Distributed Planning and Coordination to Support Lean Construction

by

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B.S. (Yonsei University) 1993
M.S. (Yonsei University) 1995

A dissertation submitted in partial satisfaction of the
requirements for the degree of

Doctor of Philosophy
in
Engineering-Civil and Environmental Engineering
in the
GRADUATE DIVISION
of the

UNIVERSITY OF CALIFORNIA, BERKELEY

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Spring 2003

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Abstract

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Construction planning is a complex process that involves coordination between many project participants on- and off-site. As projects have been increasing in size and complexity, the number of participants involved in a single project has also increased. Numerous studies have suggested that the traditional project management tools, which are often used in a centralized top-down control environment, do not meet the production management requirements of today's projects. They have reported that the current communication tools do not adequately support the coordination efforts required to successfully deliver projects.

This research presents a Distributed Planning and Control (DP&C) method based on a distributed control paradigm. The DP&C helps in improving production planning performance by adopting the Last Planner System (LPS) and thereby providing reliable communication channels in order support the creation of coordinated schedules at appropriate levels of detail.

The DP&C method is supported by a tool called WorkMovePlan, which extends the Last Planner tools, WorkPlan and DePlan. WorkMovePlan uses synchronization technology for the collaborative creation of coordinated production plans based on explicit resource and space assignments. As proven during the conceptualization, development, and validation of WorkMovePlan, technology is no longer a barrier to implementing distributed planning and coordination thanks to wide acceptance of personal computers, wireless computing, Internet connectivity, and programming frameworks. The main barriers to implementation are (1) acknowledgement of uncertainty and approaches for managing it, (2) acceptance of the underlying, distributed control paradigm, and (3) willingness to break with traditional contractual arrangements, organizational structures, and common practices of the construction industry. These barriers suggest that many aspects of project management still need further investigation in order to achieve better alignment with production management. It is the author's belief that project management and production management tools need to work hand-in-hand in order to support the successful delivery of projects.

It is expected that the DP&C method or similar methods will gain in acceptance in the construction industry as the shortcomings of the centralized control paradigm become increasingly evident and as Lean Construction continues to prove that it is a theoretically sound-, though radically different alternative to how projects are delivered.

Professor Iris D. Tommelein, Chair

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ACKNOWLEDGMENTS

During this research, I have had the honor to work with the greatest minds in the field of Lean Construction. It has been and will continue to be a great journey to further develop lean ideas, surrounded by the founders and leaders of the field.

First, I would like to thank Prof. Iris Tommelein for her continuous guidance and support. Throughout the years of my research, she has always been there to provide me with valuable insights and challenges. Her dedication to her research and her students deserve the greatest admiration. I would also like to thank Prof. Glenn Ballard for playing a significant role in my journey. I am sure that I am in an envious position among the students all over the world for having had easy access to the developer of the Last Planner System and bounce off ideas with him. I also am grateful to Prof. Phil Kaminsky for his teachings, patience, and support. His teachings have helped me gain additional perspective on my research. I would like to thank all three professors for working around the clock to help me finish my dissertation. I would also like to thank Prof. Won Cheol Cho at Yonsei University for his support. His recommendation to go study abroad and “the” plane ticket has finally reached its goal.

Second, I would like to thank Todd Zabelle, president of Pacific Contracting and Strategic Project Solutions (SPS), for his continuous trust and support. He has helped me during the early years of my research by providing me with experience and knowledge and giving access to Pacific Contracting as a testing ground. I am also honored to now be working at SPS. SPS has given me an opportunity to develop and implement Distributed Planning and Coordination tools, based in part on ideas developed in this dissertation, and apply them on several extremely large and complex projects. My gratitude goes out to all SPS team members for providing me with interesting challenges and making things happen.

Third, I would like to thank the University of California and the National Science Foundation (NSF). The implementation of WorkPlan was supported with funding from the University of California, Berkeley. Subsequent research to expand WorkPlan's capabilities and the development of WorkMovePlan was funded by grant CMS-9622308 from NSF whose support is gratefully acknowledged. Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the University of California, Berkeley, or of NSF.

