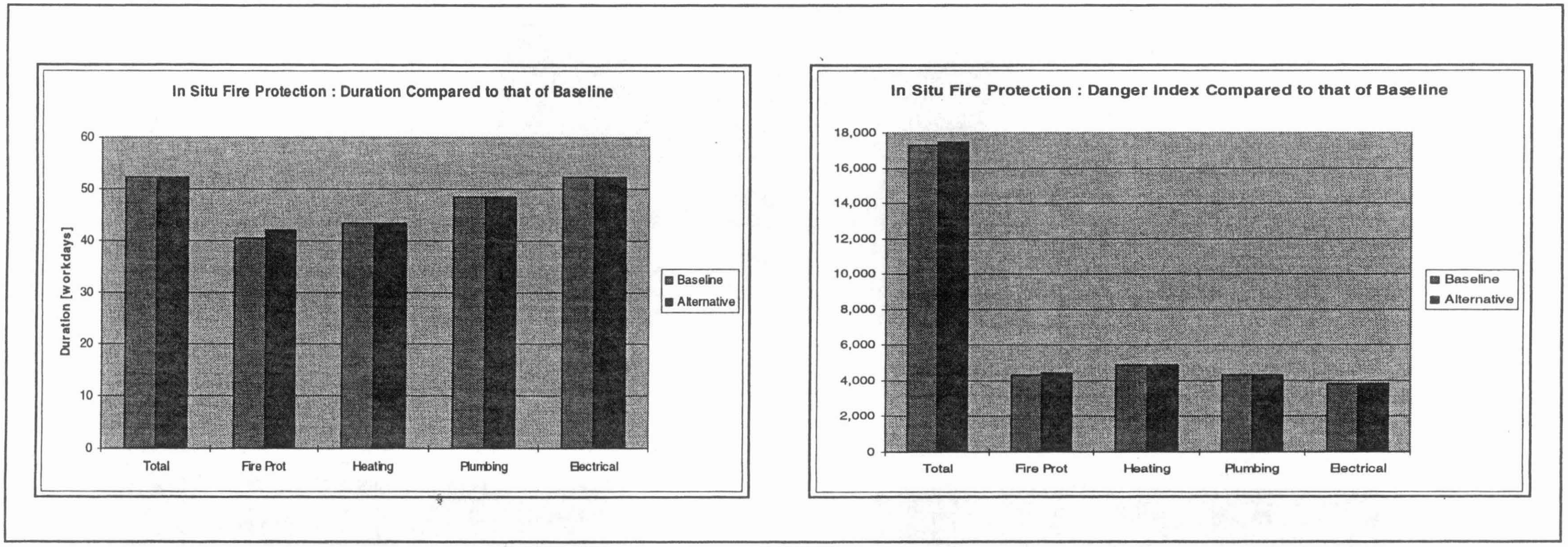


Figure 5.10 : Summary of Results for Scenario 2-2-1 (In-Situ Fire Protection) Compared to Baseline (continued)

Performance Measure	**% Change**
Duration	No change
Duration-Based Cost	+ 0.8 %
Cost of Utilized Resources	+ 4 %
% Resource Utilization	+ 0.9 %
Danger Index	+ 3.5 %

Table 5.15: Impacts at the Whole Project Level for Scenario 2-2-1

At the system level the impacts are, of course, higher as shown in Table 5.16

Performance Measure	**% Change**
Duration	+ 4%
Duration-Based Cost	+ 4%
Cost of Utilized Resources	+ 20%
% Resource Utilization	+ 4 %
Danger Index	+ 16%

Table 5.16: Impacts at the System Level for Scenario 2-2-1

A significant difference can be observed between the increase in duration and duration-based cost and the increase in cost of utilized resources. This difference shows that while the total number of man hours required to complete the installation of the fire protection system increases significantly for this scenario, not all of these additional man hours translate directly into additional project duration. Some of the preparation activities are performed in parallel to the installation of other units and mostly make use of resources that would otherwise be idle (baseline scenario). This observation is supported by the fact that the percentage of resource utilization increases significantly with respect to the baseline scenario.

No impacts can be observed at the inter-system level since the fire protection system does not present inter-system dependencies with other systems.

5.2.2.3 Scenario 2-2-2: In-situ Fabrication vs. Prefabrication of Heating Pipes.

The layout of the heating system is similar to that of the fire protection system, but less centralized. The horizontal distribution follows the shape of the building, along the external wall, crossing through the room partitions on the side opposite to that of the fire protection system. One major difference between the fire protection and the heating system is that the heating system includes a supply and a return line which run parallel to one another, whereas the fire protection system consists only of one supply line. In the baseline configuration, the segments of the horizontal distribution pipes are prefabricated to the length of each room and bundled together to include one segment of supply and one segment of return line of equal length. All of the segments are prefabricated (100% extent of prefabrication) and do not require any preparation work before installation. This scenario assesses impacts of in-situ fabrication versus prefabrication of the horizontal heating pipes.

Changes in the Meta-Model

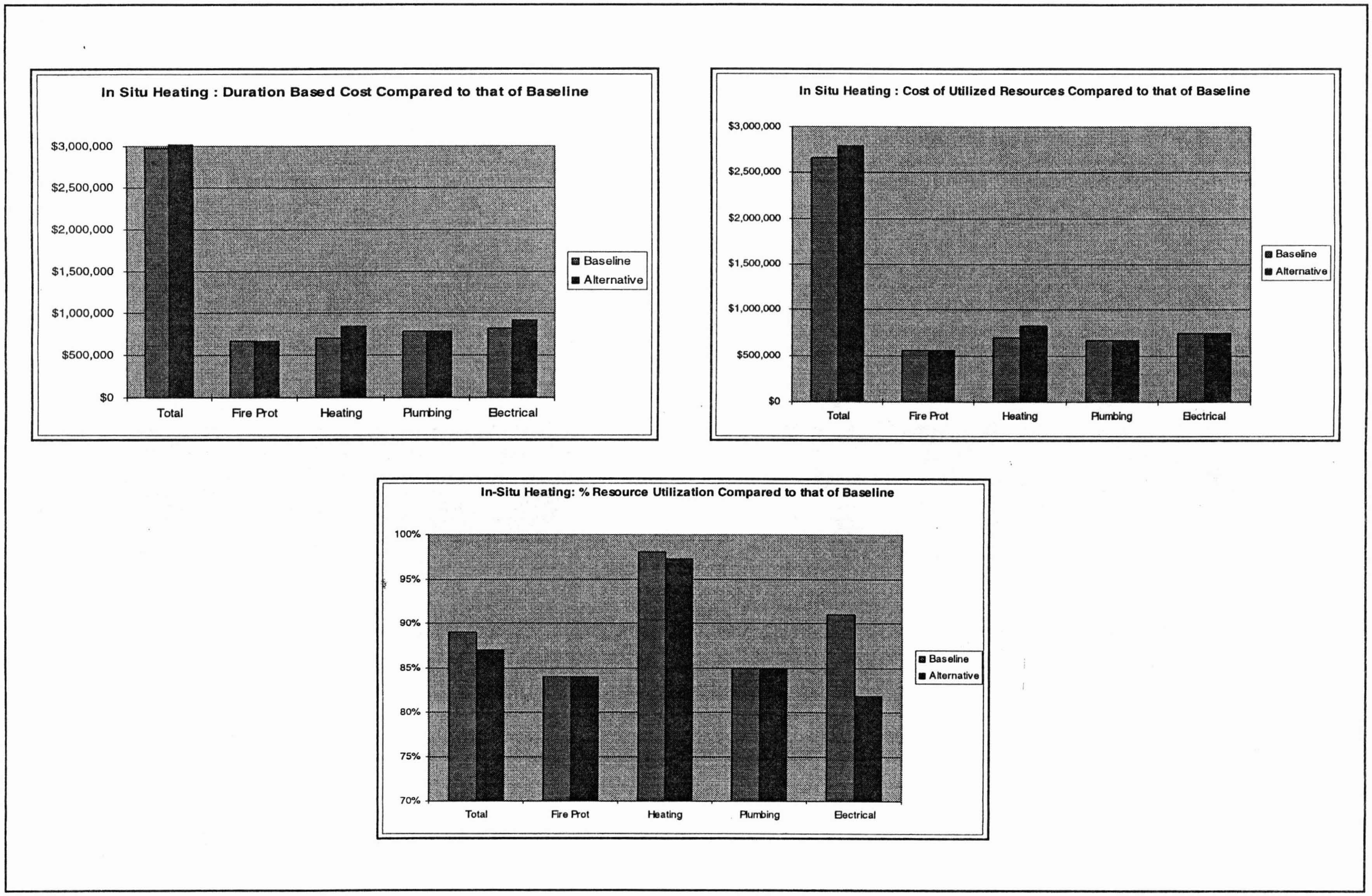
Pipe preparation, including cutting, bending and threading, is a sub-process of pipe installation which can be performed in parallel with the placement of the hangers and the coring activities. While the standard version of the metamodel includes by default the preparation stage in the installation process, for the purposes of this scenario, an alternative path was built which excludes the preparation phase. A value of the variable "Prefabrication" can be set for each branch in the corresponding input file. By switching from "yes" to "no" it is possible to represent the in-situ fabrication of the horizontal units. A major difference that was not observed for the in-situ fabrication of the fire protection pipes is the fact that by separating supply and return lines (no longer bundled together off site) the number of pipes to be installed doubles. This increase in the number of pipes to be placed is accounted for at the input files level for both runs and branches.

The impacts of in-situ fabrication at the whole project level are significantly higher than in the fire protection system. The project completion time is still driven by the installation of the electrical system, but due to the inter-system process link between the heating and the electrical systems, an increase in overall project duration can be observed.

Performance Measure	**% Change**
Duration	+ 11%
Duration-Based Cost	+ 8%
Cost of Utilized Resources	+ 5%
% Resource Utilization	- 3 %
Danger Index	+ 1 %

Table 5.17: Impacts at the Whole Project Level for Scenario 2-2-2

The increase in number of man hours required to complete the project (as measured by the cost of utilized resources) is in percentage smaller than the increase in actual number of hours required to complete the project (as measured by the duration-based cost). This difference reveals the presence of inter-system process constraints that stretch the actual duration of the project beyond the minimum required, by increasing resource idle time. This effect of on-site fabrication contrast the one observed in the fire protection system (scenario 2-2-1), even though the type and level of on-site fabrication introduced in the two scenarios is exactly the same. An interesting contrast that leads the percentage



In Situ Heating : Duration Based Cost Compared to that of Baseline

In Situ Heating : Cost of Utilized Resources Compared to that of Baseline

In-Situ Heating: % Resource Utilization Compared to that of Baseline

Figure 5.11 : Summary of Results for Scenario 2-2-2 (In-Situ Heating) Compared to Baseline

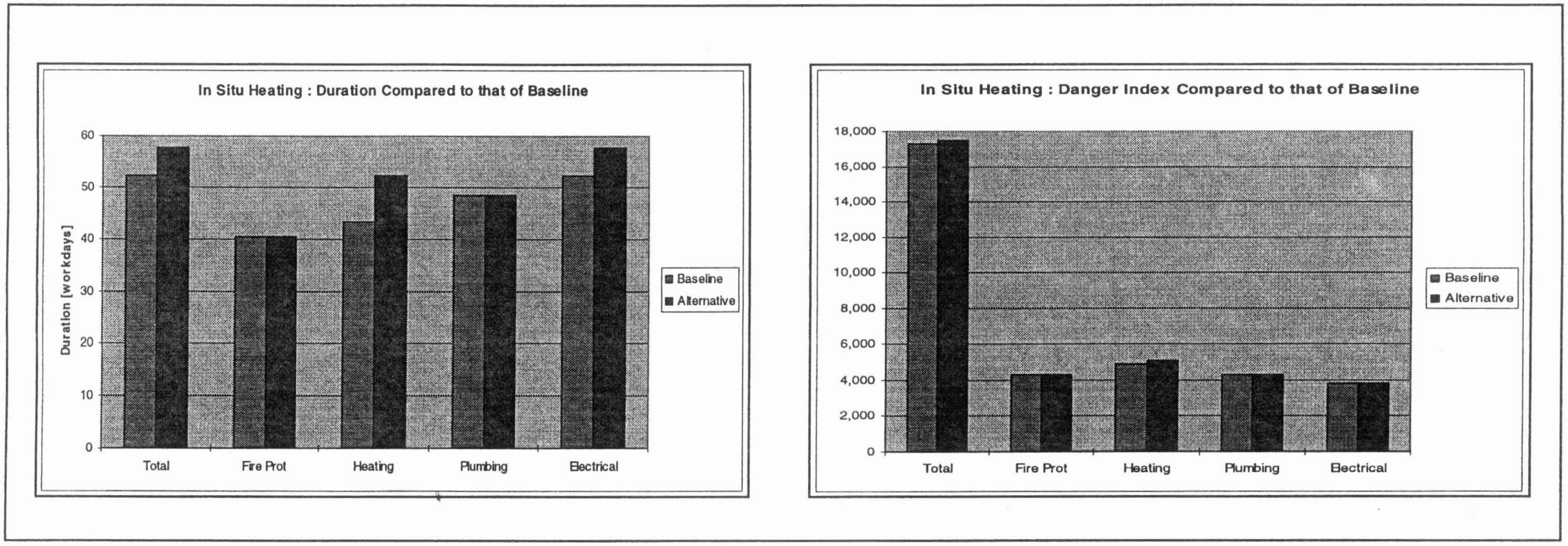


Figure 5.12 : Summary of Results for Scenario 2-2-2 (In-Situ Fire Heating) Compared to Baseline (continued)

utilization of resources to decrease by 3%, rather than increase (by 16%) as in scenario 2-2-1. The danger index for the whole project only increases by 1% (prefabrication activities expose the workers to minimal danger since they are performed on the ground and do not require the use of particularly dangerous equipment).

As shown in Table 5.18, high impacts can be observed at the system level.

Performance Measure	**% Change**
Duration	+ 20 %
Duration-Based Cost	+ 20 %
Cost of Utilized Resources	+ 19 %
% Resource Utilization	- 0.8 %
Danger Index	+ 4 %

Table 5.18: Impacts at the System Level for Scenario 2-2-2

The fact that the increase in duration, duration-based cost, and cost of utilized resources are approximately the same at the system level, shows that the increase in man hours required to install the heating system translates in an equivalent increase in actual installation time. Resource utilization for installation the heating system is quite high in the baseline scenario, so the additional pipe preparation activities cannot make use of resource idle time. This observation confirms that the difference between the increase in cost of utilized resources and duration-based cost for the whole project is not generated at the system level, but is due to inter-system process dependencies, as explained in the following.

Performance Measure	**% Change**
Duration	+ 11 %
Duration-Based Cost	+ 11 %
Cost of Utilized Resources	No Change
% Resource Utilization	- 10 %
Danger Index	No Change

Table 5.19: Impacts at the Inter-System Level for Scenario 2-2-2

At the inter-system level, significant impacts can be observed in the electrical system. The duration for the electrical system increases by 11 % (same as overall project). Duration-based cost also increases, because the increase in installation time for the horizontal pipes of the heating system causes an increase in idle time for the crews of electricians on each floor. Since no changes are introduced in the electrical system itself, both the cost of utilized resources and the danger index remain the same as in the baseline configuration. The percentage resource utilization decreases due to the additional resource idle time.

Scenario 2-2-3: In-situ Fabrication vs. Prefabrication of Plumbing Risers.

In the baseline configuration of Baker House the layout of the domestic plumbing system is highly decentralized. Almost every room's wall sink is fed by a set of separate plumbing risers that run through a vertical chase, located in the room itself. The set of risers that run through each room include hot water supply and return lines, cold water supply, waste water return, drain and ventilation pipes. The presence of horizontal distribution pipes in the baseline configuration is minimal, and mostly concentrated around the bathroom fixtures. The greatest portion of the installation process revolves around the placement of the vertical risers and plumbing fixtures. In order to expedite the installation process, the contractor chose to prefabricate 100% of the plumbing risers. Prefabricated riser segments are pre-bundled in units that can be installed as a single pipe and include connecting elements for each of the pipes in the bundle. This scenario compares project performance for the two opposite cases of preparing and installing each pipe as separate and of installing pre-bundled units.

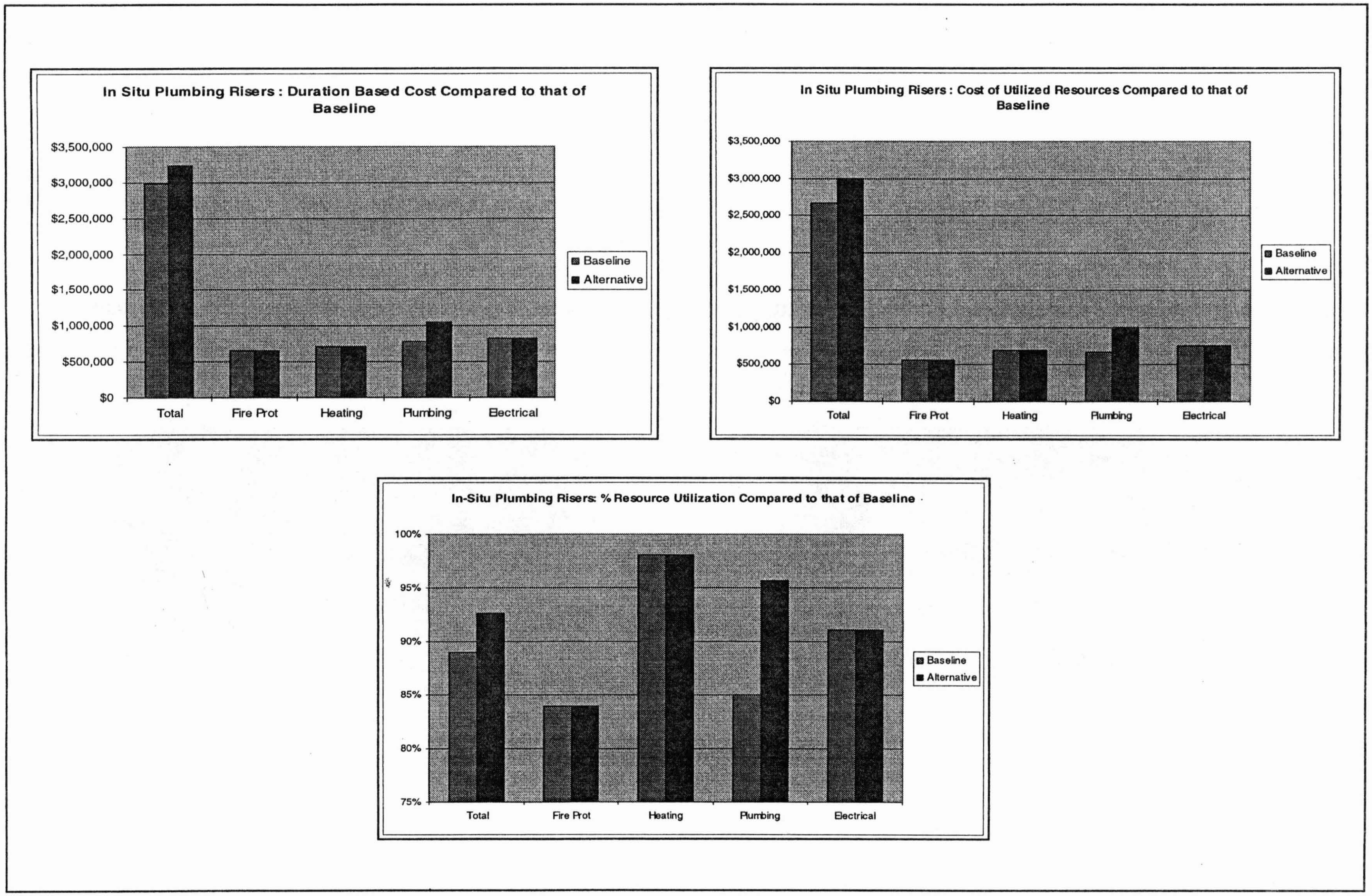
Changes in the Meta-Model.

The installation of pre-bundled riser units required significant changes in the metamodel. A new installation sub-process was created in parallel to the standard pipe installation sub-process. New entity attributes were defined to describe the properties of the pre-bundled units, such as the number of pipe segments included in each bundle and the type of connections required between prefabricated units. Again it is the value (yes/no) of the attribute called "Prefabrication" that routes the pipe segments in either one of the installation sub-processes.

Results

On-site preparation and installation of the plumbing risers produces significant impacts on the performance of the whole project. Project duration increases by 22% with respect to the baseline (prefabricated segments). When each of the riser segments is placed as a separate unit, the plumbing system becomes the one that takes the longest to be installed and thus directly drives the duration of the whole project. In the baseline scenario the electrical system drives the duration of the project instead.

The index of workers' exposure to danger for the whole project increases by 15%, a significant increase given that the preparation activities per se are not high risk activities. In this case it is the extremely large number of pipe segments to be processed that makes the cumulated danger index for the project much higher.


In Situ Plumbing Risers : Duration Based Cost Compared to that of Baseline

In Situ Plumbing Risers : Cost of Utilized Resources Compared to that of Baseline

In-Situ Plumbing Risers: % Resource Utilization Compared to that of Baseline

Figure 5.13 : Summary of Results for Scenario 2-2-3 (In-Situ Plumbing Risers) Compared to Baseline

Performance Measure	**% Change**
Duration	+ 22%
Duration-Based Cost	+ 9%
Cost of Utilized Resources	+ 12.5%
% Resource Utilization	+ 4 %
Danger Index	+ 15 %

Table 5.20: Impacts at the Whole Project Level for Scenario 2-2-3

Major impacts can be observed at the system level.

Performance Measure	**% Change**
Duration	+ 32 %
Duration-Based Cost	+ 33 %
Cost of Utilized Resources	+ 50 %
% Resource Utilization	+ 13 %
Danger Index	+ 58 %

Table 5.21: Impacts at the System Level for Scenario 2-2-3

The in-situ fabrication of the plumbing risers does not generate immediate effects on the installation of the other systems. There are no intersystem process dependencies that tie the installation of the plumbing system to the others, therefore the performance of the other processes remains the same as in the baseline configuration. However, a great portion of the changes in performance measures that are observed at the system level, is directly reflected in the performance of the project as a whole.

Scenario 2-2-4: In-situ Fabrication vs. Prefabrication of Plumbing Fixtures.

In the baseline configuration the fixture groups are delivered to the site preassembled and already provided with the stub-outs required to connect them to the supply and return lines. This scenario tests the impacts of on-site assembly of the fixture groups. The benefits from off-site fabrication are significant on larger fixture groups such as the bathroom fixtures, however only a limited number of these are present in the building. The largest number of fixtures actually consists of the wall sinks present in each room, and these allow only for a limited extent of prefabrication. This is the main reason why the impacts of in-situ fabrication of the fixtures are not as dramatic as the impacts of in-situ fabrication of the vertical risers.

Changes in the Meta-Model.