Finally, I would like to express my gratitude to many people in my family. I would like to thank my parents for their continuous love and support. They were always there for me when I needed them. I would like to thank my parents-in-law for their continuous caring and support. I would also like to thank Hyeon Cheol, my brother, for his love despite the additional responsibilities he has had to accept since I left Korea. Finally, I would like to thank Hye Won, my wife, for her continuous support and always being understanding despite my crazy business travel schedules. I would also like to thank Young Joo for being my daughter and the most beautiful child. Watching you grow is the most amazing thing in the world.

May 22, 2003

Hyun Jeong Choo

1 INTRODUCTION

Planning during construction is a distributed and complex process that involves coordination between many parties. As modern construction projects become increasingly complex, dynamic, and pressed for time, the number of specialized parties involved in each project has increased. Although specialization within projects may offer flexibility and benefits to the industry, it has at the same time resulted in tremendous costs in the form of fragmented decision-making (Howard et al. 1989). To make matters more complicated, some general contractors have adopted a contract-brokering role rather than the role of coordinating production (Tommelein and Ballard 1997a). This has exacerbated the fragmentation among parties. As a direct result of general contractors adopting the role of brokers and projects becoming more technologically complex requiring specialized skills, specialty contractors have become responsible for a larger percentage—if not all—of the on-site and off-site production work. As involvement of specialized parties increase, the project organizations are also becoming larger both vertically as well as horizontally. Therefore, coordinating the efforts of these parties to successfully complete a project today is a difficult challenge. The solution to this challenge does not solely depend on changing the way project participants work together and the changing systems that support these participants. People and systems need to work in a synergistic and self-reinforcing fashion to achieve true coordination (Collaborative Process Institute 1997).

In efforts to improve the "people" aspect of coordination, some owners and contractors have focused on improving the interaction between project participants. They have implemented partnering sessions or similar team-building programs in order to promote team-working relationships and improve communication in an effort to improve coordination. However, these programs will only provide a partial solution to the problem unless a total solution, i.e., process, system, and organizational structure, that reinforces these programs, is put in place.

With advances in Internet and Intranet technology, many forms of online project management tools have emerged, e.g. ProjectNet (Citadon 2001), Team Builder (E-Builder 2001), ProjectPoint (Buzzsaw 2001), Constructw@re (Constructware 2001), ProjectTalk (Meridian Project Systems 2001), Buildpoint (Buildpoint 2001), Project|Center (Bricsnet 2001), etc. Most of these tools serve as a common platform for project participants to share project-related documents, e.g., drawings (schematics, engineering drawings, and shop drawings), requests for information (RFIs), requests for quotation (RFQs), change orders, and schedules. Having one source for all relevant information helps the project participants to have the latest information as soon as it becomes available and to avoid the use of outdated material while minimizing the overall cost and duration of communication. However, without a rethinking of processes which use these tools, they alone provide only limited advantages.

O'Brien (2000a) states that processes of all project participants need to be investigated in order to best design and use these tools to support daily operations. Additionally, these coordination efforts usually remain at the project level and rarely consider the production level. Coordination at the production level needs to complement and reinforce these project level coordination efforts. To coordinate at the production level, detailed information regarding logistic issues and work assignments is needed, which includes the specification of labor, equipment, materials, and space use. Neither the online project management tools nor partnering sessions get down to such specifics.

To successfully complete a project, some party (preferably one that has a large stake in the project) needs to (re)assume the role of a production coordinator and guide the efforts of specialty contractors. The role of the coordinator is not to exert centralized control, but rather to provide a process, system, organizational structure, and culture to empower and support specialty contractors to provide input and feedback.

Whoever assumes the coordination role needs to acknowledge that the best planning solution cannot be guaranteed without the input and feedback from all (other) specialty contractors because the information and means must be available to generate and evaluate all alternatives. Developing alternatives requires collaborative process among all project participants, with the coordinator assuming the role of a referee when alternatives generated by different participants are in conflict. The optimal scenario is when special contractors are persuaded that their own interests are best served by collaboration. When each party is planning to optimize its own portion of work, the coordinator should try to determine what alternative is best for the project as a whole. However, coordinator may not have the knowledge to select what's best for the project as a whole.