The metamodel, by default includes on-site fabrication of the fixtures. The handling and installation of prefabricated fixtures has been represented as a separate sub-process which constitutes an alternative processing path for the fixtures. Routing of the fixtures into either path is determined based on the value (yes/no) of the attribute "Prefabrication" which is read from an input file containing all the properties of each plumbing fixture.

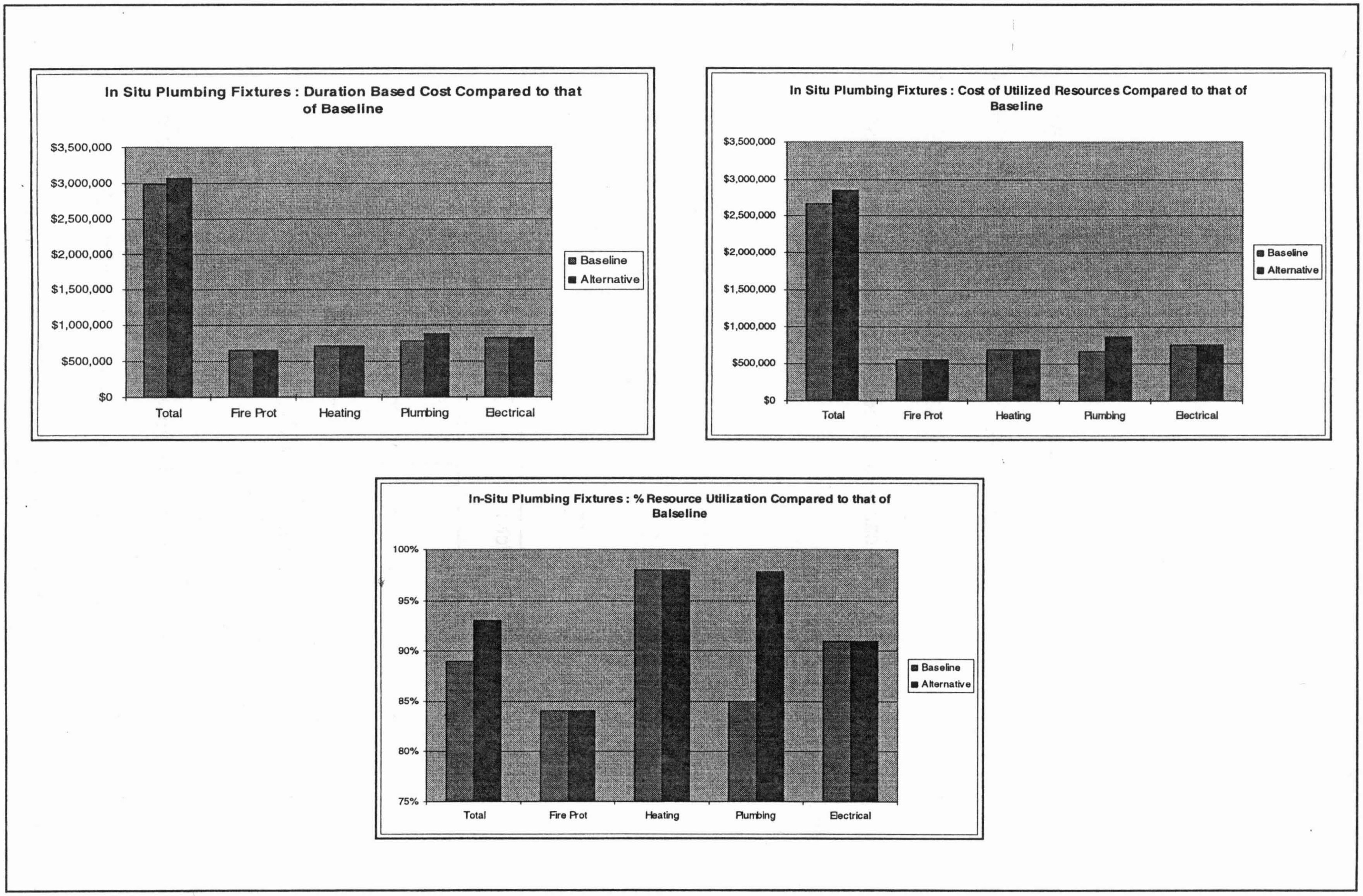
Results

The results observed for the in-situ fabrication of the plumbing fixtures in comparison to the baseline, are analogous in nature to those observed for the in-situ fabrication of the plumbing risers, but significantly smaller in scale. This difference in scale is due to the significantly different extent of prefabrication that the fixtures and the risers respectively represent within the baseline scenario.

Performance Measure	**% Change**
Duration	+ 4 %
Duration-Based Cost	+ 3 %
Cost of Utilized Resources	+ 7 %
% Resource Utilization	+ 4 %
Danger Index	+ 1.5 %

Table 5.22: Impacts at the Whole Project Level for Scenario 2-2-4

The increase in project duration compared to the baseline, is still driven by the plumbing system, however in this case the installation of the plumbing and of the electrical systems have very similar duration (52.2 and 53.8 workdays respectively).



In Situ Plumbing Fixtures : Duration Based Cost Compared to that of Baseline

In Situ Plumbing Fixtures : Cost of Utilized Resources Compared to that of Baseline

In-Situ Plumbing Fixtures : % Resource Utilization Compared to that of Balseline

Figure 5.15 : Summary of Results for Scenario 2-2-4 (In-Situ Plumbing Fixtures) Compared to Baseline

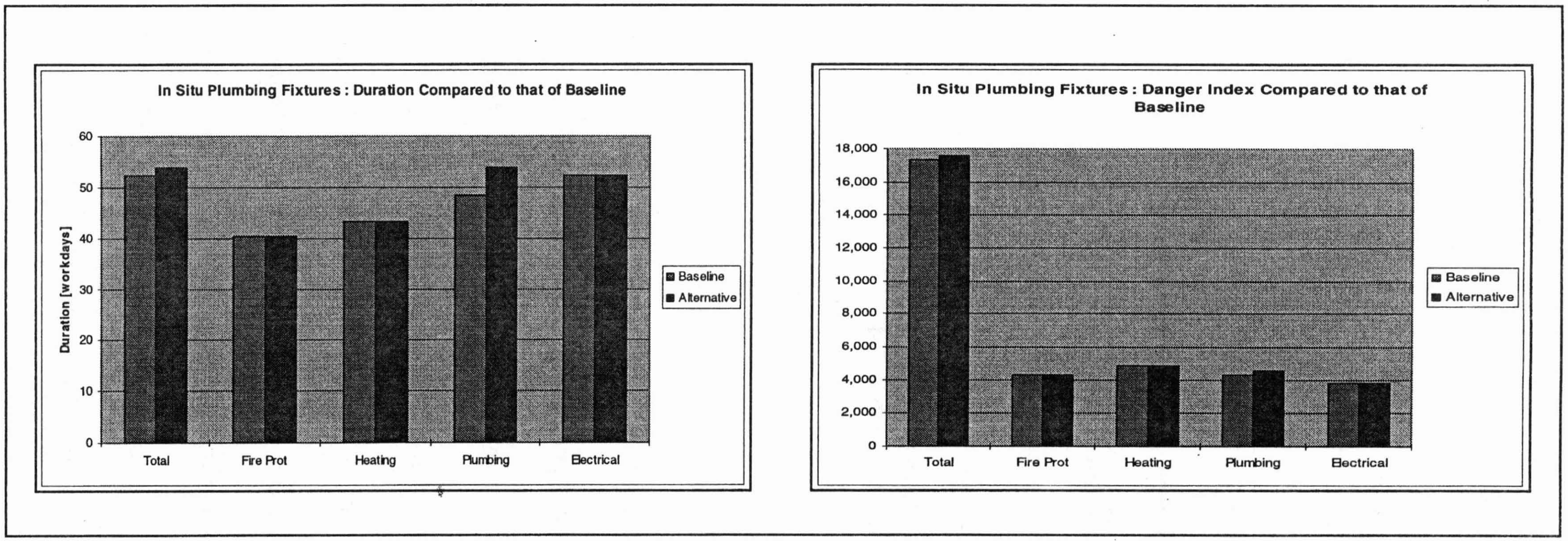


Figure 5.16 : Summary of Results for Scenario 2-2-4 (In-Situ Plumbing Fixtures) Compared to Baseline (continued)

At the system level, the increases in performance measures are more significant, but still not as remarkably high as those observed for the in-situ fabrication of the vertical risers.

Performance Measure	**% Change**
Duration	+ 11 %
Duration-Based Cost	+ 11 %
Cost of Utilized Resources	+ 29 %
% Resource Utilization	+ 16 %
Danger Index	+ 6 %

Table 5.23: Impacts at the System Level for Scenario 2-2-4

The impacts of off-site fabrication of components alters the performance of the installation of fire protection, heating and plumbing systems in different ways, depending on the extent of prefabrication (percentage of the whole) and on the process interdependencies between the system of introduction and all of the other systems. Prefabrication of the horizontal pipes for the fire protection system gives limited benefits in terms of cost and duration, both at the system level and at the whole project level, chiefly because the design of the fire protection system makes its installation process independent of all of the other systems. The same level of prefabrication for the heating system produces significant impacts both at the inter-system level (relationship with electrical installation process) and at the whole project level: the layout of the heating system is, in fact, spatially tied to the layout of the electrical system. The respective horizontal pipes and conduits follow the same path along the building and share the same supporting tray, which forces the heating pipes, larger in section, to be placed before the electrical conduits on each floor. This spatial link between the two systems makes the rate of installation of the electrical conduits highly dependent on the rate of installation of the heating pipes. Moreover the duration of the whole project for this scenario is driven by the installation of the electrical system, hence off-site fabrication of the heating pipes directly translates into faster installation of the electrical system and reduction of overall project duration and cost.

Prefabrication of the plumbing risers, as well as of the plumbing fixtures are also tested as separate scenarios. The extent of prefabrication for the plumbing risers is considerably higher than for the plumbing fixtures, as reflected in the respective impacts at the whole project level: important ones for the prefabrication of the plumbing risers and moderate ones for the plumbing fixtures.

5.2.3 Impacts of Design Alternatives

Design alternatives are defined as changes in the facility design that alter the layout, the nature and/or the type of one or more systems or components. As part of this case study the impacts of three major design alternatives are evaluated: changes in layout (centralized vs. decentralized), changes in system components (flexible vs. rigid pipes) and changes in the nature of one whole system (air-based vs. water-based heating).

5.2.3.1 Scenario 3-1: Centralized vs. Decentralized Layout.

Design changes in the system layout, particularly centralization versus decentralization of the vertical risers, were analyzed with respect to the overall layout of the water-based service systems (i.e. plumbing, heating and fire protection). Centralizing the layout means shifting from a primarily vertical layout, with a number of vertical risers close to the number of usage points, to a largely horizontal layout, where few risers feed the usage points through a long network of horizontal pipes on each floor. In the baseline configuration of the Baker House project, the only system (besides the electrical system) that is fairly centralized is the fire protection system.

A new scenario was created and tested, that adopted the same centralized layout as in the fire protection system, for the heating and the plumbing systems as well. Not only does this shift represents a significant design change in terms of number and type of units to be installed, but it also introduces an additional inter-system process constraint, between the installation of the fire protection and the plumbing system. This constraint, driven by spatial requirements, ties the rate of installation of the horizontal pipes of the fire protection system to that of the horizontal pipes of the plumbing system (in the same way as in the baseline configuration the rate of installation of the electric conduits depends on the rate of installation of the heating pipes).

Changes in the Meta-Model

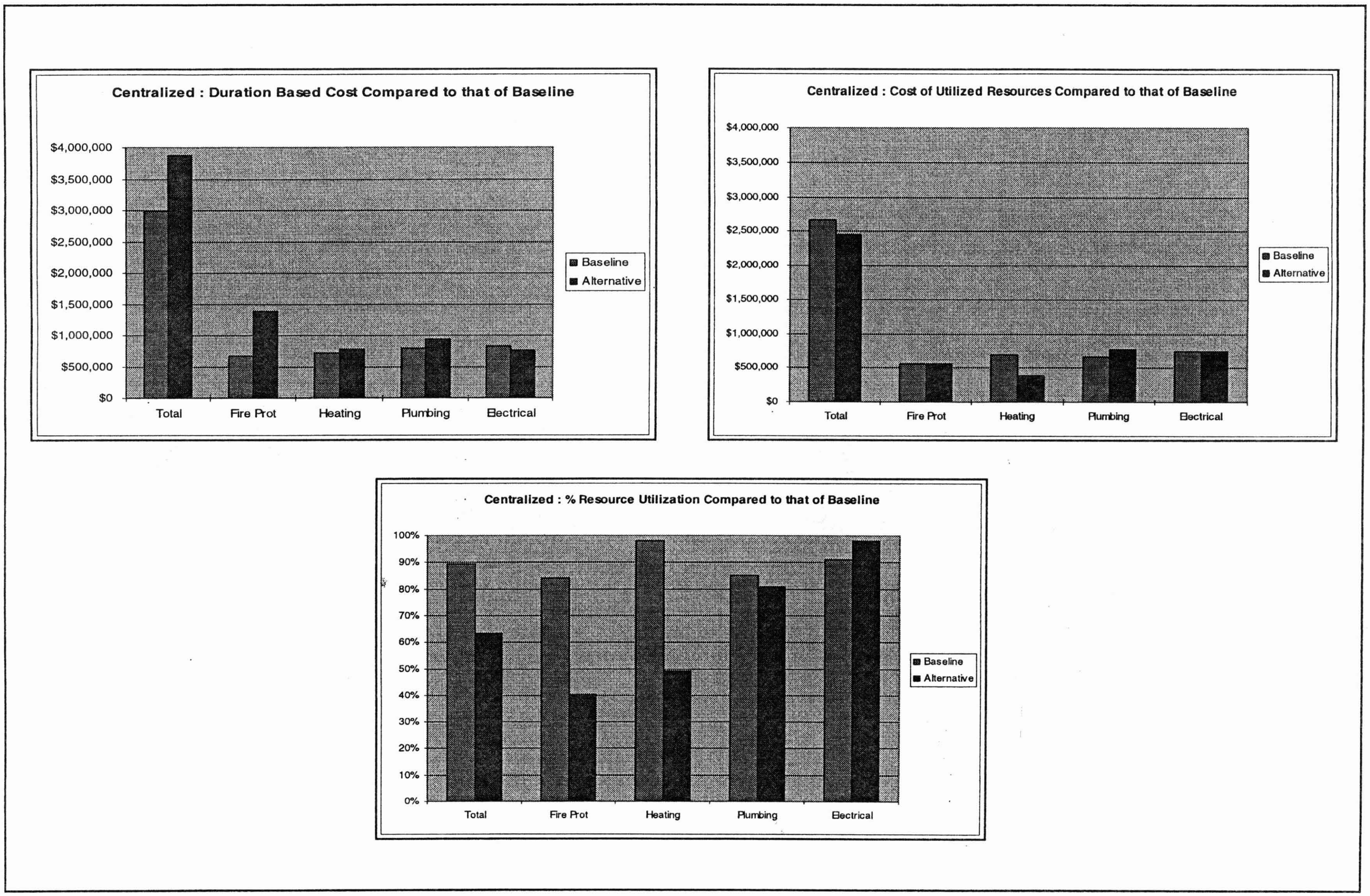
Moving from a decentralized layout to a completely centralized one affects the structure of the metamodel. Additional spatial constraints require the placement of the horizontal distribution for the plumbing system to be completed on a given floor before the horizontal distribution for the fire protection system can start to be installed on the same floor. A process link between the plumbing and the fire protection systems was introduced that based on the status of the installation of the plumbing pipes on a given floor holds or releases for installation the fire protection pipes belonging to that floor.

Changes in layout have no impact on the structure of the individual system modules which the metamodel is composed of. The modules are system and material specific, and thus independent of the particular design specifications and layout for each system. As long as the nature of each system and the type of components remain the same, the shift from a decentralized to a centralized layout only reduces the number of vertical risers to be installed and increases the number of horizontal pipe segments. Changes in the number of entities (e.g. parts and components) to be installed does not change the type of activities to be performed and thus are only reflected in the input quantities that are directly read from files at the beginning of the simulation. The metamodel per se only contains information on how to process specific entity types, that are part of the chosen set of material specific system types, but has the built-in flexibility to represent any facility design and layout, by varying the input quantities of entities and the corresponding attributes.

The only changes required to represent the centralized layout of the water distribution systems were mainly at the input files level, where the facility design and layout are described, in terms of number and types of parts. Specifically the quantities that were changed are the number of vertical riser segments and the number and size of the horizontal pipe segments.

Results

The effects of the additional process constraint at the whole project level are major increases in overall project duration (62%) and in duration-based cost (30%). In addition, it is now the installation of the fire protection system, instead of the electrical system, that drives the duration and overall cost of the project. The change in design (number and type of units to be installed) actually reduces the cost of utilized resources, both at the system and at the whole project level, but also introduces a change in the inter-system dependencies, which thereby determines the overall progress rate and project duration. The combined impact of these two effects is a reduction of resource utilization [cost of utilized resources/duration-based cost] equal to 30%.


Centralized : Duration Based Cost Compared to that of Baseline

Centralized : Cost of Utilized Resources Compared to that of Baseline

Centralized : % Resource Utilization Compared to that of Baseline

Figure 5.17 : Summary of Results for Scenario 3-1 (Centralized) Compared to Baseline

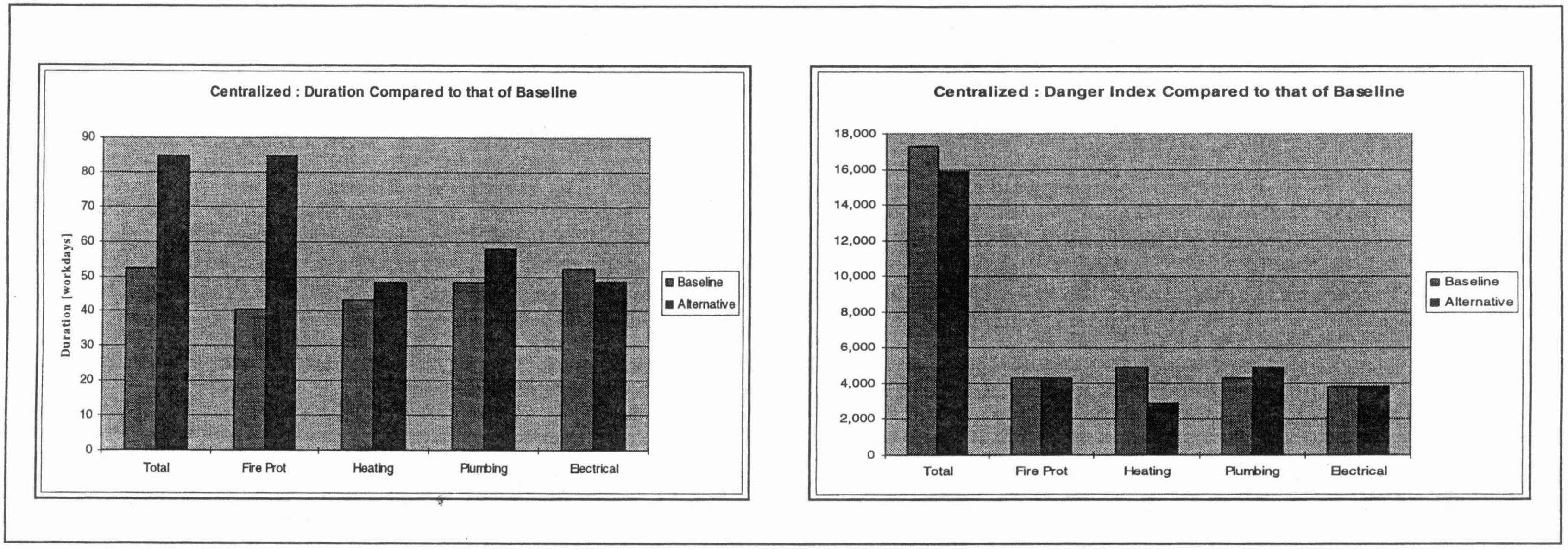


Figure 5.18 : Summary of Results for Scenario 3-1 (Centralized) Compared to Baseline (continued)

Performance Measure	% Change
Duration	+ 62 %
Duration-Based Cost	+ 30 %
Cost of Utilized Resources	+ 8 %
% Resource Utilization	+ 30 %
Danger Index	+ 8 %

Table 5.24: Impacts at the Whole Project Level for Scenario 3-1

At the system level both duration and duration-based cost increase for all of the water-based systems, while they decrease for the electrical system.

Performance Measure	% Change
Duration	+ 110 %
Duration-Based Cost	+ 108 %
Cost of Utilized Resources	No Change
% Resource Utilization	- 52 %
Danger Index	No Change

Table 5.25: Impacts at the System Level for Scenario 3-1 (Fire Prot.)

It is interesting to notice that the presence of an additional inter-system process dependency between the plumbing and the fire protection systems, introduces major changes in performance for the installation of the fire protection system, (110% increase in duration and duration-based cost) where no change in layout was introduced. The layout of the fire protection system is already centralized in the original facility design and is taken as reference for the centralization of the other two water-based systems.

The cost of utilized resources and the worker's danger index remain unchanged for the fire protection system, while resource utilization decreases by 52% (consistent with the increase in duration-based cost).

Performance Measure	**% Change**
Duration	+ 11 %
Duration-Based Cost	+ 11 %
Cost of Utilized Resources	- 44 %
% Resource Utilization	- 50 %
Danger Index	- 41 %

Table 5.26: Impacts at the System Level for Scenario 3-1 (Heating)

The cost of utilized resources and the worker's danger index for the heating system are significantly lower in the centralized configuration (44% and 41% lower than in the baseline). Resources utilization also decreases dramatically (50%), due to the combined effect of the increase in duration-based cost and the decrease in cost of utilized resources.

This finding is quite interesting and calls attention to the impacts of interdependencies among the processes and activities pertaining to the installation of a given system. Technical and resource constraints for the heating system generate delays in the placement of the different parts and components that do not allow for optimal resource utilization within the scope of installation of this system.

Performance Measure	**% Change**
Duration	+ 20 %
Duration-Based Cost	+ 20 %
Cost of Utilized Resources	+ 15 %
% Resource Utilization	- 4 %
Danger Index	+ 14 %

Table 5.27: Impacts at the System Level for Scenario 3-1 (Plumbing)

For the plumbing system both the cost of utilized resources and the danger index increase. Consistently, the utilization of resources decreases, since the increase in duration-based cost is higher than the increase in cost of utilized resources.

No change was introduced in the electrical system, therefore both the cost of utilized resources and the danger index remain unchanged in this scenario. However, the decrease in duration-based cost leads to an increase in resource utilization.

Performance Measure	**% Change**
Duration	- 7 %
Duration-Based Cost	- 7 %
Cost of Utilized Resources	No Change
% Resource Utilization	+ 7 %
Danger Index	No Change

Table 5.28: Impacts at the Inter-System Level for Scenario 3-1 (Electrical)

This scenario represents a significant example of how process interdependencies among the systems of a facility can produce unexpected performance outcomes both at the whole project level and at the system level. A decrease in the cost of utilized resources, which measures the bare cost of performing each of the required activities, would lead to expect an overall decrease in duration and thus in duration-based cost for the whole project. The presence of process links among the systems due to spatial constraints forces project duration to be longer than in the baseline scenario and significantly increases duration-based cost. The most surprising outcome is in the installation of the fire protection system. No physical change is actually introduced in this system (the layout remains the same and, thus the cost of utilized resources does not change with respect to the baseline scenario), however both duration and duration based cost increase by 110%.

Another interesting outcome that can be observed in this scenario is that although the overall duration and duration-based cost for the installation of the heating system increase, the duration and duration-based cost for installation of the electrical system decrease. Again, an unexpected outcome, since the increase in duration for the installation of the heating system would lead to expect longer wait time, and thus larger resource idle time, for the crews of electricians in the placement of the horizontal conduits. However, the fact that the number of vertical risers to be installed in the centralized configuration of the heating system is significantly lower than in the baseline design, increases the availability of resources for the installation of the horizontal distribution pipes. This increased availability of resources, earlier into the installation process (the completion of the installation of the vertical risers is reached earlier than in the baseline scenario), allows for a more efficient allocation of resources on each floor. In addition, the presence of a significantly large number of horizontal pipe segments to be installed prioritizes the installation of the horizontal pipes over the installation of the fixtures (i.e. radiators) with respect to the allocation of resources. This more efficient distribution of resources in the heating system makes the progress on the installation of the electric conduits smoother (e.g. reduces wait time between one floor and the next) and shorter.

5.2.3.2 Scenario 3-2: Centralized Layout with Flexible Plumbing Pipes.

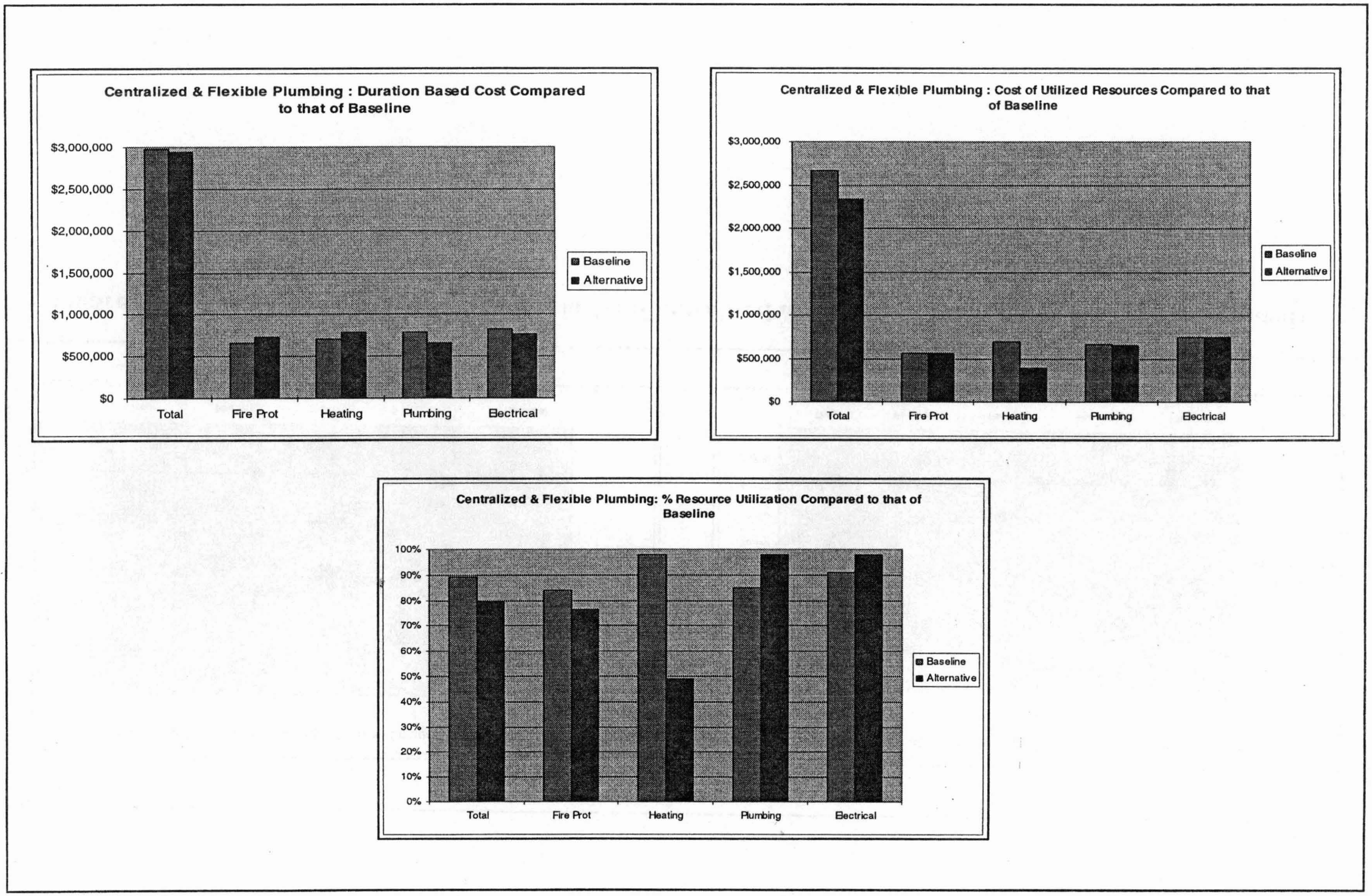
This scenario consists of the same centralized configuration analyzed in section 5.2.3.1 but also involves the replacement of rigid pipes with flexible ones in the domestic plumbing system. Flexible pipes can be pulled to the required length and need a minimal number of connections [2]. Their installation is much faster compared to that of rigid pipes [2], thus loosening the dependence of fire protection on plumbing that was observed in the purely centralized configuration. Faster installation of plumbing pipes has impacts at the individual system level (shorter completion times for the plumbing system), at the intersystem level (shorter completion time, lower costs and higher resource utilization for the fire protection system), and at the whole project level (the installation of the fire protection system no longer drives the duration of the project as a whole, and overall duration and cost are much lower than in the purely centralized configuration and indeed lower than in the original decentralized configuration.)

Changes in the Meta-Model

The structure of the metamodel, and the logical dependencies among the processes do not change with respect to the purely centralized configuration. The choice between flexible and rigid pipes is an option already built into the plumbing model at the material and system specific level [2]. The two different sub-processes can alternatively be selected by appropriate setting of the "material" attribute of each pipe (i.e. "flexible' or "rigid').

Results

The introduction of flexible pipes in the domestic plumbing system significantly changes the performance of the whole project compared to the purely centralized scenario. As observed in section 5.2.3.1 the rate of installation of the horizontal pipes for the plumbing



Centralized & Flexible Plumbing : Duration Based Cost Compared to that of Baseline

Centralized & Flexible Plumbing : Cost of Utilized Resources Compared to that of Baseline

Centralized & Flexible Plumbing: % Resource Utilization Compared to that of Baseline

Figure 5.19 : Summary of Results for Scenario 3-2 (Centralized & Flexible) Compared to Baseline

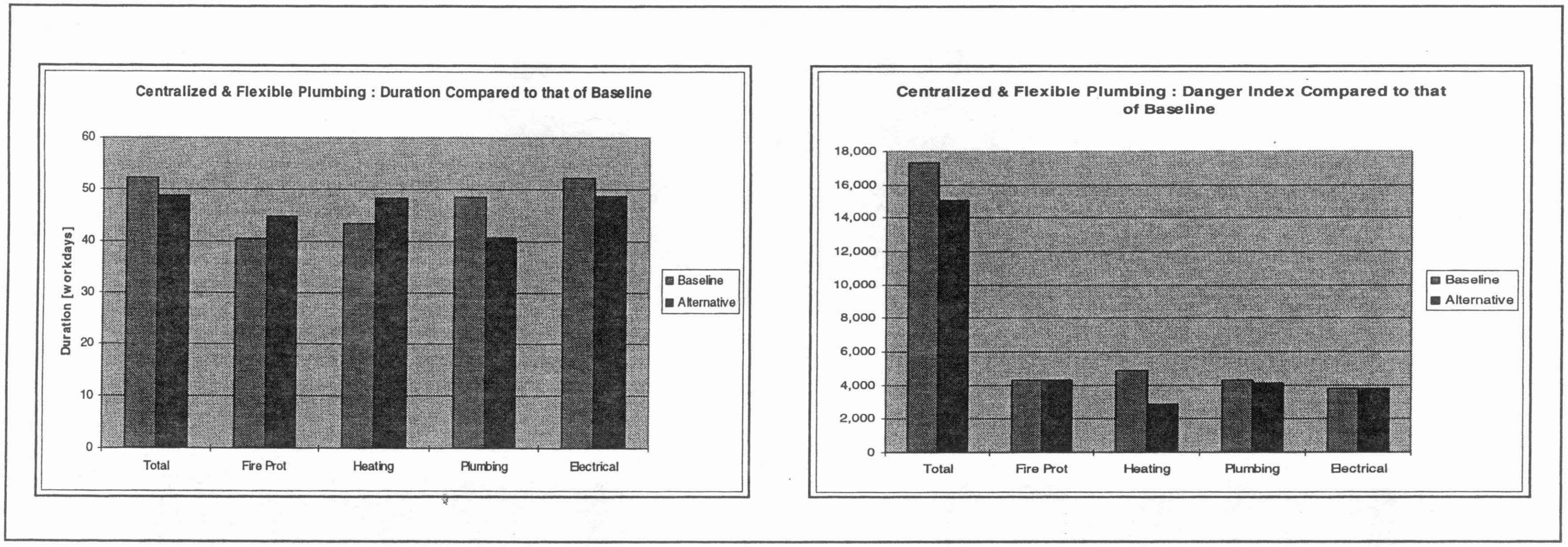


Figure 5.20 : Summary of Results for Scenario 3-2 (Centralized & Flexible) Compared to Baseline (continued)

system constituted a major bottleneck for the installation of the fire protection system on each floor, to the point that the fire protection system would drive the duration of the overall project and virtually double it with respect to the baseline scenario. The possibility to speed up the installation of the horizontal pipes for the plumbing system, as represented by the introduction of flexible pipes, compensates for the bottleneck effects of the additional process link between the plumbing and the fire protection systems. As a matter of fact, project duration and duration-based cost decrease to slightly lower values than in the baseline scenario. The cost of utilized resources and the danger index are also lower than in the purely centralized configuration (12% and 13% less than the baseline, respectively). Overall resource utilization increases by 25% with respect to the purely centralized configuration, but remains 11% lower than in the baseline.

Performance Measure	**% Change**
Duration	- 7 %
Duration-Based Cost	- 1.5 %
Cost of Utilized Resources	- 12 %
% Resource Utilization	- 25 %
Danger Index	- 8 %

Table 5.29: Impacts at the Whole Project Level for Scenario 3-2

At the system level only the fire protection and the plumbing systems are affected by the introduction of flexible pipes. The performance measures for the heating and the electrical systems remain exactly the same as in the purely centralized configuration.

Performance Measure	**% Change**
Duration	- 16 %
Duration-Based Cost	- 16 %
Cost of Utilized Resources	- 2.5 %
% Resource Utilization	+ 16 %
Danger Index	- 4.5 %

Table 5.30: Impacts at the System Level for Scenario 3-2 (Plumbing)

The duration for the plumbing system is shorter than in the baseline configuration and leads to an equivalent reduction in duration-based cost (16%). Faster installation of the plumbing pipes (30% faster than in the purely centralized configuration) causes a major decrease in duration and duration-based cost for the fire protection system with respect to the purely centralized configuration (approximately 47% lower for both of them). The installation of the fire protection system no longer drives the duration of the whole project as in the purely centralized configuration (the electrical does as in the baseline scenario). The cost of utilized resources and the danger index for the fire protection system remain the same as in the purely centralized configuration (and thus the same as in the baseline), while the percentage of resource utilization almost doubles (increases by 90% compared to the purely centralized configuration).

Performance Measure	**% Change**
Duration	+ 10 %
Duration-Based Cost	+ 10 %
Cost of Utilized Resources	No Change
% Resource Utilization	- 9 %
Danger Index	No Change

Table 5.31: Impacts at the System Level for Scenario 3-2 (Fire Prot.)

5.2.3.3 Scenario 3-3: Air-Based vs. Water-Based Heating.

This scenario examines the impacts of changing the nature of a whole system. Specifically, a comparison is made between water-based and air-based heating system, while keeping the basic layout unchanged.

This design change completely alters the nature of the heating system. In particular, it represents a shift from a closed loop type of system, characterized by supply and return pipes, to an open loop type of system, characterized by supply ducts only. The most interesting aspect of this design change is that no significant impacts can be identified at the system level (the time required to install a given length of air ducts is actually longer than the time required to install an equal length of water pipes, however no return line is required in the air-based configuration. Coincidentally, for this particular size and layout, the effects compensate so as not to produce significant changes in the performance measures at the system level). However, significant impacts can be observed at the intersystem level: the installation of the electrical system is faster and the associated costs are lower. This effect is mostly determined by the different rate of installation of both the vertical and the horizontal units in the air-based system, as compared to the baseline design, which overall increases efficiency in the installation of the electrical system (shorter idle time of resources while waiting for the horizontal heating conduits to be placed). Increased efficiency in the installation of the electrical system has significant impacts on the project as a whole, since reduction in completion time for the electrical system directly translates in an equivalent reduction in project duration, and consequently decreases project cost.

Changes in the Meta-Model

For the analysis of this scenario a whole process module (i.e air-based heating) was substituted into the structure of the metamodel. The same logical dependency between the electrical and the heating systems was maintained as the one present in the baseline scenario (the air ducts need to be placed before the electrical installation can be undertaken on each floor).

Results

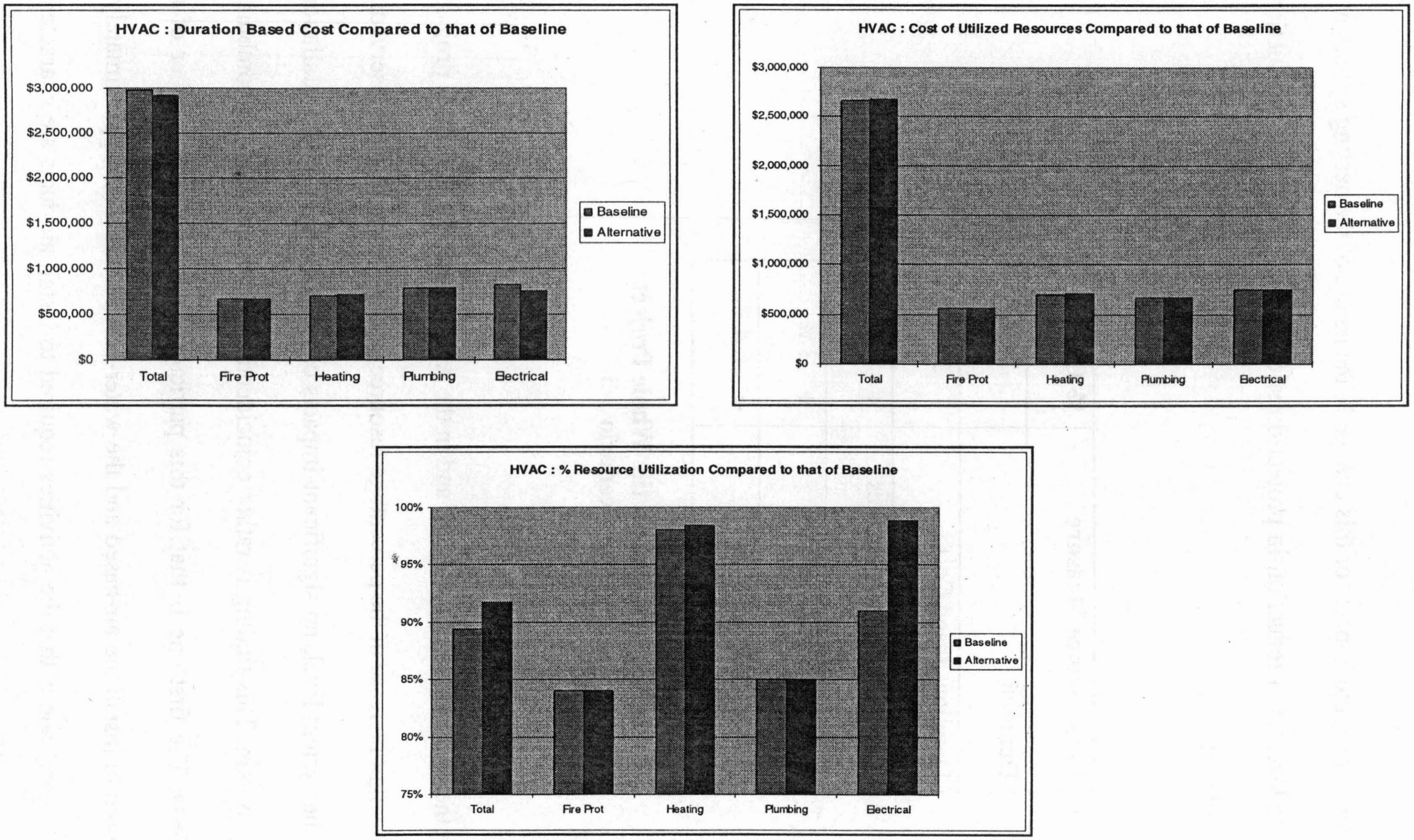
As anticipated above, the impacts of this change in the nature of the heating system at the whole project level are a reduction in project duration and a corresponding reduction in duration-based cost.

Performance Measure	**% Change**
Duration	- 7 %
Duration-Based Cost	- 2 %
Cost of Utilized Resources	+ 0.5 %
% Resource Utilization	+ 3 %
Danger Index	+ 0.4 %

Table 5.32: Impacts at the Whole Project Level for Scenario 3-3

Changes in the cost of utilized resources and in the danger index for the whole project are minimal. A slight increase in the percentage resource utilization can also be observed.

At the system level, no significant impacts can be observed in the installation of the heating system. This finding is rather coincidental, and results from the combination of two effects. The first one is that for this particular layout the total number of man hours required to install the air-based and the water-based heating are approximately the same. The second one is that the activities required to install air ducts are characterized by the same level of danger as those required to install hot water pipes.



HVAC : Duration Based Cost Compared to that of Baseline

HVAC : Cost of Utilized Resources Compared to that of Baseline

HVAC : % Resource Utilization Compared to that of Baseline

Figure 5.21 : Summary of Results for Scenario 3-3 (HVAC) Compared to Baseline

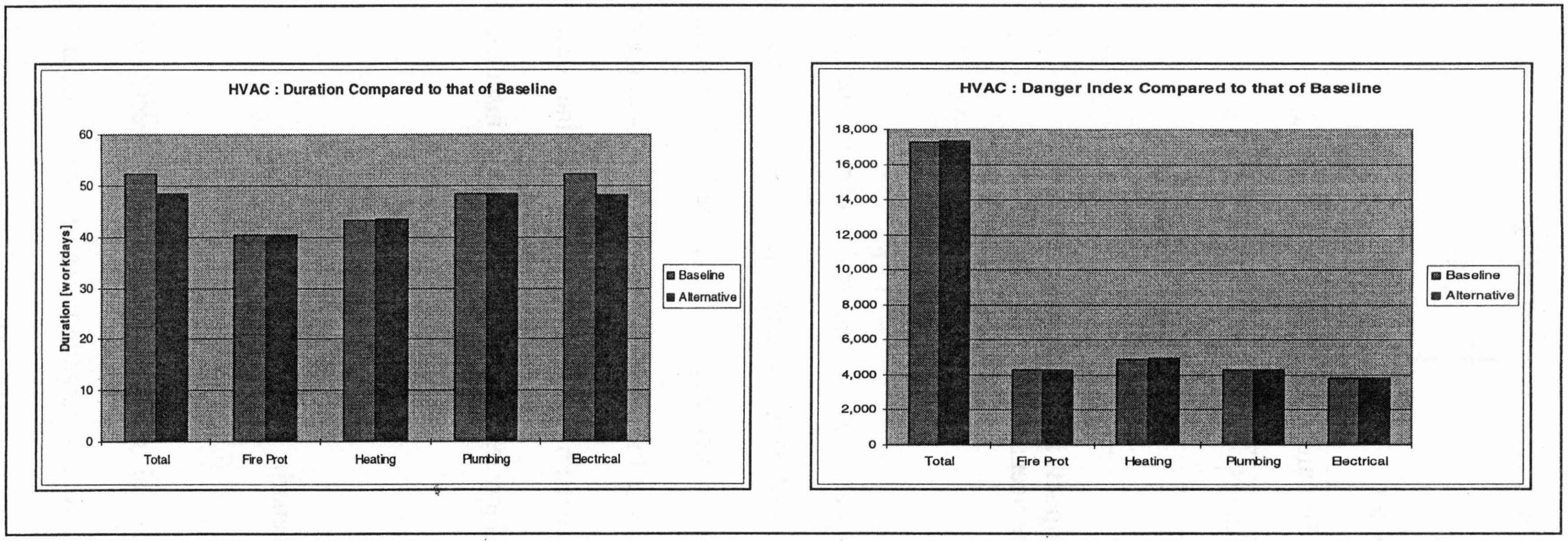


Figure 5.22 : Summary of Results for Scenario 3-3 (HVAC) Compared to Baseline (continued)

Performance Measure	**% Change**
Duration	- 8 %
Duration-Based Cost	- 8 %
Cost of Utilized Resources	No Change
% Resource Utilization	+ 9 %
Danger Index	No Change

Table 5.33: Impacts at the Inter-System Level for Scenario 3-3 (Electrical)

At the inter-system level the installation of the electrical system is affected by the change in the type of heating system adopted. Duration and duration-based cost for the electrical system are both lower than the corresponding figures in the baseline scenario. Since no change was introduced specifically in the electrical system itself, both the cost of utilized resources and the danger index remain the same as in the baseline scenario, while the percentage of resource utilization increases, due to the decrease in installation time.