The coordinator does not need to resolve all conflicts. If several specialty contractors find a solution to work out a foreseen conflict, the coordinator has only to see whether the solution is in harmony with the overall project goal. Traditionally, this responsibility would belong to a general contractor, but there have been situations where a specialty contractor has taken on that role. For instance, a mechanical contractor working as the prime contractor, and a traditional general contracting firm working as a subcontractor for them, successfully completed a Silicon Valley project (Rosenbaum 1997). Specialty contractors can also create self-governing teams that can perform coordination functions. In this scenario, third-party coordinator is not required.

Coordination needs occur in two distinct but tightly linked areas. First are actual physical production resources, e.g., labor, equipment, material, and space. Material not only refers to raw material, but also work-in-process (WIP). Second is information. Designers and engineers usually use some form of engineering drawings, specifications, shop drawings, and sometimes 3-D models to express information regarding what to build. Construction managers, superintendents, and foremen usually use some form of schedule to express the sequence of construction, and assembly drawings to identify interfaces fit between different parts and components. However, these forms of information usually are not sufficient in meeting all informational requirements for coordination. They need to be supported by additional information regarding resource availability, site conditions, permit issues, etc. These additional pieces of information are usually several horizontal and/or vertical levels removed within a project organization from the party requiring the information. In some cases, they may reside among many participants and/or several project organization levels (Cohenca-Zall et al. 1994). In other cases, it may be unclear what information is required or the source of the information may be unclear so that it needs to be located before information can be obtained.

These situations manifest short-comings in two distinct but related factors, i.e., communication and production planning. Well-structured communication will allow project participants to easily locate and communicate with corresponding participants about their informational needs. Well-structured planning at different levels as needed will identify what information must be available in order to support coordination efforts. Failure in either of these factors can be detrimental to coordination effort.

The participants of the project as a team, with the support of the planning and communication system, has to be(come) responsible for "coordinating information regarding the coordination of resources." One way to represent the coordination information is using a "coordination schedule" that explains how production units[1] need to interact in order to collaboratively attain the project goal. Creating coordination schedules is not an easy task: planning during construction is an on-going and complex process that involves many participants. Increasing numbers of project participants and time pressure demands tighter coordination because the relationship between participants and their tasks can no longer be thought of as purely sequential. In many cases, the relationship tends to be reciprocal. This means that information or the work output from one activity affecting the decisions made for another activity and vice versa at the same time. Also, task sequencings based on resource dependencies and shared resources are not strictly sequential, but can dynamically be changed based on decisions and negotiations regarding resource loading. However, traditional CPM or PERT views have largely neglected reciprocal dependencies and resource dependencies. Thus, an explicit way to capture these relationships is needed. This representation needs to be reinforced with continuous communication to insure that all relevant and up-to-date information is

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[1] Production unit (PU) refers to "a group of direct production workers that do or share responsibility for similar work, drawing on the same skills and techniques" (Lean Construction Institute 1999).

made available to the party that needs it and when it is needed (e.g., before an activity starts). This effort not only needs to focus on notifying all participants of the assumptions and decisions that have been made, but also on representing sets of alternatives for consideration during schedule coordination.

Distributed planning and coordination (DP&C) involves interaction between all participants at all levels in the project hierarchy, i.e., the owner, general contractor, specialty contractors, and vendors/suppliers. The goal of the proposed distributed and coordinated planning system is not to eliminate face-to-face weekly or daily production meetings, but to make them more efficient by judiciously disseminating the necessary and only relevant information to those participants that need it. A distributed planning and coordination system will enable the involved participants to identify potential conflicts ahead of time of their meeting. Affected participants can study identified problems, obtain more information if needed before the meeting, and then spend meeting time constructively solving coordination problems, rather than detecting them, or generating creative alternatives. Even when there are no conflicts, participants can use their shared plans to better understand how, when, where, and with whom they are going to coordinate the use of shared resources.