5.2.4 Scenario 4: Worst Case Scenario.

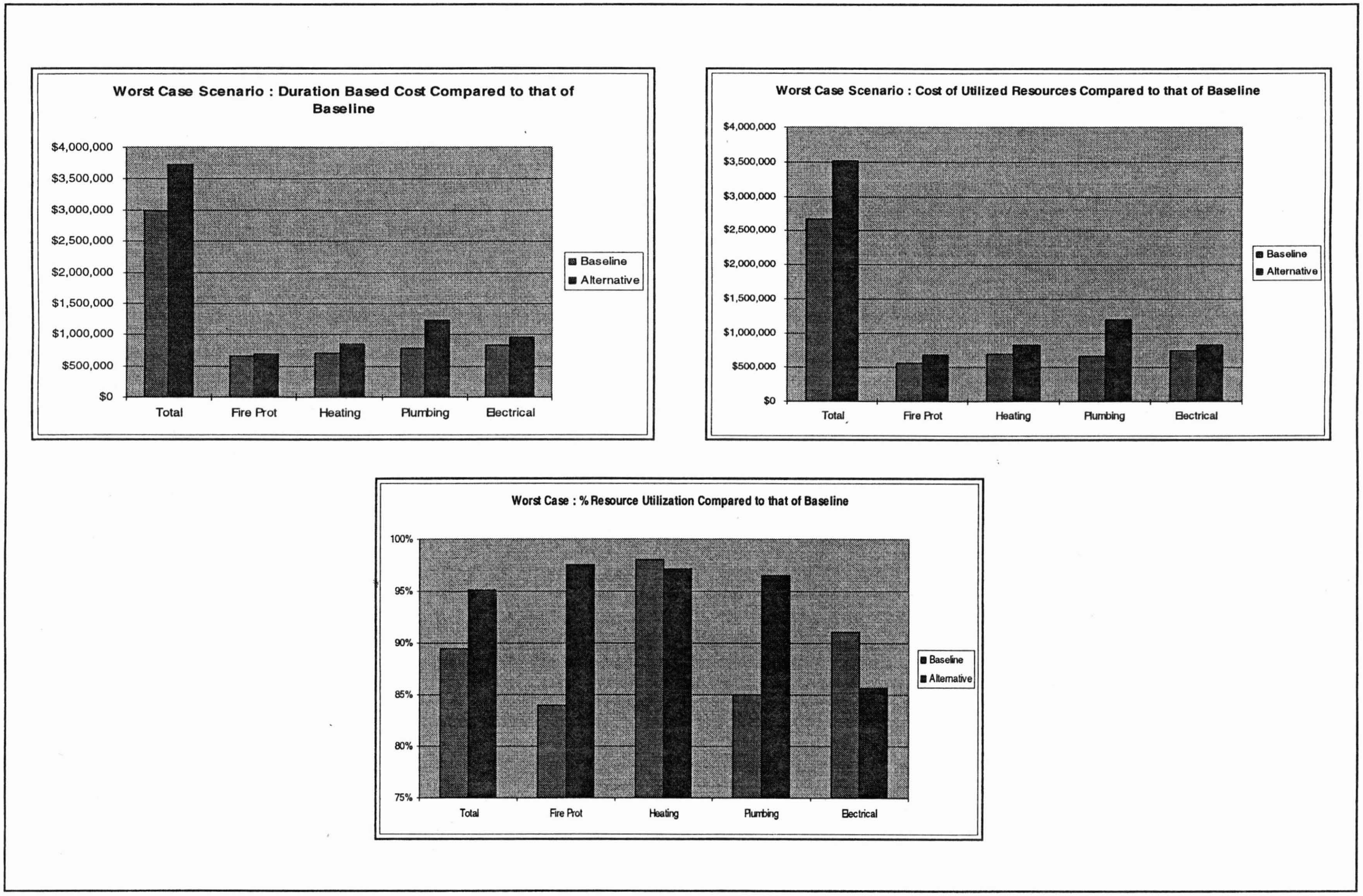
The worst case scenario combines all the process alternatives described in this chapter (section 5-2-2), and evaluates the total savings in terms of time, costs, and worker safety that extensive prefabrication and reuse of the existing electric conduits generated in the actual project. Specifically the worst case scenario entails on-site fabrication of the plumbing risers (see scenario 2-2-3) and of the plumbing fixtures (see scenario 2-2-4), on-site fabrication of the horizontal water distribution pipes for the fire protection and heating systems (scenarios 2-2-1 and 2-2-2), and installation of new electric conduits (see scenario 2-1). The benefits of extensive prefabrication and reuse of existing electric conduits are estimated comparing the values of the performance measures for the worst case scenario to those obtained for the baseline.

Changes in the Meta-Model

The fact that all of the units are fabricated on site and that new electric conduits are installed does not modify the logical interdependencies among the processes. However, all of the changes that are described in the different sub-sections of section 5.2.2 apply simultaneously.

Results

The different aspects of project performance are significantly influenced by the combined effects of the process alternatives that are simultaneously introduced in the project. Project duration, driven in this case by the installation of the plumbing system increases by 45%, while duration-based cost increases by 24%. The cost of utilized resources is 32% higher than in the baseline scenario and the danger index for the whole project is



Worst Case Scenario : Duration Based Cost Compared to that of Baseline

Worst Case Scenario : Cost of Utilized Resources Compared to that of Baseline

Worst Case : % Resource Utilization Compared to that of Baseline

Figure 5.23 : Summary of Results for Scenario 4 (Worst Case) Compared to Baseline

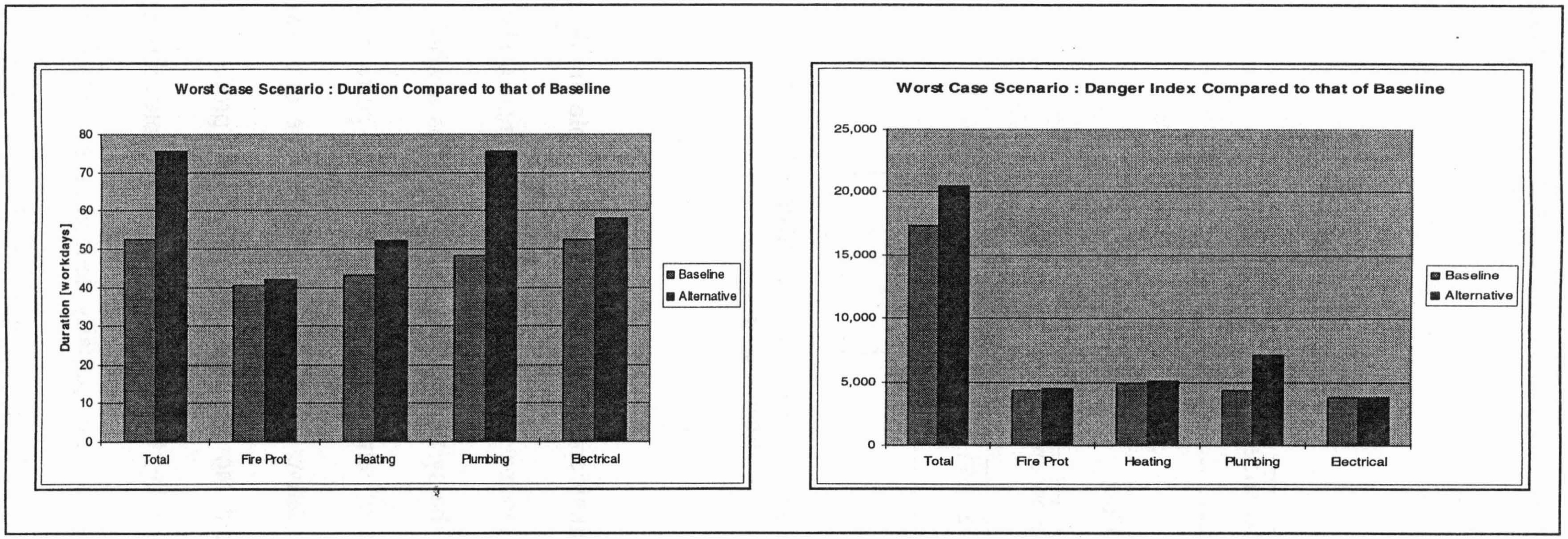


Figure 5.24 : Summary of Results for Scenario 4 (Worst Case) Compared to Baseline (continued)

also 18% higher. The percentage of resource utilization is about 6% higher than in the baseline scenario.

Performance Measure	**% Change**
Duration	+ 45 %
Duration-Based Cost	+ 24 %
Cost of Utilized Resources	+ 32 %
% Resource Utilization	+ 6 %
Danger Index	+ 18 %

Table 5.34: Impacts at the Whole Project Level for Scenario 4

At the system level process interdependencies play a key role in determining the combined effects of the process alternatives introduced in this scenario. The performance measures evaluated for each of the systems and for the project as a whole in the worst case scenario are not the result of simple superposition of the performance measures evaluated for each process alternative introduced separately. The only two systems in which the effects are maintained moving from the individual process change to the combined process changes are the heating and the fire protection systems. The installation of these two systems does not actually depend on the rate of installation of other systems, thus the results obtained in the context of the worst case scenario are exactly the same as those obtained in scenario 2-2-1 (in-situ fire protection) and in scenario 2-2-2 (in-situ heating).

Performance Measure	% Change
Duration	+ 57 %
Duration-Based Cost	+ 57 %
Cost of Utilized Resources	+ 79 %
% Resource Utilization	+ 14 %
Danger Index	+ 65 %

Table 5.35: Impacts at the System Level for Scenario 4 (Plumbing)

Major combined effects are observed in the plumbing and in the electrical system. For the study of the worst case scenario two process alternatives were introduced in the plumbing system: the in-situ fabrication of the plumbing risers (see scenario 2-2-3) and the in-situ fabrication of the fixtures (see scenario 2-2-4). The combined impacts of these two process alternatives give interesting results due to the process interdependencies within the plumbing system itself. Duration and duration-based cost of the installation of the plumbing system in the worst case scenario are considerably higher than those observed in either scenario 2-2-3 (in-situ fabrication of plumbing risers) or scenario 2-2-4 (in-situ fabrication of plumbing fixtures), but also considerably lower than the sum of the respective values for the two scenarios. The major process interdependency in the plumbing system is caused by a technical constraint that links the rate of installation of the fixtures to the rate of installation of the supply and return pipes. The fixtures cannot be placed until the entire loop of supply and return pipes pertaining to the same riser group (e.g. fed by the same vertical riser) has been installed and tested [2]. The in-situ fabrication of the vertical risers not only adds preparation time to the installation of each single pipe, but it also increases dramatically the number of vertical units to be placed, since the pipe segments belonging to the same riser unit are no longer bundled together for installation. The increase in installation time of the vertical units reflects into additional delays in the start time for the placement of the plumbing fixtures (which already take longer to be installed, since they are no longer prefabricated). This technical constraint in addition to resource availability sets the rate of progress on the installation of the plumbing system. As a result, both duration and duration-based cost for the installation of the plumbing system, in this scenario, increase by 57%. The cost of utilized resources increases by 79% and the workers' exposure to danger increases by 65%. Correspondingly, resource utilization increases by 14%. It is interesting to notice that the increase in the cost of utilized resources is higher than the increase in duration-based cost. This difference can partly be explained by the fact that the preparation activities pertaining to the fixtures, based on resources availability, can be undertaken while the riser units are being placed. Similarly, the preparation of the riser segments can be performed in parallel to the installation of other units.

Performance Measure	% Change
Duration	+ 12 %
Duration-Based Cost	+ 16 %
Cost of Utilized Resources	+ 10 %
% Resource Utilization	- 6 %
Danger Index	+ 16 %

Table 5.36: Impacts at the System and Inter-System Level for Scenario 4 (Electrical)

In the electrical system the combination of two effects can be observed, the inter-system effects of the changes introduced in the heating system (see scenario 2-2-2) and the "within-the-system" effects of the placement of new electric conduits as opposed to the re-use of the existing ones (see scenario 2-1). It is interesting to notice that while the installation of the electrical system in scenario 2-1 (replacement of electric conduits) takes 4% longer than in the baseline, the installation of the electrical system in the worst case scenario only takes 1% longer than in scenario 2-2-2 (in-situ fabrication of the horizontal heating conduits). The meaning of this difference is that the increase in installation time due to the placement of new conduits mostly absorbs the resource idle time generated in the electrical system by the rate of installation of the horizontal heating pipes. The differential increase in installation time for the horizontal heating and electrical distribution is such that the completion of the heating system on one floor occurs shortly before the completion of the installation of the electrical distribution on the floor immediately below. Idle time for the crews of electricians is then much shorter than in scenario 2-2-2, as supported by the fact that resource utilization for the electrical system in the worst case scenario is 5% higher than in scenario 2-2-2.

In comparison to the baseline configuration, as shown in Table 5.37, duration and duration based cost for the electrical installation are significantly higher. The cost of utilized resources and the danger index are both higher, while the resource utilization is lower.

5.3 Summary

The case study presented in this chapter analyzes the different levels of impact of different types and levels of technological change across 10 possible project scenarios. Simulated scenario testing produces comprehensive results at three levels of analysis, system, inter-system, and whole project level, which would have not been accessible through other methods.

5.3.1 Summary of Results by Type of Design and Process Change

The results of this analysis can be grouped with respect to five general types of design and process changes: 1) prefabrication of components, 2) centralization of layout, 3) changes in materials and components, 4) changes in the nature of a whole system, 5) organizational changes in resource allocation and system definition.

The impacts of off-site fabrication of components (scenarios 2-2-1 through 2-2-4) alters the performance of the installation of fire protection, heating and plumbing systems in different ways, depending on the extent of prefabrication (percentage of the whole) and on the process interdependencies between the system of introduction and all of the other systems. Prefabrication of the horizontal pipes for the fire protection system gives limited benefits in terms of cost and duration, both at the system level and at the whole project level, chiefly because the design of the fire protection system makes its installation process independent of all of the other systems. The same level of prefabrication for the heating system produces significant impacts both at the inter-system level (relationship with electrical installation process) and at the whole project level: the layout of the heating system is, in fact, spatially tied to the layout of the electrical system. The respective horizontal pipes and conduits follow the same path along the building and share the same supporting tray, which forces the heating pipes, larger in section, to be placed before the electrical conduits on each floor. This spatial link between the two systems makes the rate of installation of the electrical conduits highly dependent on the rate of installation of the heating pipes. Moreover the duration of the whole project for this scenario is driven by the installation of the electrical system, hence off-site fabrication of the heating pipes directly translates into faster installation of the electrical system and reduction of overall project duration and cost.

Prefabrication of the plumbing risers, as well as of the plumbing fixtures are also tested as separate scenarios. The extent of prefabrication for the plumbing risers is considerably higher than for the plumbing fixtures, as reflected in the respective impacts at the whole project level: important ones for the prefabrication of the plumbing risers and moderate ones for the plumbing fixtures. The decrease in project duration is 22% for the prefabrication of the plumbing risers, and only 4% for the prefabrication of the plumbing fixtures. Duration-based cost and cost of utilized resources decrease respectively by 9% and 12.5% for the prefabrication of the plumbing risers, by 3% and 7% for the prefabrication of the plumbing fixtures.

Design changes in the system layout, particularly centralization versus decentralization of vertical risers (scenario 3-1, were analyzed with respect to the overall layout of the water-based service systems (i.e. plumbing, heating and fire protection). Centralizing the layout means shifting from a primarily vertical layout, with a number of vertical risers close to the number of usage points, to a largely horizontal layout, where few risers feed the usage points through a long network of horizontal pipes on each floor. In the baseline configuration of the Baker House project, the only system (besides the electrical system) that is fairly centralized is the fire protection system.

A new scenario was created that adopted the same centralized layout as in the fire protection system, for the heating and the plumbing systems as well. Not only does this shift represents a significant design change in terms of number and type of units to be installed, but it also introduces an additional inter-system process constraint, between the installation of the fire protection and the plumbing system. This constraint, driven by spatial requirements, ties the rate of installation of the horizontal pipes of the fire protection system to that of the horizontal pipes of the plumbing system (in the same way as in the baseline configuration the rate of installation of the electric conduits depends on the rate of installation of the heating pipes).

The effects of the additional process constraint at the whole project level are an increase in overall project duration and in duration-based cost. In addition, it is now the installation of the fire protection system, instead of the electrical system, that drives the duration and overall cost of the project. The change in design (number and type of units to be installed) actually reduces the cost of utilized resources, both at the system and at the whole project level, but introduces a change in the inter-system dependencies, which thereby determines the overall progress. The combined impact of these two effects is a reduction of resource utilization [cost of utilized resources/duration-based cost].

Changes in materials and components were analyzed in scenario 3-2. This scenario consisted of the same centralized configuration but also involved the replacement of rigid pipes with flexible ones in the domestic plumbing system. Flexible pipes can be pulled to the required length and need a minimal number of connections. Their installation is much faster compared to that of rigid pipes [2], thus loosening the dependence of fire protection on plumbing that was observed in the purely centralized configuration. Faster installation of plumbing pipes has impacts at the individual system level (shorter completion times for the plumbing system), at the intersystem level (shorter completion time, lower costs and higher resource utilization for the fire protection system), and at the whole project level (the installation of the fire protection system no longer drives the duration of the project as a whole, and overall duration and cost are much lower than in the purely centralized configuration and indeed shorter than in the original decentralized configuration.)

Changes in the nature of the whole system were examined in the comparison between water-based and air-based heating system, while keeping the basic layout unchanged (scenario 3-3). This design change has interesting implications since it represents a shift from a closed loop type of system, characterized by supply and return pipes, to an open loop type of system, characterized by supply ducts only. What is most interesting about this design change is that no significant impacts can be identified at the system level (the time required to install a given length of air ducts is actually longer than the time required to install an equal length of water pipes, but no return line is required in the air-based configuration. Coincidentally, for this particular size and layout, the effects compensate to produce insignificant changes in the performance measures at the system level.) However, significant impacts can be observed at the intersystem level: the installation of the electrical system is faster and the associated costs are lower. This effect is mostly determined by the different rate of installation of both the vertical and the horizontal units in the air-based system, as compared to the hot water heating system, which overall increases efficiency in the installation of the electrical system (shorter idle time of resources while waiting for the horizontal heating conduits to be placed). Increased efficiency in the installation of the electrical system has significant impacts on the project as a whole, since reduction in completion time for the electrical system directly translates in an equivalent reduction in project duration, and consequently decreases project cost.

Finally, the definition of the individual systems and the allocation of resources was altered in scenario 1-2 (shared resources), which studies the impacts of a purely organizational change. This scenario does not modify the nature of the design or of the process activities, but simply combines the crews assigned to the installation of the water distribution systems (domestic plumbing, hot water heating and fire protection systems).

This scenario specifically assesses the benefits of shared and re-assignable resources, without changing the total number of resources allocated. In organizational terms, this scenario compares the impacts of hiring separate sub-contractors, one for each of the systems, or a single sub-contractor for the installation of the three systems. Although it is common knowledge that flexibility in resource allocation improves project performance in terms of duration and cost, this scenario brings important insights on "optimal" resource allocation, by showing that the optimum for each individual system is sub-optimal for the whole project

Increased flexibility in resource allocation reduces the duration and the duration-based cost with respect to the combination of the three systems (5% reduction in project duration and 8% reduction in project cost). At the system level, only the plumbing system directly benefits from this change in terms of duration, while the heating and fire protection systems take longer to complete than in the baseline configuration.

The costs of utilized resources and danger indices for the project and for the individual systems do not change, since design and project activities are exactly the same as in the baseline configuration, and so is the total number and type of resources for the project.

5.3.2 Summary of Results on the Impacts of Inter-System Process Dependencies

The observation of the simulated results across the different scenarios examined in this dissertation shows unexpected results that could have not been predicted intuitively or without explicitly accounting for inter-system process dependencies in the representation of the construction processes. Table 5.37 shows the percentage change in the performance measures across the alternative scenarios in comparison to the baseline. Figures 5.25 and 5.26 summarize the simulated results for the different scenarios at the whole project level. Figures 5.27 through 5.34 summarize the results at the system level.

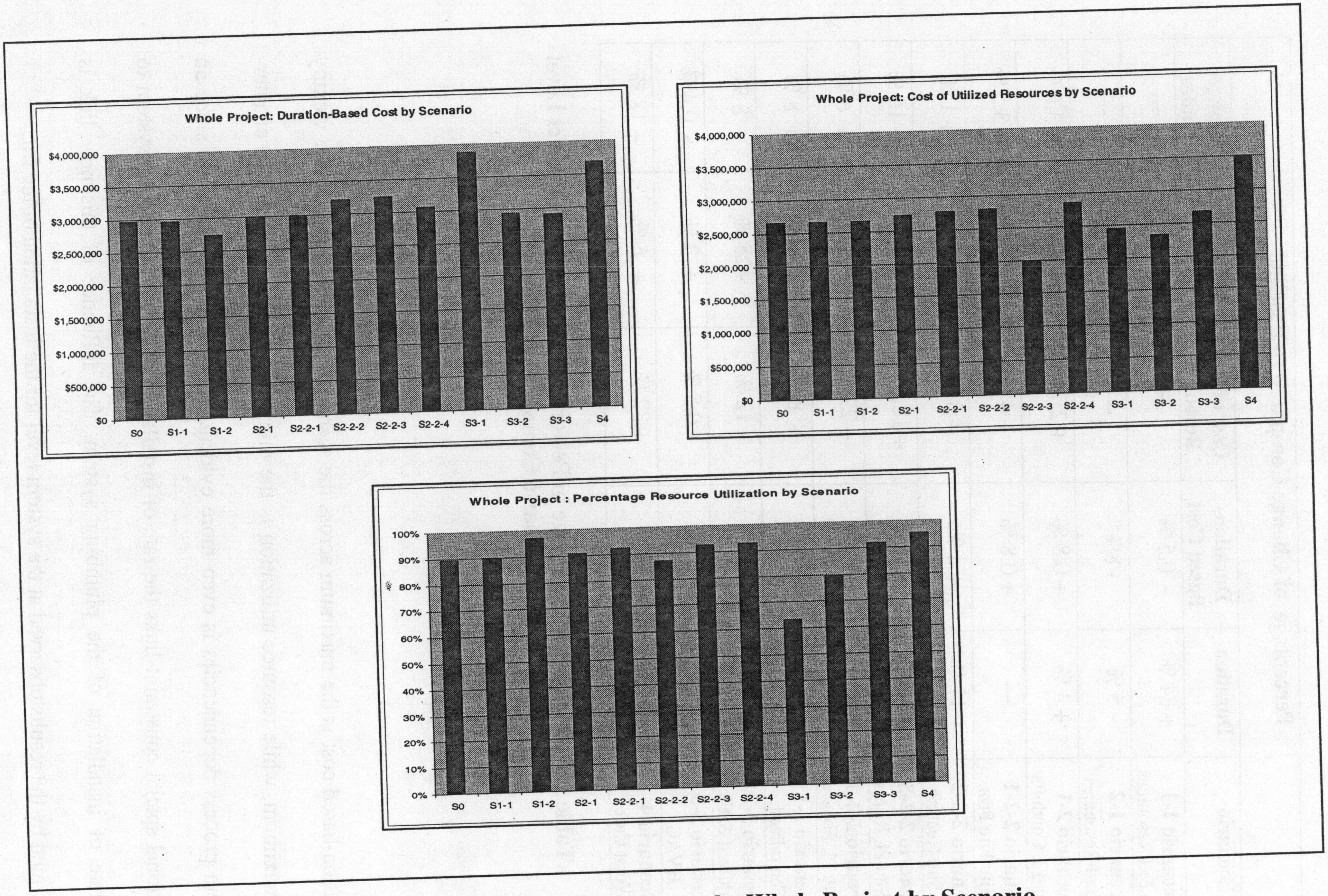
The first interesting result can be observed in the so called "worst case scenario". As observed in the summary of results, this scenario is not the worst in an absolute sense, but it is intuitively the "worst-expected scenario". In this case intuition could find confirmation in the fact that both the cost of utilized resources and the danger index for this scenario at the whole project level are maximum, showing that the actual number of man hours required to complete the project are the highest among the scenarios. However, these two performance measures are not dynamic in the context of the construction process, meaning that they are not affected by inter-system process dependencies. The actual project duration and duration-based costs, that are directly influenced by inter-system process dynamics, are higher than the average for the scenarios (but still much closer to the average than to the maximum values), showing that inter-system process dynamics drives project duration and actual project cost away from the expected.

The opposite is true for the centralized scenario. While, based on man hours requirements, this scenario would be expected to be nearly the "best scenario" (the values of cost of utilized resources and danger index are very close to the minimum ones across the scenarios, with the minimum occurring in the centralized and flexible scenario) with lowest duration and duration based cost, the actual duration and duration based cost prove it to be nearly the worst.

Percentage of Change Compared to Baseline					
Scenario	**Duration**	**Duration-Based Cost**	**Cost of Util. Resources**	**% Resource Utilization**	**Danger Index**
Scenario 1-1 Reduced Resources	+ 84 %	- 0.5 %	---	+ 0.5 %	---
Scenario 1-2 Shared Resources	- 5 %	- 8%	---	+ 9 %	---
Scenario 2-1 Repl. El. Conduits	+ 4 %	+ 0.8 %	+ 2.7 %	+ 1.8 %	+ 3.6 %
Scenario 2-2-1 In-Situ Fire Prot.	---	+ 0.8 %	+ 4 %	+ 0.9 %	+ 3.5 %
Scenario 2-2-2 In-Situ Heating	+ 11 %	+ 8 %	+ 5 %	- 3 %	+ 1 %
Scenario 2-2-3 In-Situ Pl. Risers	+ 22 %	+ 9 %	+ 12.5 %	+ 4 %	+ 15 %
Scenario 2-2-4 In-Situ Pl. Fixtures	+ 11 %	+ 11 %	+ 29 %	+ 16 %	+ 6 %
Scenario 3-1 Centralized	+ 62 %	+ 30 %	+ 8 %	+ 30 %	+ 8 %
Scenario 3-2 Centralized & Flex.	- 7 %	- 1.5 %	- 12 %	- 25 %	- 8 %
Scenario 3-3 HVAC	- 7 %	- 2 %	+ 0.5 %	+ 3 %	+ 0.4 %
Scenario 4 Worst Case	+ 45 %	+ 24 %	+ 32 %	+ 6 %	+ 18 %

Table 5.37: Percentage of Change in Performance at the Whole Project Level For Each Scenario Compared to Baseline

Duration-based cost is the maximum across the scenarios, and duration is in the vicinity the maximum, while resource utilization is the minimum. In this case the role of inter-system process dependencies is even more evident than in the previous case, since an additional spatial constraint links the rate of installation of the fire protection system to the rate of installation of the plumbing system. The influence of this new link is confirmed by the results observed at the system level for the installation of the fire



Whole Project: Duration-Based Cost by Scenario

Whole Project: Cost of Utilized Resources by Scenario

Whole Project : Percentage Resource Utilization by Scenario

Figure 5.25 : Summary of Results for the Whole Project by Scenario

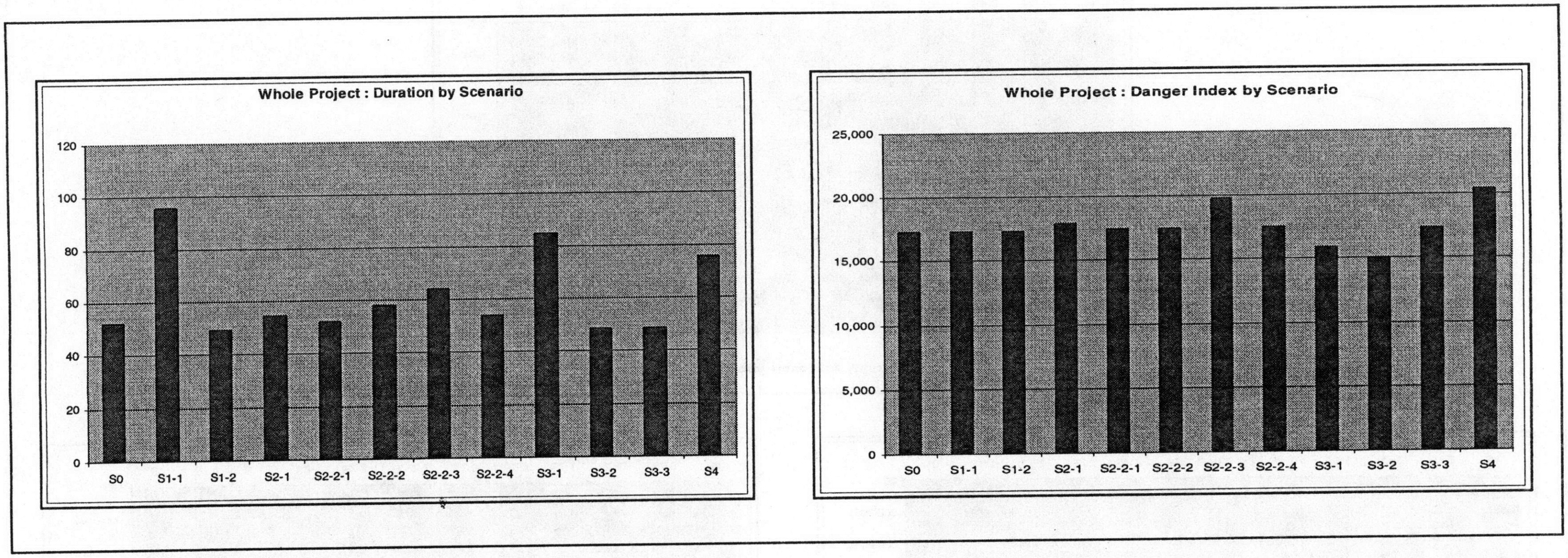
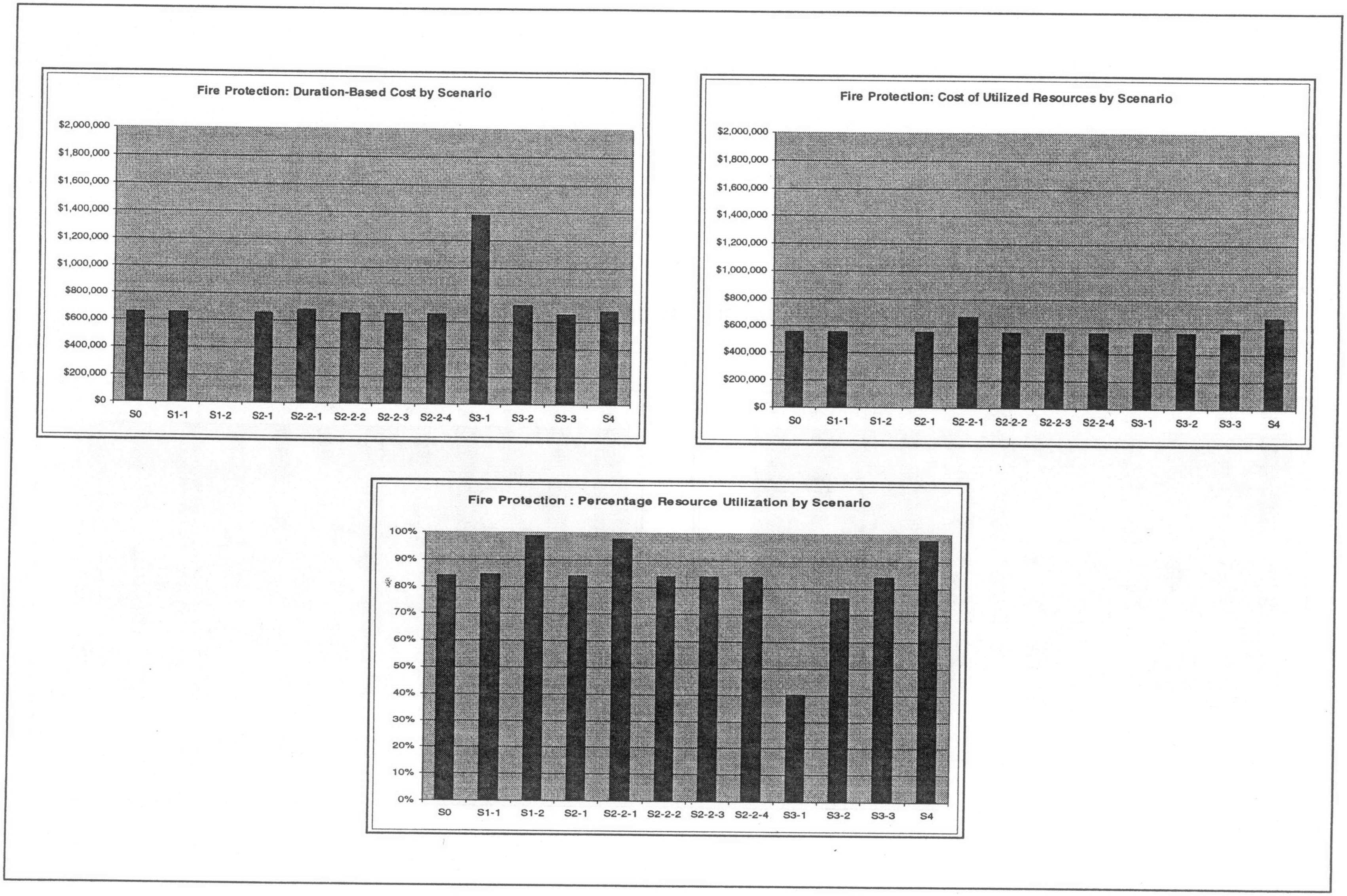


Figure 5.26 : Summary of Results for the Whole Project by Scenario



Fire Protection: Duration-Based Cost by Scenario

Fire Protection: Cost of Utilized Resources by Scenario

Fire Protection : Percentage Resource Utilization by Scenario

Figure 5.27 : Summary of Results for the Fire Protection System by Scenario

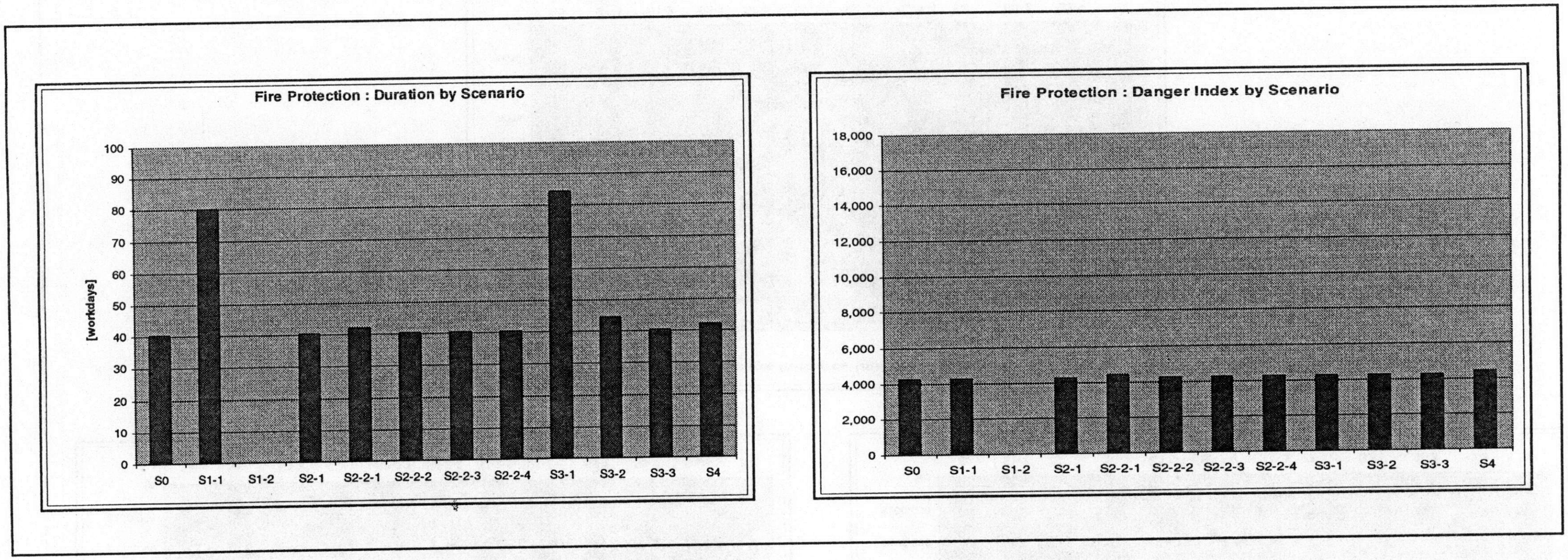


Figure 5.28 : Summary of Results for the Fire Protection System by Scenario

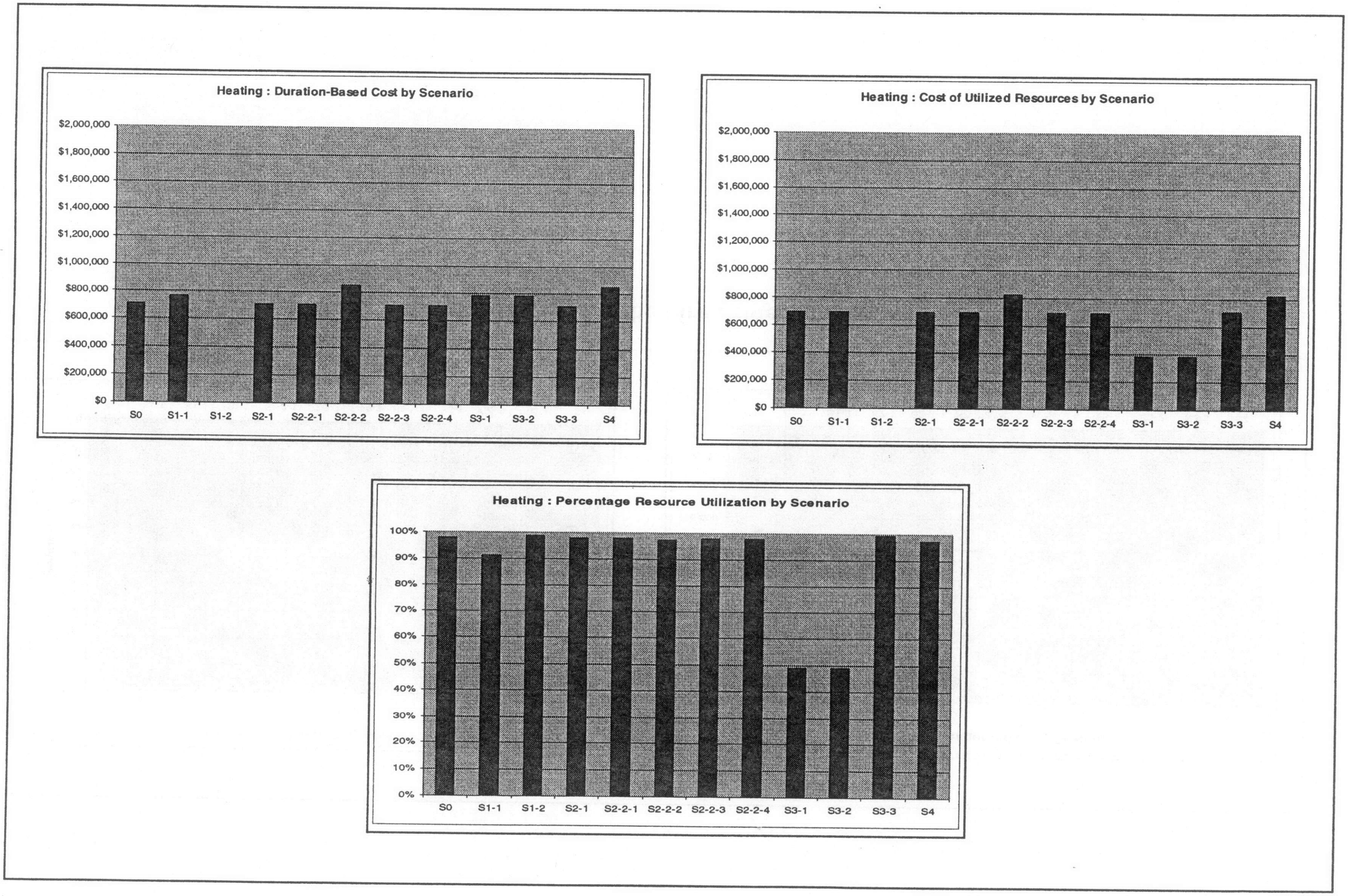
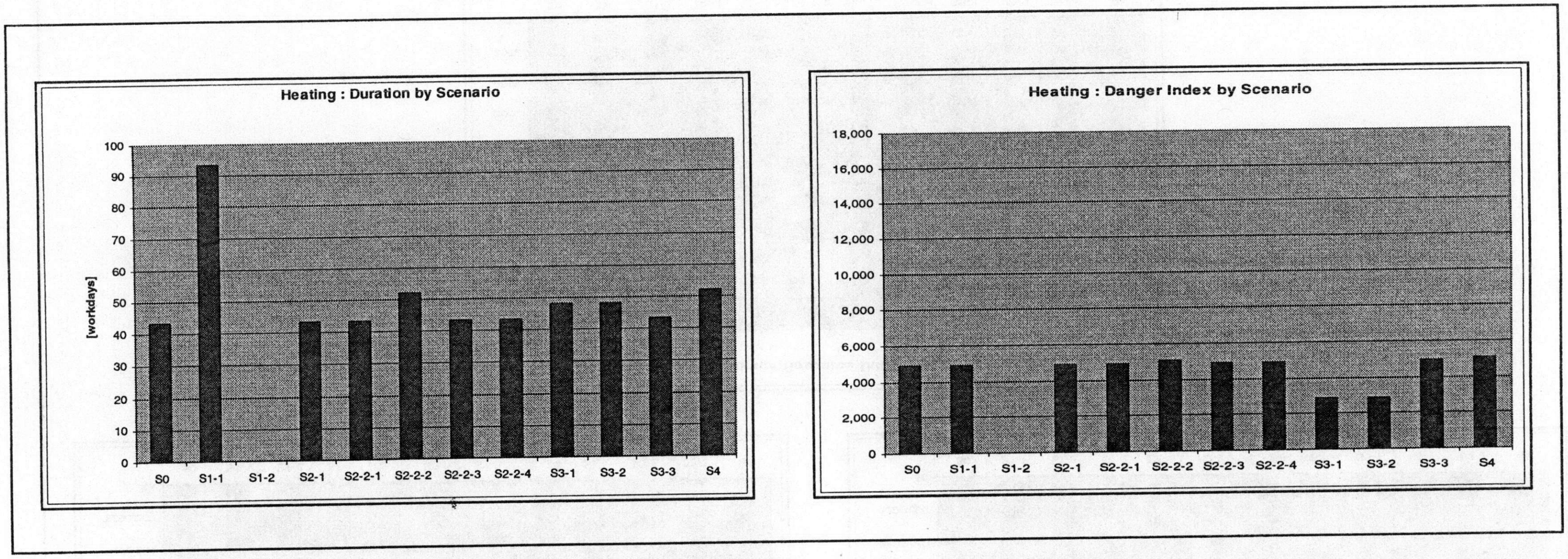
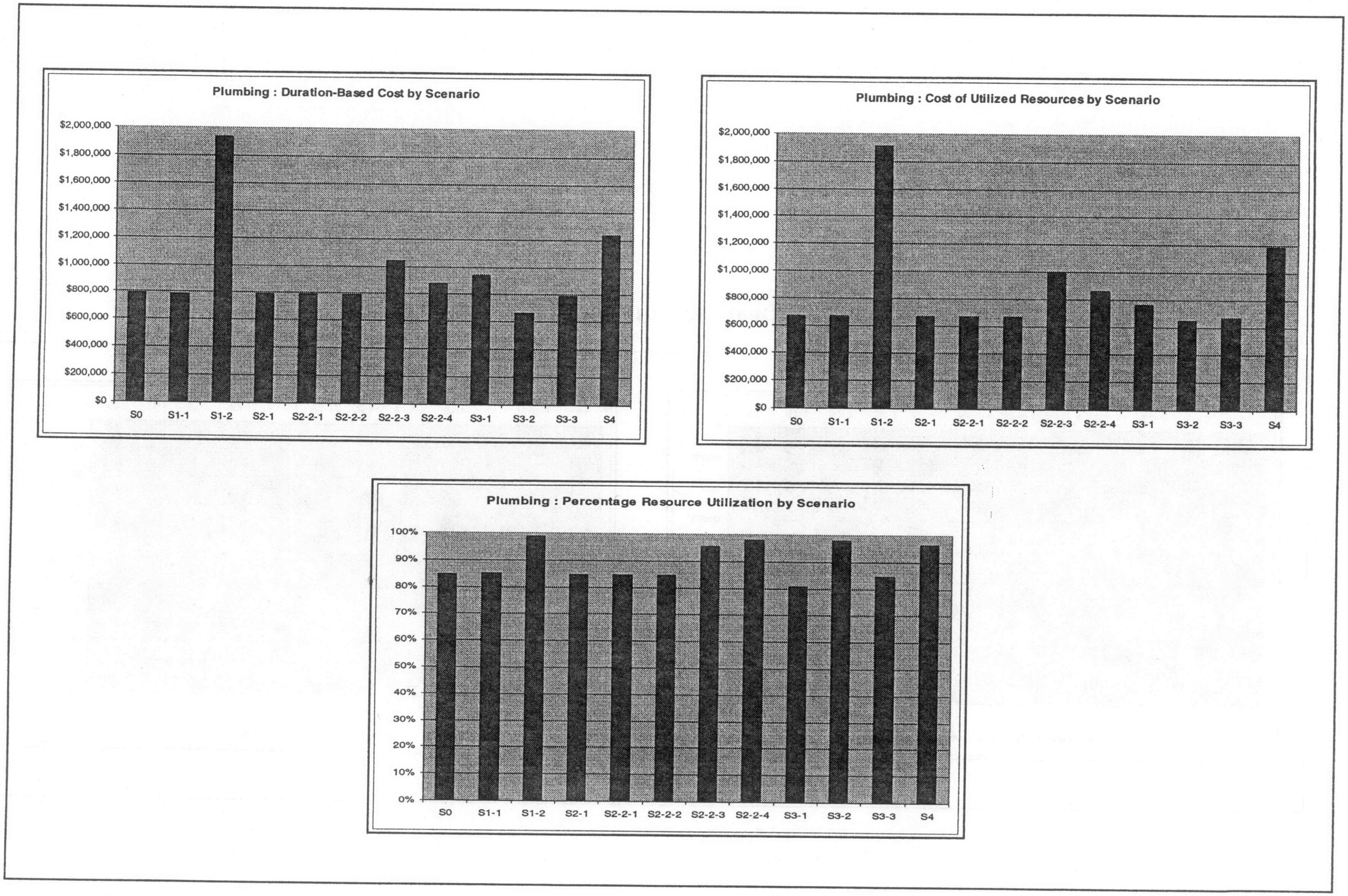


Figure 5.29 : Summary of Results for the Heating System by Scenario


Heating : Duration by Scenario

Heating : Danger Index by Scenario

Figure 5.30 : Summary of Results for the Heating System by Scenario


Plumbing : Duration-Based Cost by Scenario

Plumbing : Cost of Utilized Resources by Scenario

Plumbing : Percentage Resource Utilization by Scenario

Figure 5.31 : Summary of Results for the Plumbing System by Scenario

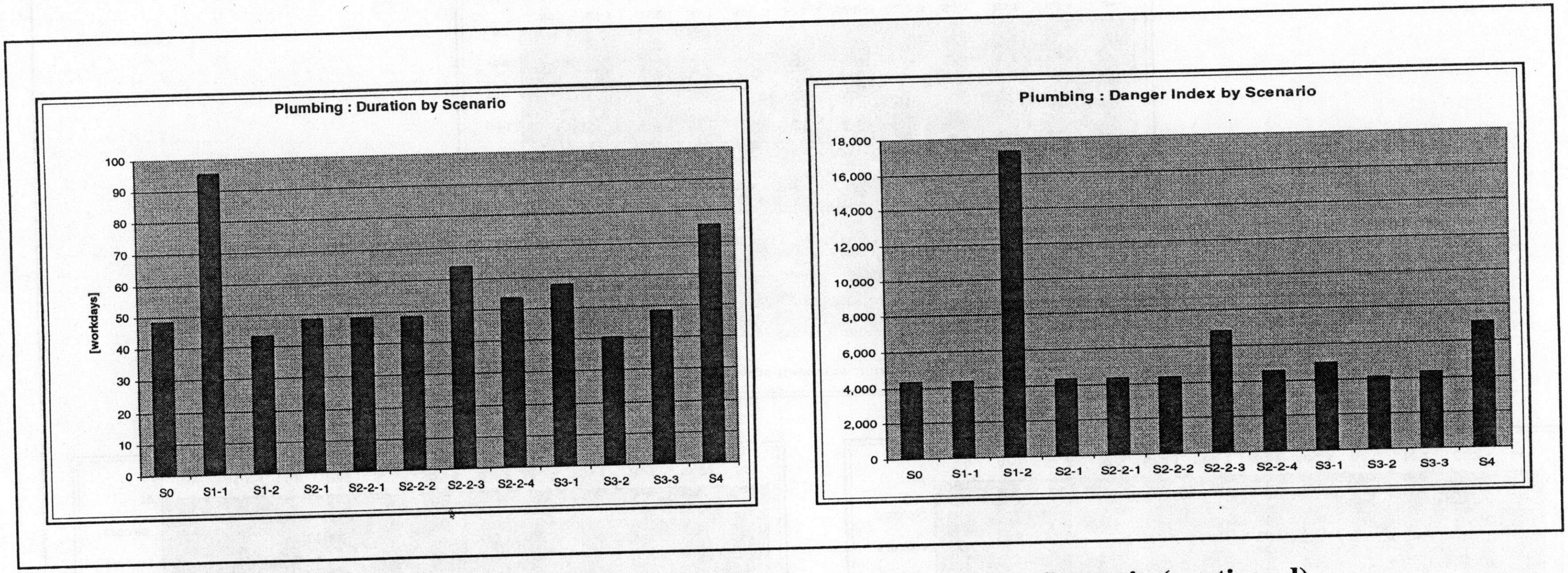


Figure 5.32 : Summary of Results for the Plumbing System by Scenario (continued)

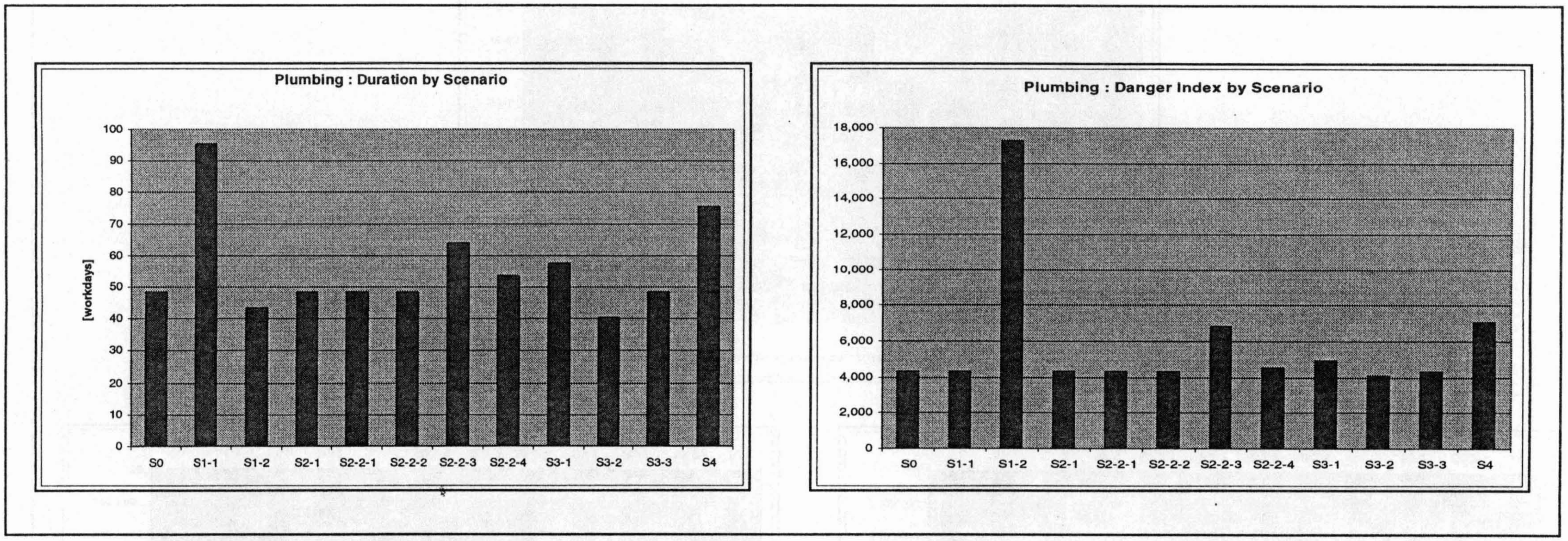


Figure 5.32 : Summary of Results for the Plumbing System by Scenario (continued)

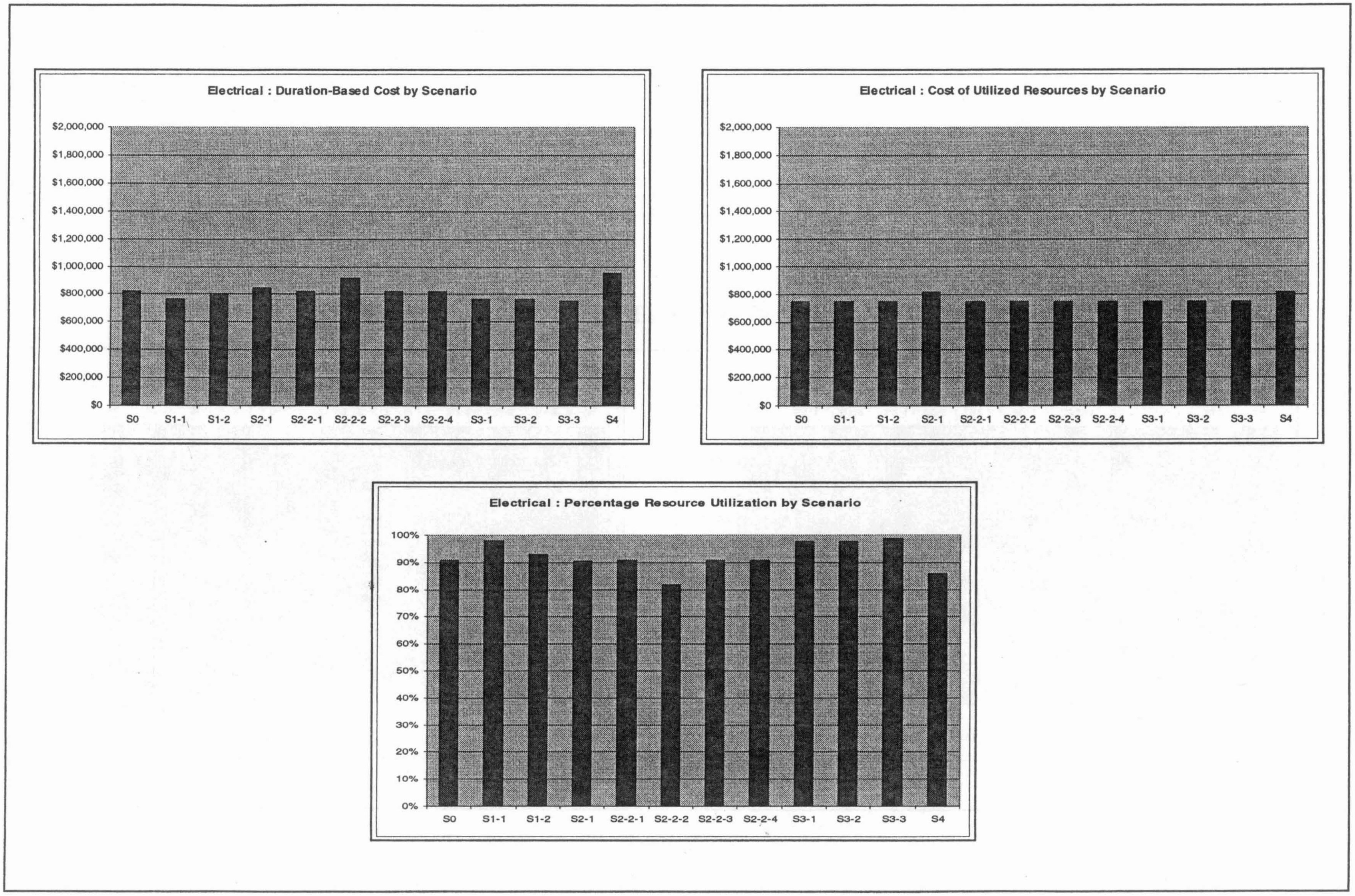


Figure 5.33 : Summary of Results for the Electrical System by Scenario

protection system. The dependence of this system on the rate of installation of the plumbing system creates long periods of resource idle time (as shown by 40% resource utilization) and pushes duration and duration-based cost for the installation of the fire protection system to become the highest among the other scenarios. Even more surprising is the fact that no change is actually introduced in the layout of the fire protection system, which is already centralized in the baseline configuration. So in this case the highest impact at the system level, due to inter-system process dependencies, is observed in the system that remains unchanged and is directly reflected in project duration (indirectly in other performance measures).

Most interesting is the combination of centralized layout and flexible horizontal distribution pipes for the plumbing system. While the layout remains unchanged with respect to the previous case, and thus would lead to expect highest duration and duration-based cost and lowest resource utilization, the introduction of a different material in the distribution of the plumbing pipes reverses the situation. The fact that flexible plumbing pipes can be pulled to the required length, without requiring any intermediate connections, highly reduces the installation time for the horizontal distribution of the plumbing system. Since the installation time of the horizontal plumbing distribution constrains the rate of progress that can be made in the installation of the fire protection system, faster installation of the plumbing pipes directly translates in reduced idle time for the fire protection system (loosens the constraint between the two) and thus reduces overall project duration that in the purely centralized configuration was driven by the fire protection system, while in this case it. This scenario highlights the combined effects of complementary design changes. In this case the combined effects bring the actual duration and duration-based cost of the whole project to values that are much closer to the expected: as the cost of utilized resources and the danger index are minimum among the scenarios, both duration and duration-based cost become nearly the lowest. The combined effects of complementary changes also brings up the issue of coordination. In some cases the expected benefits from the introduction of a change cannot be fully accrued without proper coordination and adjustment among the systems. The introduction of a complementary change can completely alter the performance measures obtained with respect to the first change. Similarly, the introduction of a change

Another surprising example is provided by the substitution of air-based HVAC ducts to hot-water-based heating pipes in the heating system. As discussed in the previous section, the replacement of an entire system that is different not only in terms of materials and in terms of components but alters the system layout shifting from a closed loop type of system to an open loop type of system, brings relatively small changes in the performance of the project as a whole, Most of these changes are produced at the inter-system level, since hardly any variation in performance measures can be appreciated at the system level. The fact that no change is observed at the system level is obviously coincidental for that particular system size and layout, given that the replacement of an entire system produces major changes in the installation processes at the task level and also highly changes the number of parts and components to be installed (the number of duct segments is reduced by half in the new configuration, given that no return conduits are required by this design). Changes at the whole project level are determined exclusively by the spatial links between the installation of the electrical system and the installation of the HVAC ducts.

The study of an organizational change as in Scenario 1-2, tests the benefits of flexible resource allocation, by merging the crews of plumbers for the three water based service systems into a single pool of common resources. This scenario proves that optimization with respect to the individual systems, processes or components is not necessarily optimal for the purposes of the whole. This phenomenon is typical of complex large-scale systems and processes where the links among components and sub-processes make the effects highly non-linear. So the sum of optimal sub-processes does not necessarily produce optimal processes. Although this is a well known concept, established design theories and planning methods still tend to optimize at the sub-process/sub-system level and then focus on the whole.

Other interesting results are produced by the baseline scenario. The baseline scenario that per se represents the actuality of the production process for the Baker House eproject, represents the best compromise solution (trade-off) across all the values of the performance measures. Although none of the duration, costs and danger index are absolute minimum among the scenarios, nor is the resource utilization the absolute maximum, either at the whole project level or at the individual system level, each of the performance measures for the project as a whole remains within a small percentage off the absolute best values across the different scenarios.

As shown in Table 5.37, the best values of performance measures across all the scenarios remain within 7% and 12% off the baseline, with 7% less in project duration, which gives the minimum deviation from the optimum on the performance measure that was most critical to the success of this project. It is important to note that the best values of performance are not concentrated in one single scenario, but are dispersed among the scenarios, so the best performance on duration may not be matched by the best performance in cost or safety. For example, minimum project duration is achieved in Scenario 3-3 (HVAC), lowest duration-based cost and highest resource utilization are found in Scenario 1-2 (Shared Resources), while minimum cost of utilized resources and minimum danegr index are shown in Scenario 3-2 (Centralized and Flexible).

This proves that in complex large-scale projects experience and experiential knowledge about design and production is the most valuable tool, and overall leads to best results, or best compromises among project objectives. For this reason, this research is empirically based. It gathers experiential knowledge about the design and production processes and incorporates into a tool that bot only makes the existing knowledge available for use, but also builds "fast new experience" through simulation experiments.

CHAPTER 6 : SUMMARY AND CONCLUSIONS

The analysis conducted on the Baker House project brings significant insights on the impacts of change in complex large-scale systems. The first key conclusion from this study is that production performance for complex large-scale projects is multi-attribute. Changes in design and technology can be fully appreciated only through comprehensive analysis conducted at multiple levels (i.e. at the system, inter-system, and project levels) and with respect to multiple dimensions (i.e. the performance measures of duration, costs, danger indices and resource utilization).

Another key conclusion is that secondary and tertiary impacts of change significantly influence overall and system performance. These hidden impacts of change, which heavily affect the relevant performance measures, can be directly related to the presence of inter-system dependencies among the production processes. Inter-system dependencies build their effects at the task-component level, and their impacts on production process performance can be fully captured only by modeling processes and inter-process links at this level of detail. The analysis with focus on inter-system process dependencies constitutes a new powerful tool to address overall production performance for complex projects. The approach is entirely modular and directly applicable to a large variety of complex and dynamic projects outside the construction industry.

Specific conclusions from the case study reveal that the concepts of “best” and “optimum” are relative to the performance measure and to level of perspective (e.g. system or project level). The comparison of the results for the different scenarios shows that the best combination of design and technology varies across the different performance measures. Scenario-specific analysis shows that the optimization of the production process at the system level does not necessarily lead to the optimum for the whole project, and that the ripple effects of change due to inter-system process dynamics produce highly unexpected performance outcomes.

For example, Scenarios 3-1 and 3-2 and Scenario 3-3 (with alternatives in the design layout through centralization and system changes) show that only by explicitly representing inter-system process links at the appropriate level of detail is it possible to capture secondary and tertiary effects of changes. In Scenario 3-1 (centralized layout), for example, the system that is most heavily affected by the centralization of the layout for the water-based systems is the only one that was already fully centralized in the baseline scenario (i.e. fire protection). This secondary effect of the centralization of the heating and domestic plumbing systems, can be directly related to the additional inter-system process link that becomes effective in this scenario, which is the spatial link between the installation of horizontal plumbing and fire protection pipes. Tertiary effects can also be observed in this scenario since the installation of the fire protection system drives project duration. Similarly, Scenario 3-2, which combines centralized layout and flexible pipes for the plumbing system, shows that by loosening the constraint due to this spatial link, the secondary effect on the fire protection system is highly reduced and no tertiary effect on project duration can any longer be found. Scenario 3-3, which replaces the hot water heating with a HVAC system, shows interesting secondary and tertiary effects related to the spatial link between the installation of the horizontal heating and electrical distribution, in the absence of primary effects on the system where the change is first introduced. Heavy secondary impacts of this change can be found in the performance of the electrical installation process and reflected in the form of tertiary impacts on project duration.

These examples demonstrate that the specification and the representation of production processes at the aggregate level (e.g. system level) fail to capture important impacts of design and technology changes, that are determined by inter-system process dependencies.

Scenario 1-2, which tests the benefits of shared and re-assignable resources among the water-based service systems shows that the optimal production process (in this case in terms of resource allocation) across multiple product sub-systems is not necessarily the result of individual process optimization at the sub-system or component level. Based on this evidence, the specification and optimization of the production processes by design unit, which works for conglomerates, may lead to sub-optimal solutions in the context of complex large-scale projects.

The results observed in Scenario 4 and in Scenario 3-1 are not only counter-intuitive but factually opposite to what estimates based on the pure number of man hours required to complete the project would predict. Scenario 4 that would be expected to perform the worst, shows values of duration and duration-based costs that are close to the scenarios' average. Scenario 3-1 that would be expected to perform the best appears to be the worst, showing the highest duration-based cost, the lowest resource utilization and nearly the longest project duration. Although in other scenarios, such as Scenario 3-2, there is a close match between these estimates and the actual project duration and duration-based cost, these findings make performance estimates based exclusively on man hour requirements inadequate for the assessment of complex large-scale projects.

Estimates based on man hour requirements, found in the traditional project planning tools and in several simulation packages, reveal to be misleading because they neglect the impacts of inter-system process dependencies.

The value of experiential knowledge in design and planning for complex large-scale project is shown by the simulated results for the baseline scenario. This scenario, which is representative of the actual construction project, as designed and planned by the parties involved in the project, achieves the best compromise across all of the performance measures. In addition, the minimum deviation from the optimum is in project duration, which was the most critical aspect of performance for this project.

This research acknowledges the value of experiential knowledge in complex large-scale projects. One of the major efforts of this research was to maintain a tight connection between the development of the theory and empirical evidence gathered from the industry. Construction projects that are the object of simulated scenario testing for this research heavily rely on methodologies and techniques that are experiential. Knowledge about construction processes is contextual and tacit in nature. Competencies are fragmented and mostly tied to the experience and knowledge of individuals involved in construction projects. This research has captured unspoken and fragmented aspects of construction activities through site observations and personal interviews with industry members and makes it available in the form of a computer-based simulation tool. Not only does the tool make organized use of existing construction knowledge in the representation of multiple interdependent construction processes, but it also enables professionals to quickly build new, integrated, knowledge through simulation and scenario testing.

In particular, the tool provides the means to compare the benefits of design and technology changes across multiple alternatives and with respect to multiple measures of performance. The strength of the tool lies in its ability to capture ripple effects that the introduction of a change in one system may have on the progress of other building systems during the construction process. The construction industry can greatly benefit form the ability to make these assessments early in the design and planning stages. Owners, designers and contractors are often faced with a great deal of uncertainty and risk, especially with respect to the introduction of new designs and innovative technologies. In addition to the project duration and cost issues associated with an innovation, the implications of an innovation must be assessed with regards to regulatory, safety, and technical constraints. In a context where full-scale prototyping is prohibitively costly and time consuming, the availability of a tool that can assist project teams in the assessment of these implications can significantly reduce the risks and uncertainties associated with innovation. The ability to gauge their perceived benefits prior to their use in the field, significantly lowers the barriers to the implementation of potentially superior designs and methods and may lead overall to more active development and diffusion of new technologies throughout the industry.

The simulation model also constitutes a viable tool for real-time project monitoring and control during construction. Using the model project managers can quickly assess the impacts of different courses of action, in terms of activity scheduling and resource allocation, and adjust their plans according to new, unexpected, conditions that may arise on the site.

Future research may address the improvement of the simulation tool towards an integrated design package. The dynamic process simulation tool, as developed in this research, reads the design specification for each alternative directly from input files that are built by the user based on the detailed drawings of a facility or based upon the quantity take-off. This process although feasible can be time consuming depending on the experience of the user and his/her familiarity with the project. Each single component and part that is included in the design needs to be specified in terms of relevant properties (attributes) and in terms of spatial location within the facility. One significant improvement that would help the diffusion of the tool and its efficient use during design would be to interface the simulation tool with a design package that would enable to customize a scenario directly from the drawings. For instance, 3-D CAD drawings of a facility could be linked to the process models to automatically produce duration, cost, and safety estimates for each design and technology alternative considered for a given project.

The dynamic process simulation tool was specifically developed to provide the means to compare design and technology alternatives across a range of performance measures. While for the purpose of this study it was most useful to evaluate the impacts of change separately on each aspect of performance, the use of the tool in the industry may benefit from multi-objective optimization. In specific applications, depending on project goals, individual aspects of performance such as project cost or duration may drive the choice of a specific combination of design and technology alternatives. A valuable improvement would be to interface the simulation model with an optimization tool to select the best combination of design and technology alternatives based on specified project objectives.

On the theoretical side, future research may address applications outside the specific context of the construction industry. The theoretical approach, as formulated for this research, is in general applicable to the production of a large variety of complex large-scale systems. Any production process that involves the performance of multiple activities and tasks in the same location and at the same time is influenced by the presence of inter-system process links, where the activities that lead to the production of one system or component influence the rate of progress that can be made in the production of other product systems and components. While the specific application of the theory for this research was focused on the construction of large occupied facilities, immediate applications could be extended to aircrafts, ships and any other complex large-scale system.

Most interesting would also be the study of complex processes that lead to the production of systems other than complex and large-scale, such as batch production as opposed to the production of unique customized products. The same theory would directly apply to other types of complex processes in which process dynamics affects the rate of production, such as the fabrication of semiconductors for the computer industry, or baking processes, where the current status of a product with respect to critical process stages determines the next step in the production process.

Future research may also extend the scope of this work to incorporate in a single framework operational and production performance as design objectives. This way, it would be possible to evaluate each combination of design and technology alternatives simultaneously in terms of performance of the product in use and in terms of the performance of the interdependent production processes, for the most integrated approach to the design of complex systems.

APPENDIX 1 : EXPERT SYSTEMS AND NEURAL NETWORKS

Expert systems are the first commercial application of the work done in the field of artificial intelligence. By definition an expert system is a computer program that simulates the thought process of a human expert to solve complex decision problems in a specific domain (Badiru 1992). An expert system is an interactive computer-based decision tool that uses both facts and heuristics to solve difficult decision problems based on knowledge acquired from an expert (Levine et al. 1990). Applications which are calculation-intensive or deterministic are not good candidates for expert systems. Conventional computer programs are based on factual knowledge and work under mathematical and boolean operators in their execution. The best application candidates for expert systems are those requiring expert heuristics for solving problems under uncertain conditions. Humans solve problems on the basis of a mixture of factual and heuristic knowledge, where heuristic knowledge includes intuition, judgement and logical inferences. Successful expert systems merge human knowledge with computer power to solve problems within the boundaries of a particular domain (Badiru 1992). Specific areas of interest such as diagnosing, learning, designing and planning are example of domains. Expert systems are suitable for knowledge intensive problems that are typically solved by human experts. Because expert systems depend on human knowledge, if human experts are unable to solve a given problem, then no successful expert system can be developed to solve that problem either (Badiru 1992).

The classical computer programs may be very flexible and capable of dealing with very complex situations, but they cannot solve any problem that the programmer did not foresee when he/she wrote the program. Everything that a conventional program does is predictable or pre-established. A program that is designed to exhibit intelligence, on the other hand, is expected to do things that have not been explicitly programmed. In essence, an intelligent program consists of a complex set of rules on how to process data. In addition it has a certain amount of information in the form of a data base.

Creating an artificial intelligence system that has flexibility, creativity and learning ability of the human biological system is a major goal of artificial intelligence. Many models of our intelligent biological system have been developed, and each was designed to function the same way our brain and nervous system function. The "artificial neural system model" is based upon the representation of human neurons and their interactions as building blocks. In classical artificial intelligence, experts are used to supplying their own tested methods and knowledge to give the computer the basis for appropriate answers within a specific domain. An expert system is such that if no new knowledge in a specific domain is available, the domain knowledge and the methods to handle such knowledge stop growing. In contrast neural systems learn directly by interacting with the domain and do not need expert knowledge about the domain. Given enough time and experience or training the neural system will learn everything about the domain, even what it is presently not known by the experts in the field (Levine et al. 1990). Neural systems are built to imitate the intelligent human biological process of learning, self-modification, and learning by making inferences. Expert system knowledge is bounded by what is actually known about the established domain. Neural systems extract the knowledge directly from the domain during the training sessions, and the self-modification of a neuron system provides a dynamic learning experience (Badiru 1992).

The human neuron system consists of networks of highly interconnected neurons, each of which performs a discrete computation at any given moment. The results of each computation are transmitted to other neurons along a neural pathway of connections called synapses. Each neuron can send such results to as many as 10,000 other neurons as input signals in the form of voltages. These signals can either inhibit other neurons from sending signals or excite them to send signals to other neurons. Artificial neural networks reproduce biological neural structures by using artificial neurons as building blocks. Artificial neural networks can be trained to make inferences within a given domain when a sufficient number of data points is available in that domain. The network is trained on sets of inputs and corresponding ideal outputs. During the training sessions the connections between active (excited) neurons become stronger while the connections between inhibited neurons become weaker. This way of self-adjusting allows the network to represent systems and processes characterized by strongly non-linear behavior, or such that an explicit relationship between inputs and outputs cannot be formalized. The larger the number of data points available for training, the more accurate is the response of the network when tested on new input data (not use for training). Best results are obtained when the network is used within the range of inputs used for training, the network is not very accurate when asked to extrapolate outputs outside the range of training inputs.

The number of data points required to train the network and the time required to train it significantly increase as the complexity of the relationships between inputs and outputs increases. While the realization of expert systems requires a base of expert knowledge that provides the grounds for decision rules, the applicability of neural networks depends on the availability of actual data points for the network to be trained on.

APPENDIX 2 : CALCULATIONS OF THE PERFORMANCE MEASURES FOR THE DIFFERENT SCENARIOS

BASELINE DESIGN

Duration	417.6 hrs		
TB Cost $	2,977,829		
ABCost $	2660717	% of Overall Cost =	89.35089
Danger Ix	17278.2		

Fire Prot. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	782	1.82	1423.24	4981.34	1962.648
Install	Hangers	39.4	820	0.967	792.94	2775.29	1093.464
Prepare	Vert. Pipe	7.6	24	0.75	18	63	4.788
Install	Supply	46.2	12	0.65	7.8	27.3	12.6126
Install	Standpip	35.6	12	1.13	13.56	47.46	16.89576
Install	Sprinklers	57	756	0.783	591.948	2071.818	1180.936
Test	Riser Gr.	9.9	4	5.35	21.4	74.9	7.4151
	TOTAL			6.1	2868.888	10041.11	**4278.76**

Fire Prot. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1434.444	87042.06
Journeym	37.42	9.73	10.85	58	2868.888	166395.5
Apprentice	33.95	8.83	9.85	52.62	5737.776	301921.8
	TOTAL					**555359.3**

Fire Prot. ABC = 555359.3
Fire Prot. TBC = 660960 Ratio = 84.02314

Heating Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	912	1.2	1094.4	3830.4	1509.178
Install	Hangers	39.4	1958	0.967	1893.386	6626.851	2610.979
Prepare	Vert. Pipe	7.6	228	0.75	171	598.5	45.486
Install	Supply	46.2	114	0.65	74.1	259.35	119.8197
Install	Return Pip	35.6	114	1.13	128.82	450.87	160.5097
Install	Radiators	57	378	0.583	220.374	771.309	439.6461
	TOTAL			5.28	3582.08	12537.28	**4885.618**

Heating Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1791.04	108680.3
Journeym	37.42	9.73	10.85	58	3582.08	207760.6
Apprentice	33.95	8.83	9.85	52.62	7164.16	376978.1
TOTAL						**693419**

Heating	ABC =	693419		
Heating	TBC =	707880	Ratio =	97.95715

Plumbing Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Vert. Pipe	41.96	252	3.68	927.36	3245.76	1361.921
Install	Fixtures	35.1	832	2.34	1946.88	6814.08	2391.742
Connect	DWV Legs	39.4	520	0.65	338	1183	466.102
Testing	Riser Gr.	9.9	42	5.35	224.7	786.45	77.85855
	TOTAL			6.02	3436.94	12029.29	**4297.624**

Plumbing Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1718.47	104276.8
Journeym	37.42	9.73	10.85	58	3436.94	199342.5
Apprentice	33.95	8.83	9.85	52.62	6873.88	361703.6
TOTAL						**665322.8**

Plumbing	ABC =	665322.8		
Plumbing	TBC =	787440	Ratio =	84.49188

Electr. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Horiz. *	49.3	1928	0.497175	958.5534	3354.937	1653.984
Install	Vertical *	56.1	42	1.54	64.68	226.38	126.9992
Install	Fixtures *	66.9	1320	0.4	528	1848	1236.312
Wiring &	Finishing	9.9	1396	1.65	2303.4	8061.9	798.1281
Test	Building	9.9	1	2.25	2.25	7.875	0.779625
	TOTAL			2.437175	3856.883	13499.09	**3816.203**

* include 9.9% risk electrical shock

Electr. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1928.442	117017.8
Electrician	37.42	9.73	10.85	58	3856.883	223699.2
Apprentice	33.95	8.83	9.85	52.62	7713.767	405898.4
TOTAL						**746615.5**

Electr.	ABC =	746615.5		
Electr.	TBC =	821548	Ratio =	90.87911

REDUCED RESOURCES

Duration	767.5 hrs		
TB Cost $	2,962,284		
ABCost $	2660717	% of Overall Cost =	89.81977
Danger Ix	17278.2		

Fire Prot. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	782	1.82	1423.24	4981.34	1962.648
Install	Hangers	39.4	820	0.967	792.94	2775.29	1093.464
Prepare	Pipes	7.6	24	0.75	18	63	4.788
Install	Supply	46.2	12	0.65	7.8	27.3	12.6126
Install	Standpip	35.6	12	1.13	13.56	47.46	16.89576
Install	Sprinklers	57	756	0.783	591.948	2071.818	1180.936
Test	Riser Gr.	9.9	4	5.35	21.4	74.9	7.4151
	TOTAL			6.1	2868.888	10041.11	**4278.76**

Fire Prot. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1434.444	87042.06
Journeym	37.42	9.73	10.85	58	2868.888	166395.5
Apprentice	33.95	8.83	9.85	52.62	5737.776	301921.8

TOTAL **555359.3**

Fire Prot. ABC = 555359.3
Fire Prot. TBC = 655860 Ratio = 84.67651

Heating Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	912	1.2	1094.4	3830.4	1509.178
Install	Hangers	39.4	1958	0.967	1893.386	6626.851	2610.979
Prepare	Pipes	7.6	228	0.75	171	598.5	45.486
Install	Supply	46.2	114	0.65	74.1	259.35	119.8197
Install	Return Pip	35.6	114	1.13	128.82	450.87	160.5097
Install	Radiators	57	378	0.583	220.374	771.309	439.6461
	TOTAL			5.28	3582.08	12537.28	**4885.618**

Heating Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1791.04	108680.3
Journeym	37.42	9.73	10.85	58	3582.08	207760.6
Apprentice	33.95	8.83	9.85	52.62	7164.16	376978.1
TOTAL						**693419**

Heating ABC = 693419
Heating TBC = 761940 Ratio = 91.00704

Plumbing Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Vert. Pipe	41.96	252	3.68	927.36	3245.76	1361.921
Install	Fixtures	35.1	832	2.34	1946.88	6814.08	2391.742
Connect	DWV Legs	39.4	520	0.65	338	1183	466.102
Testing	Riser Gr.	9.9	42	5.35	224.7	786.45	77.85855
	TOTAL			6.02	3436.94	12029.29	**4297.624**

Plumbing Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1718.47	104276.8
Journeym	37.42	9.73	10.85	58	3436.94	199342.5
Apprentice	33.95	8.83	9.85	52.62	6873.88	361703.6
TOTAL						**665322.8**

Plumbing ABC = 665322.8
Plumbing TBC = 782340 Ratio = 85.04267

Electr. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Horiz. *	49.3	1928	0.497175	958.5534	3354.937	1653.984
Install	Vertical *	56.1	42	1.54	64.68	226.38	126.9992
Install	Fixtures *	66.9	1320	0.4	528	1848	1236.312
Wiring &	Finishing	9.9	1396	1.65	2303.4	8061.9	798.1281
Test	Building	9.9	1	2.25	2.25	7.875	0.779625
	TOTAL			2.437175	3856.883	13499.09	**3816.203**

* include 9.9% risk electrical shock

Electr. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1928.442	117017.8
Electrician	37.42	9.73	10.85	58	3856.883	223699.2
Apprentice	33.95	8.83	9.85	52.62	7713.767	405898.4
TOTAL						**746615.5**

Electr. ABC = 746615.5
Electr. TBC = 762144 Ratio = 97.96252

SHARED RESOURCES

Duration 394.9 hrs
TB Cost $ 2,741,196
ABCost $ 2660648 % of Overall Cost = 97.06157
Danger Ix 17277.71

Plumbing Heating & Fire Protection Combined Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	1694	1.486	2517.284	8810.494	3471.335
Install	Hangers	39.4	2778	0.967	2686.326	9402.141	3704.444
Prepare	Vert. Pipe	7.6	252	0.75	189	661.5	50.274
Install	Supply	46.2	126	0.65	81.9	286.65	132.4323
Install	Stp/Return	35.6	126	1.13	142.38	498.33	177.4055
Install	Vert. Plum	41.96	252	3.68	927.36	3245.76	1361.921

Install	Sprinklers	57	756	0.783	591.948	2071.818	1180.936
Install	Radiators	57	378	0.583	220.374	771.309	439.6461
Install	Fixtures	35.1	832	2.34	1946.88	6814.08	2391.742
Connect DWV Legs		39.4	520	0.65	338	1183	466.102
Test	Riser Gr.	9.9	46	5.35	246.1	861.35	85.27365
	TOTAL			18.369	9887.552	34606.43	**13461.51**

Plumbing Heating & Fire Protection Combined Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	4943.776	299988.3
Journeym	37.42	9.73	10.85	58	9887.552	573478
Apprentice	33.95	8.83	9.85	52.62	19775.1	1040566
TOTAL						**1914032**

Shared ABC = 1914032

Shared TBC = 1936620 Ratio = 98.83365

Electr. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Horiz. *	49.3	1928	0.497175	958.5534	3354.937	1653.984
Install	Vertical *	56.1	42	1.54	64.68	226.38	126.9992
Install	Fixtures *	66.9	1320	0.4	528	1848	1236.312
Wiring &	Finishing	9.9	1396	1.65	2303.4	8061.9	798.1281
Test	Building	9.9	1	2.25	2.25	7.875	0.779625
	TOTAL			2.437175	3856.883	13499.09	**3816.203**

* include 9.9% risk electrical shock

Electr. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1928.442	117017.8
Electrician	37.42	9.73	10.85	58	3856.883	223699.2
Apprentice	33.95	8.83	9.85	52.62	7713.767	405898.4
TOTAL						**746615.5**

Electr. ABC = 746615.5
Electr. TBC = 821548.8 Ratio = 90.87902

REUSE OF ELECTRIC CONDUITS

Duration 434.9 hrs
TB Cost $ 3,002,880
ABCost $ 2731629 % of Overall Cost = 90.96697
Danger Ix 17910.29

Fire Prot. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	782	1.82	1423.24	4981.34	1962.648
Install	Hangers	39.4	820	0.967	792.94	2775.29	1093.464
Prepare	Vert. Pipe	7.6	24	0.75	18	63	4.788
Install	Supply	46.2	12	0.65	7.8	27.3	12.6126
Install	Standpip	35.6	12	1.13	13.56	47.46	16.89576
Install	Sprinklers	57	756	0.783	591.948	2071.818	1180.936
Test	Riser Gr.	9.9	4	5.35	21.4	74.9	7.4151
	TOTAL			6.1	2868.888	10041.11	**4278.76**

Fire Prot. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1434.444	87042.06
Journeym	37.42	9.73	10.85	58	2868.888	166395.5
Apprentice	33.95	8.83	9.85	52.62	5737.776	301921.8
TOTAL						**555359.3**

Fire Prot. ABC = 555359.3
Fire Prot. TBC = 660960 Ratio = 84.02314

Heating Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	912	1.2	1094.4	3830.4	1509.178
Install	Hangers	39.4	1958	0.967	1893.386	6626.851	2610.979
Prepare	Vert. Pipe	7.6	228	0.75	171	598.5	45.486
Install	Supply	46.2	114	0.65	74.1	259.35	119.8197
Install	Return Pip	35.6	114	1.13	128.82	450.87	160.5097
Install	Radiators	57	378	0.583	220.374	771.309	439.6461
	TOTAL			5.28	3582.08	12537.28	**4885.618**

Heating	**Cost**					
	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1791.04	108680.3
Journeym	37.42	9.73	10.85	58	3582.08	207760.6
Apprentice	33.95	8.83	9.85	52.62	7164.16	376978.1
	TOTAL					**693419**

Heating ABC = 693419
Heating TBC = 707880 Ratio = 97.95715

Plumbing	**Safety**	**Index**					
		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Vert. Pipe	41.96	252	3.68	927.36	3245.76	1361.921
Install	Fixtures	35.1	832	2.34	1946.88	6814.08	2391.742
Connect	DWV Legs	39.4	520	0.65	338	1183	466.102
Testing	Riser Gr.	9.9	42	5.35	224.7	786.45	77.85855
	TOTAL			6.02	3436.94	12029.29	**4297.624**

Plumbing	**Cost**					
	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1718.47	104276.8
Journeym	37.42	9.73	10.85	58	3436.94	199342.5
Apprentice	33.95	8.83	9.85	52.62	6873.88	361703.6
	TOTAL					**665322.8**

Plumbing ABC = 665322.8
Plumbing TBC = 787440 Ratio = 84.49188

Electr.	**Safety**	**Index**					
		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Horiz. *	49.3	1928	0.687175	1324.873	4637.057	2286.069
Install	Vertical *	56.1	42	1.54	64.68	226.38	126.9992
Install	Fixtures *	66.9	1320	0.4	528	1848	1236.312
Wiring &	Finishing	9.9	1396	1.65	2303.4	8061.9	798.1281
Test	Building	9.9	1	2.25	2.25	7.875	0.779625
	TOTAL			2.627175	4223.203	14781.21	**4448.288**

* include 9.9% risk electrical shock

Electr. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	2111.602	128132
Electrician	37.42	9.73	10.85	58	4223.203	244945.8
Apprentice	33.95	8.83	9.85	52.62	8446.407	444449.9
TOTAL						**817527.7**

Electr. ABC = 817527.7

Electr. TBC = 846660 Ratio = 96.55915

IN SITU FIRE PROTECTION

Duration 417.6 hrs

TB Cost $ 3,002,513

ABCost $ 2774251 % of Overall Cost = 92.39765

Danger Ix 17434.21

Fire Prot. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	782	1.82	1423.24	4981.34	1962.648
Install	Hangers	39.4	820	0.967	792.94	2775.29	1093.464
Prepare	Pipes	7.6	806	0.75	604.5	2115.75	160.797
Install	Supply	46.2	12	0.65	7.8	27.3	12.6126
Install	Standpip	35.6	12	1.13	13.56	47.46	16.89576
Install	Sprinklers	57	756	0.783	591.948	2071.818	1180.936
Test	Riser Gr.	9.9	4	5.35	21.4	74.9	7.4151
	TOTAL			6.1	3455.388	12093.86	**4434.769**

Fire Prot. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1727.694	104836.5
Journeym	37.42	9.73	10.85	58	3455.388	200412.5
Apprentice	33.95	8.83	9.85	52.62	6910.776	363645
TOTAL						**668894**

Fire Prot. ABC = 668894

Fire Prot. TBC = 685644 Ratio = 97.55704

Heating Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	912	1.2	1094.4	3830.4	1509.178
Install	Hangers	39.4	1958	0.967	1893.386	6626.851	2610.979
Prepare	Vert. Pipe	7.6	228	0.75	171	598.5	45.486
Install	Supply	46.2	114	0.65	74.1	259.35	119.8197
Install	Return Pip	35.6	114	1.13	128.82	450.87	160.5097
Install	Radiators	57	378	0.583	220.374	771.309	439.6461
	TOTAL			5.28	3582.08	12537.28	**4885.618**

Heating Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1791.04	108680.3
Journeym	37.42	9.73	10.85	58	3582.08	207760.6
Apprentice	33.95	8.83	9.85	52.62	7164.16	376978.1
TOTAL						**693419**

Heating ABC = 693419
Heating TBC = 707880 Ratio = 97.95715

Plumbing Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Vert. Pipe	41.96	252	3.68	927.36	3245.76	1361.921
Install	Fixtures	35.1	832	2.34	1946.88	6814.08	2391.742
Connect	DWV Legs	39.4	520	0.65	338	1183	466.102
Testing	Riser Gr.	9.9	42	5.35	224.7	786.45	77.85855
	TOTAL			6.02	3436.94	12029.29	**4297.624**

Plumbing Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1718.47	104276.8
Journeym	37.42	9.73	10.85	58	3436.94	199342.5
Apprentice	33.95	8.83	9.85	52.62	6873.88	361703.6
TOTAL						**665322.8**

Plumbing ABC = 665322.8
Plumbing TBC = 787440 Ratio = 84.49188

Electr. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Horiz. *	49.3	1928	0.497175	958.5534	3354.937	1653.984
Install	Vertical *	56.1	42	1.54	64.68	226.38	126.9992
Install	Fixtures *	66.9	1320	0.4	528	1848	1236.312
Wiring &	Finishing	9.9	1396	1.65	2303.4	8061.9	798.1281
Test	Building	9.9	1	2.25	2.25	7.875	0.779625
	TOTAL			2.437175	3856.883	13499.09	**3816.203**

* include 9.9% risk electrical shock

Electr. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1928.442	117017.8
Electrician	37.42	9.73	10.85	58	3856.883	223699.2
Apprentice	33.95	8.83	9.85	52.62	7713.767	405898.4
TOTAL						**746615.5**

Electr. ABC = 746615.5
Electr. TBC = 821548.8 Ratio = 90.87902

IN SITU HEATING

Duration 462.9 hrs
TB Cost $ 3,211,205
ABCost $ 2793125 % of Overall Cost = 86.9806
Danger Ix 17460.15

Fire Prot. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	782	1.82	1423.24	4981.34	1962.648
Install	Hangers	39.4	820	0.967	792.94	2775.29	1093.464
Prepare	Pipes	7.6	24	0.75	18	63	4.788
Install	Supply	46.2	12	0.65	7.8	27.3	12.6126
Install	Standpip	35.6	12	1.13	13.56	47.46	16.89576
Install	Sprinklers	57	756	0.783	591.948	2071.818	1180.936
Test	Riser Gr.	9.9	4	5.35	21.4	74.9	7.4151
	TOTAL			6.1	2868.888	10041.11	**4278.76**

Fire Prot. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1434.444	87042.06
Journeym	37.42	9.73	10.85	58	2868.888	166395.5
Apprentice	33.95	8.83	9.85	52.62	5737.776	301921.8
	TOTAL					**555359.3**

Fire Prot.	ABC =	555359.3		
Fire Prot.	TBC =	660960	Ratio =	84.02314

Heating Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	912	1.2	1094.4	3830.4	1509.178
Install	Hangers	39.4	1958	0.967	1893.386	6626.851	2610.979
Prepare	Pipes	7.6	1140	0.75	855	2992.5	227.43
Install	Supply	46.2	114	0.65	74.1	259.35	119.8197
Install	Return Pip	35.6	114	1.13	128.82	450.87	160.5097
Install	Radiators	57	378	0.583	220.374	771.309	439.6461
	TOTAL			5.28	4266.08	14931.28	**5067.562**

Heating Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	2133.04	129432.9
Journeym	37.42	9.73	10.85	58	4266.08	247432.6
Apprentice	33.95	8.83	9.85	52.62	8532.16	448962.3
	TOTAL					**825827.8**

Heating	ABC =	825827.8		
Heating	TBC =	849660	Ratio =	97.19509

Plumbing Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Vert. Pipe	41.96	252	3.68	927.36	3245.76	1361.921
Install	Fixtures	35.1	832	2.34	1946.88	6814.08	2391.742
Connect	DWV Legs	39.4	520	0.65	338	1183	466.102
Testing	Riser Gr.	9.9	42	5.35	224.7	786.45	77.85855
	TOTAL			6.02	3436.94	12029.29	**4297.624**

Plumbing Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1718.47	104276.8
Journeym	37.42	9.73	10.85	58	3436.94	199342.5
Apprentice	33.95	8.83	9.85	52.62	6873.88	361703.6
TOTAL						**665322.8**

Plumbing ABC = 665322.8

Plumbing TBC = 787440 Ratio = 84.49188

Electr. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Horiz. *	49.3	1928	0.497175	958.5534	3354.937	1653.984
Install	Vertical *	56.1	42	1.54	64.68	226.38	126.9992
Install	Fixtures *	66.9	1320	0.4	528	1848	1236.312
Wiring &	Finishing	9.9	1396	1.65	2303.4	8061.9	798.1281
Test	Building	9.9	1	2.25	2.25	7.875	0.779625
	TOTAL			2.437175	3856.883	13499.09	**3816.203**

* include 9.9% risk electrical shock

Electr. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1928.442	117017.8
Electrician	37.42	9.73	10.85	58	3856.883	223699.2
Apprentice	33.95	8.83	9.85	52.62	7713.767	405898.4
TOTAL						**746615.5**

Electr. ABC = 746615.5

Electr. TBC = 913144.7 Ratio = 81.76311

IN SITU PLUMBING RISERS

Duration 511.3 hrs

TB Cost $ 3,233,645

ABCost $ 2993411 % of Overall Cost = 92.5708

Danger Ix 19802.2

Fire Prot. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	782	1.82	1423.24	4981.34	1962.648
Install	Hangers	39.4	820	0.967	792.94	2775.29	1093.464
Prepare	Pipes	7.6	24	0.75	18	63	4.788
Install	Supply	46.2	12	0.65	7.8	27.3	12.6126
Install	Standpip	35.6	12	1.13	13.56	47.46	16.89576
Install	Sprinklers	57	756	0.783	591.948	2071.818	1180.936
Test	Riser Gr.	9.9	4	5.35	21.4	74.9	7.4151
	TOTAL			6.1	2868.888	10041.11	**4278.76**

Fire Prot. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1434.444	87042.06
Journeym	37.42	9.73	10.85	58	2868.888	166395.5
Apprentice	33.95	8.83	9.85	52.62	5737.776	301921.8
TOTAL						**555359.3**

Fire Prot. ABC = 555359.3
Fire Prot. TBC = 660960 Ratio = 84.02314

Heating Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	912	1.2	1094.4	3830.4	1509.178
Install	Hangers	39.4	1958	0.967	1893.386	6626.851	2610.979
Prepare	Pipes	7.6	228	0.75	171	598.5	45.486
Install	Supply	46.2	114	0.65	74.1	259.35	119.8197
Install	Return Pip	35.6	114	1.13	128.82	450.87	160.5097
Install	Radiators	57	378	0.583	220.374	771.309	439.6461
	TOTAL			5.28	3582.08	12537.28	**4885.618**

Heating Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1791.04	108680.3
Journeym	37.42	9.73	10.85	58	3582.08	207760.6
Apprentice	33.95	8.83	9.85	52.62	7164.16	376978.1
TOTAL						**693419**

Heating ABC = 693419
Heating TBC = 707880 Ratio = 97.95715

Plumbing Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Vert. Pipe	41.96	1260	2.1	2646	9261	3885.916
Install	Fixtures	35.1	832	2.34	1946.88	6814.08	2391.742
Connect	DWV Legs	39.4	520	0.65	338	1183	466.102
Testing	Riser Gr.	9.9	42	5.35	224.7	786.45	77.85855
	TOTAL			4.44	5155.58	18044.53	**6821.618**

Plumbing Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	2577.79	156420.3
Journeym	37.42	9.73	10.85	58	5155.58	299023.6
Apprentice	33.95	8.83	9.85	52.62	10311.16	542573.2
TOTAL						**998017.2**

Plumbing ABC = 998017.2
Plumbing TBC = 1043256 Ratio = 95.66369

Electr. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Horiz. *	49.3	1928	0.497175	958.5534	3354.937	1653.984
Install	Vertical *	56.1	42	1.54	64.68	226.38	126.9992
Install	Fixtures *	66.9	1320	0.4	528	1848	1236.312
Wiring &	Finishing	9.9	1396	1.65	2303.4	8061.9	798.1281
Test	Building	9.9	1	2.25	2.25	7.875	0.779625
	TOTAL			2.437175	3856.883	13499.09	**3816.203**

* include 9.9% risk electrical shock

Electr. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1928.442	117017.8
Electrician	37.42	9.73	10.85	58	3856.883	223699.2
Apprentice	33.95	8.83	9.85	52.62	7713.767	405898.4
TOTAL						**746615.5**

Electr. ABC = 746615.5
Electr. TBC = 821548.8 Ratio = 90.87902

IN SITU PLUMBING FIXTURES

Duration 430.1 hrs
TB Cost $ 3,067,854
ABCost $ 2853987 % of Overall Cost = 93.02877
Danger Ix 17543.78

Fire Prot. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	782	1.82	1423.24	4981.34	1962.648
Install	Hangers	39.4	820	0.967	792.94	2775.29	1093.464
Prepare	Pipes	7.6	24	0.75	18	63	4.788
Install	Supply	46.2	12	0.65	7.8	27.3	12.6126
Install	Standpip	35.6	12	1.13	13.56	47.46	16.89576
Install	Sprinklers	57	756	0.783	591.948	2071.818	1180.936
Test	Riser Gr.	9.9	4	5.35	21.4	74.9	7.4151
	TOTAL			6.1	2868.888	10041.11	**4278.76**

Fire Prot. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1434.444	87042.06
Journeym	37.42	9.73	10.85	58	2868.888	166395.5
Apprentice	33.95	8.83	9.85	52.62	5737.776	301921.8
TOTAL						**555359.3**

Fire Prot. ABC = 555359.3
Fire Prot. TBC = 660960 Ratio = 84.02314

Heating Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	912	1.2	1094.4	3830.4	1509.178
Install	Hangers	39.4	1958	0.967	1893.386	6626.851	2610.979
Prepare	Pipes	7.6	228	0.75	171	598.5	45.486
Install	Supply	46.2	114	0.65	74.1	259.35	119.8197
Install	Return Pip	35.6	114	1.13	128.82	450.87	160.5097
Install	Radiators	57	378	0.583	220.374	771.309	439.6461
	TOTAL			5.28	3582.08	12537.28	**4885.618**

Heating Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1791.04	108680.3
Journeym	37.42	9.73	10.85	58	3582.08	207760.6
Apprentice	33.95	8.83	9.85	52.62	7164.16	376978.1
TOTAL						**693419**

Heating ABC = 693419
Heating TBC = 707880 Ratio = 97.95715

Plumbing Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Vert. Pipe	41.96	252	3.68	927.36	3245.76	1361.921
Install	Fixtures	35.1	832	2.34	1946.88	6814.08	2391.742
Rough In	Fixtures	7.6	832	1.2	998.4	3494.4	265.5744
Connect DWV Legs		39.4	520	0.65	338	1183	466.102
Testing	Riser Gr.	9.9	42	5.35	224.7	786.45	77.85855
	TOTAL			6.02	4435.34	15523.69	**4563.198**

Plumbing Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	2217.67	134568.2
Journeym	37.42	9.73	10.85	58	4435.34	257249.7
Apprentice	33.95	8.83	9.85	52.62	8870.68	466775.2
TOTAL						**858593.1**

Plumbing ABC = 858593.1
Plumbing TBC = 877456.2 Ratio = 97.85025

Electr. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Horiz. *	49.3	1928	0.497175	958.5534	3354.937	1653.984
Install	Vertical *	56.1	42	1.54	64.68	226.38	126.9992
Install	Fixtures *	66.9	1320	0.4	528	1848	1236.312
Wiring &	Finishing	9.9	1396	1.65	2303.4	8061.9	798.1281
Test	Building	9.9	1	2.25	2.25	7.875	0.779625
	TOTAL			2.437175	3856.883	13499.09	**3816.203**

* include 9.9% risk electrical shock

Electr. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1928.442	117017.8
Electrician	37.42	9.73	10.85	58	3856.883	223699.2
Apprentice	33.95	8.83	9.85	52.62	7713.767	405898.4
TOTAL						**746615.5**

Electr.	ABC =	746615.5		
Electr.	TBC =	821548.8	Ratio =	90.87902

CENTRALIZED

Duration	462.3 hrs		
TB Cost $	3,870,288		
ABCost $	2449299	% of Overall Cost =	63.28467
Danger Ix	15866.8		

Fire Prot. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	782	1.82	1423.24	4981.34	1962.648
Install	Hangers	39.4	820	0.967	792.94	2775.29	1093.464
Prepare	Vert. Pipe	7.6	24	0.75	18	63	4.788
Install	Supply	46.2	12	0.65	7.8	27.3	12.6126
Install	Standpip	35.6	12	1.13	13.56	47.46	16.89576
Install	Sprinklers	57	756	0.783	591.948	2071.818	1180.936
Test	Riser Gr.	9.9	4	5.35	21.4	74.9	7.4151
	TOTAL			6.1	2868.888	10041.11	**4278.76**

Fire Prot. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1434.444	87042.06
Journeym	37.42	9.73	10.85	58	2868.888	166395.5
Apprentice	33.95	8.83	9.85	52.62	5737.776	301921.8
TOTAL						**555359.3**

Fire Prot.	ABC =	555359.3		
Fire Prot.	TBC =	1380264	Ratio =	40.23573

Heating Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	782	1.2	938.4	3284.4	1294.054
Install	Hangers	39.4	820	0.967	792.94	2775.29	1093.464
Prepare	Vert. Pipe	7.6	24	0.75	18	63	4.788
Install	Supply	46.2	12	0.65	7.8	27.3	12.6126
Install	Return Pip	35.6	12	1.13	13.56	47.46	16.89576
Install	Radiators	57	378	0.583	220.374	771.309	439.6461
	TOTAL			5.28	1991.074	6968.759	**2861.46**

Heating Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	995.537	60409.19
Journeym	37.42	9.73	10.85	58	1991.074	115482.3
Apprentice	33.95	8.83	9.85	52.62	3982.148	209540.6
TOTAL						**385432.1**

Heating ABC = 385432.1

Heating TBC = 785400 Ratio = 49.07463

Plumbing Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Vert. Pipe	41.96	24	3.68	88.32	309.12	129.7068
Connect	Pipe (Hor)	39.4	782	0.98	766.36	2682.26	1056.81
Install	Hangers	39.4	820	0.697	571.54	2000.39	788.1537
Install	Fixtures	35.1	832	2.34	1946.88	6814.08	2391.742
Connect	DWV Legs	39.4	520	0.65	338	1183	466.102
Testing	Riser Gr.	9.9	42	5.35	224.7	786.45	77.85855
	TOTAL			7.697	3935.8	13775.3	**4910.373**

Plumbing Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1967.9	119412.2
Journeym	37.42	9.73	10.85	58	3935.8	228276.4
Apprentice	33.95	8.83	9.85	52.62	7871.6	414203.6
TOTAL						**761892.2**

Plumbing ABC = 761892.2

Plumbing TBC = 942480 Ratio = 80.83908

Electr. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Horiz. *	49.3	1928	0.497175	958.5534	3354.937	1653.984
Install	Vertical *	56.1	42	1.54	64.68	226.38	126.9992
Install	Fixtures *	66.9	1320	0.4	528	1848	1236.312
Wiring &	Finishing	9.9	1396	1.65	2303.4	8061.9	798.1281
Test	Building	9.9	1	2.25	2.25	7.875	0.779625
	TOTAL			2.437175	3856.883	13499.09	**3816.203**

* include 9.9% risk electrical shock

Electr. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1928.442	117017.8
Electrician	37.42	9.73	10.85	58	3856.883	223699.2
Apprentice	33.95	8.83	9.85	52.62	7713.767	405898.4
TOTAL						**746615.5**

Electr. ABC = 746615.5
Electr. TBC = 762144 Ratio = 97.96252

CENTRALIZED & FLEXIBLE

Duration 388.5 hrs
TB Cost $ 2,935,560
ABCost $ 2336293 % of Overall Cost = 79.58592
Danger Ix 15061.77

Fire Prot. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	782	1.82	1423.24	4981.34	1962.648
Install	Hangers	39.4	820	0.967	792.94	2775.29	1093.464
Prepare	Vert. Pipe	7.6	24	0.75	18	63	4.788
Install	Supply	46.2	12	0.65	7.8	27.3	12.6126
Install	Standpip	35.6	12	1.13	13.56	47.46	16.89576
Install	Sprinklers	57	756	0.783	591.948	2071.818	1180.936
Test	Riser Gr.	9.9	4	5.35	21.4	74.9	7.4151
	TOTAL			6.1	2868.888	10041.11	**4278.76**

Fire Prot. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1434.444	87042.06
Journeym	37.42	9.73	10.85	58	2868.888	166395.5
Apprentice	33.95	8.83	9.85	52.62	5737.776	301921.8
	TOTAL					**555359.3**

Fire Prot. ABC = 555359.3

Fire Prot. TBC = 726240 Ratio = 76.4705

Heating Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	782	1.2	938.4	3284.4	1294.054
Install	Hangers	39.4	820	0.967	792.94	2775.29	1093.464
Prepare	Vert. Pipe	7.6	24	0.75	18	63	4.788
Install	Supply	46.2	12	0.65	7.8	27.3	12.6126
Install	Return Pip	35.6	12	1.13	13.56	47.46	16.89576
Install	Radiators	57	378	0.583	220.374	771.309	439.6461
	TOTAL			5.28	1991.074	6968.759	**2861.46**

Heating Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	995.537	60409.19
Journeym	37.42	9.73	10.85	58	1991.074	115482.3
Apprentice	33.95	8.83	9.85	52.62	3982.148	209540.6
	TOTAL					**385432.1**

Heating ABC = 385432.1

Heating TBC = 785400 Ratio = 49.07463

Plumbing Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Vert. Pipe	41.96	24	3.68	88.32	309.12	129.7068
Pull Flex	Pipe (Hor)	39.4	422	0.36	151.92	531.72	209.4977
Install	Hangers	39.4	864	0.697	602.208	2107.728	830.4448
Install	Fixtures	35.1	832	2.34	1946.88	6814.08	2391.742
Connect	DWV Legs	39.4	520	0.65	338	1183	466.102
Testing	Riser Gr.	9.9	42	5.35	224.7	786.45	77.85855
	TOTAL			7.077	3352.028	11732.1	**4105.352**

Plumbing Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1676.014	101700.5
Journeym	37.42	9.73	10.85	58	3352.028	194417.6
Apprentice	33.95	8.83	9.85	52.62	6704.056	352767.4
TOTAL						**648885.6**

Plumbing ABC = 648885.6

Plumbing TBC = 661776 Ratio = 98.05215

Electr. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Horiz. *	49.3	1928	0.497175	958.5534	3354.937	1653.984
Install	Vertical *	56.1	42	1.54	64.68	226.38	126.9992
Install	Fixtures *	66.9	1320	0.4	528	1848	1236.312
Wiring &	Finishing	9.9	1396	1.65	2303.4	8061.9	798.1281
Test	Building	9.9	1	2.25	2.25	7.875	0.779625
	TOTAL			2.437175	3856.883	13499.09	**3816.203**

* include 9.9% risk electrical shock

Electr. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1928.442	117017.8
Electrician	37.42	9.73	10.85	58	3856.883	223699.2
Apprentice	33.95	8.83	9.85	52.62	7713.767	405898.4
TOTAL						**746615.5**

Electr. ABC = 746615.5

Electr. TBC = 762144 Ratio = 97.96252

HVAC

Duration	386.4 hrs
TB Cost $	2,913,817
ABCost $	2673107
Danger Ix	17350.94

% of Overall Cost = 91.73901

Fire Prot. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	782	1.82	1423.24	4981.34	1962.648
Install	Hangers	39.4	820	0.967	792.94	2775.29	1093.464
Prepare	Vert. Pipe	7.6	24	0.75	18	63	4.788
Install	Supply	46.2	12	0.65	7.8	27.3	12.6126
Install	Standpip	35.6	12	1.13	13.56	47.46	16.89576
Install	Sprinklers	57	756	0.783	591.948	2071.818	1180.936
Test	Riser Gr.	9.9	4	5.35	21.4	74.9	7.4151
	TOTAL			6.1	2868.888	10041.11	**4278.76**

Fire Prot. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1434.444	87042.06
Journeym	37.42	9.73	10.85	58	2868.888	166395.5
Apprentice	33.95	8.83	9.85	52.62	5737.776	301921.8
TOTAL						**555359.3**

Fire Prot. ABC = 555359.3
Fire Prot. TBC = 660960 Ratio = 84.02314

Heating Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	1126	1.32	1486.32	5202.12	2049.635
Install	Hangers	39.4	2026	0.84	1701.84	5956.44	2346.837
Prepare	Risers	7.6	228	0.75	171	598.5	45.486
Install	Risers	46.2	228	0.65	148.2	518.7	239.6394
Install	Diffusers	57	378	0.367	138.726	485.541	276.7584
	TOTAL			3.927	3646.086	12761.3	**4958.356**

Heating Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1823.043	110622.2
Journeym	37.42	9.73	10.85	58	3646.086	211473
Apprentice	33.95	8.83	9.85	52.62	7292.172	383714.1
TOTAL						**705809.3**

Heating ABC = 705809.3
Heating TBC = 710335 Ratio = 99.36288

Plumbing Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Vert. Pipe	41.96	252	3.68	927.36	3245.76	1361.921
Install	Fixtures	35.1	832	2.34	1946.88	6814.08	2391.742
Connect DWV Legs		39.4	520	0.65	338	1183	466.102
Testing	Riser Gr.	9.9	42	5.35	224.7	786.45	77.85855
	TOTAL			6.02	3436.94	12029.29	**4297.624**

Plumbing Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1718.47	104276.8
Journeym	37.42	9.73	10.85	58	3436.94	199342.5
Apprentice	33.95	8.83	9.85	52.62	6873.88	361703.6
TOTAL						**665322.8**

Plumbing ABC = 665322.8
Plumbing TBC = 787440 Ratio = 84.49188

Electr. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Horiz. *	49.3	1928	0.497175	958.5534	3354.937	1653.984
Install	Vertical *	56.1	42	1.54	64.68	226.38	126.9992
Install	Fixtures *	66.9	1320	0.4	528	1848	1236.312
Wiring &	Finishing	9.9	1396	1.65	2303.4	8061.9	798.1281
Test	Building	9.9	1	2.25	2.25	7.875	0.779625
	TOTAL			2.437175	3856.883	13499.09	**3816.203**

* include 9.9% risk electrical shock

Electr. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1928.442	117017.8
Electrician	37.42	9.73	10.85	58	3856.883	223699.2
Apprentice	33.95	8.83	9.85	52.62	7713.767	405898.4
TOTAL						**746615.5**

Electr. ABC = 746615.5
Electr. TBC = 755081.7 Ratio = 98.87877

WORST CASE SCENARIO

Duration	605 hrs		
TB Cost $	3,682,669		
ABCost $	3503537	% of Overall Cost =	95.13581
Danger Ix	21037.81		

Fire Prot. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	782	1.82	1423.24	4981.34	1962.648
Install	Hangers	39.4	820	0.967	792.94	2775.29	1093.464
Prepare	Pipes	7.6	806	0.75	604.5	2115.75	160.797
Install	Supply	46.2	12	0.65	7.8	27.3	12.6126
Install	Standpip	35.6	12	1.13	13.56	47.46	16.89576
Install	Sprinklers	57	756	0.783	591.948	2071.818	1180.936
Test	Riser Gr.	9.9	4	5.35	21.4	74.9	7.4151
	TOTAL			6.1	3455.388	12093.86	**4434.769**

Fire Prot. Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	1727.694	104836.5
Journeym	37.42	9.73	10.85	58	3455.388	200412.5
Apprentice	33.95	8.83	9.85	52.62	6910.776	363645
TOTAL						**668894**

Fire Prot.	ABC =	668894		
Fire Prot.	TBC =	685664	Ratio =	97.5542

Heating Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Connect	Pipe (Hor)	39.4	912	1.2	1094.4	3830.4	1509.178
Install	Hangers	39.4	1958	0.967	1893.386	6626.851	2610.979
Prepare	Pipes	7.6	1140	0.75	855	2992.5	227.43
Install	Supply	46.2	114	0.65	74.1	259.35	119.8197
Install	Return Pip	35.6	114	1.13	128.82	450.87	160.5097
Install	Radiators	57	378	0.583	220.374	771.309	439.6461
	TOTAL			5.28	4266.08	14931.28	**5067.562**

Heating Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	2133.04	129432.9
Journeym	37.42	9.73	10.85	58	4266.08	247432.6
Apprentice	33.95	8.83	9.85	52.62	8532.16	448962.3
TOTAL						**825827.8**

Heating ABC = 825827.8

Heating TBC = 849660 Ratio = 97.19509

Plumbing Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Vert. Pipe	41.96	1260	2.1	2646	9261	3885.916
Install	Fixtures	35.1	832	2.34	1946.88	6814.08	2391.742
Rough In	Fixtures	7.6	832	1.2	998.4	3494.4	265.5744
Connect DWV Legs		39.4	520	0.65	338	1183	466.102
Testing	Riser Gr.	9.9	42	5.35	224.7	786.45	77.85855
	TOTAL			4.44	6153.98	21538.93	**7087.193**

Plumbing Cost

	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	3076.99	186711.8
Journeym	37.42	9.73	10.85	58	6153.98	356930.8
Apprentice	33.95	8.83	9.85	52.62	12307.96	647644.9
TOTAL						**1191287**

Plumbing ABC = 1191287

Plumbing TBC = 1234200 Ratio = 96.52305

Electr. Safety Index

		% Index	# Units	Unit Time	TIME	MANTIME	INDEX
Install	Horiz. *	49.3	1928	0.687175	1324.873	4637.057	2286.069
Install	Vertical *	56.1	42	1.54	64.68	226.38	126.9992
Install	Fixtures *	66.9	1320	0.4	528	1848	1236.312
Wiring &	Finishing	9.9	1396	1.65	2303.4	8061.9	798.1281
Test	Building	9.9	1	2.25	2.25	7.875	0.779625
	TOTAL			2.627175	4223.203	14781.21	**4448.288**

* include 9.9% risk electrical shock

Electr.	**Cost**					
	Dir Lab	W Comp	O&P	Cost/Hour	# ManHrs	Tot Cost
Foreman	39.15	10.18	11.35	60.68	2111.602	128132
Electrician	37.42	9.73	10.85	58	4223.203	244945.8
Apprentice	33.95	8.83	9.85	52.62	8446.407	444449.9
	TOTAL					**817527.7**

Electr.	ABC =	817527.7		
Electr.	TBC =	913144.7	Ratio =	89.52882

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