The technological barriers to implementing a distributed planning and coordination system no longer exist thanks to the wide use of personal computers, wireless computing, Internet connectivity, and programming frameworks. However, to maximize the benefits of these technological advancements, the computer tools must have an effective planning process as a basis. The planning process advocated in this dissertation adopts a "bottom-up planning with top-down guidance" approach. This approach extends the Last Planner

System (LPS) (Ballard and Howell 1994a, b) to support multiple dependent project participants in the collaborative creation of reliable production plans.

This dissertation is composed of eight Chapters. Chapter 2 gives an overview of the research including the thesis statement, scope, and objectives. Chapter 3 reviews the literature and relevant research done by others. This review includes commercially available computer software that is relevant to the research topic. Chapter 4 describes computer programs, developed and implemented by the author, that extend the LPS to construction and design. These implementations, namely WorkPlan and DePlan, deserve a detailed explanation, as they are building blocks for a more comprehensive distributed planning and coordination system, Chapter 5 explains the proposed distributed planning and coordination method in detail, and Chapter 6 looks its implementation. This includes WorkMovePlan, a database program that supports distributed planning and coordination, as well as case studies. Chapter 7 presents the conclusions of the research by stating the contributions to knowledge and future research issues. Chapter 8 lists the bibliography and references cited in the dissertation.

2 OVERVIEW

2.1 THESIS STATEMENT

Construction planning is a distributed process done by many project participants on- and off-site. The level of detail at which planning is appropriate differs according to the role each person (or the party this person represents) plays in the project and the planning window this person or the party focuses on. Centralized planning by a single party, e.g., planner(s), construction engineer(s), etc., for an entire project is seldom possible nor desirable as no single party has all of the required specialty knowledge to enumerate the alternatives and select the best option for the project. It is even less possible and desirable as the level of plan detail increases.

Practically speaking, as the number of participants involved in a single project increases and the work they perform becomes more complicated, coordination becomes a daunting task. Thus, project participants end up making planning decisions without having all relevant information, and information that becomes available may be left unused because it is difficult to determine who needs it, when it needs to be delivered, and how to deliver it.

Advancement of communication technology, such as Internet, Intranet, wireless communication, cellular phones, and walkie-talkies, has opened up doors for coordination. Nevertheless, current coordination tools do not adequately support coordination at the production level and do not provide means to quantitatively measure the quality of the resulting plans. The best coordination will result from up-to-date and reliable information.

The thesis of this research therefore is that an interactive planning and coordination method will help to decentralize and improve planning performance by providing communication channels for reliably coordinating schedules at the appropriate level of detail.

2.2 RESEARCH OBJECTIVES

The aim of this research was to develop a methodology and tool to facilitate the interactive coordination of distributed planning information gathered from the owner, general contractor, and specialty contractors, suppliers/vendors, and shipping agents.

2.2.1 Understand the Current Construction Planning Practice

In order to improve the current practice of construction planning, a clear understanding and analysis of it is mandatory. This includes both project planning and production planning that occurs throughout the life of a project. Developing this understanding and analysis of the current planning practice includes the following steps.

2.2.1.1 Understand project planning during a construction project

It will be worthwhile to compare the current role vs. the intended role of construction project planning. Many researchers and professionals have advocated that project planning alone does not suffice in successfully managing a complex construction project. Thus, it is important to review the current role project management assumes during a construction project.

2.2.1.2 Understand production planning during a construction project

Some forms of production planning, explicit and implicit, currently exist in construction projects. However, these practices do not necessary stem from a strategically designed process; rather, they reflect the needs of field managers, i.e., superintendents and foremen, to manage their own tasks and resources. A clearer understanding of current practices will provide a better picture what requirements production planning tools must meet.

2.2.1.3 Analyze the advantages/disadvantages of the current planning practice

Understanding project planning techniques and production planning techniques in their current implementation will allow for better analysis of the advantages and disadvantages of the current planning system. Project management and production management must work in a coordinated fashion to maximize the potential benefits of using each alone and both combined. To improve the effectiveness of the current planning methodology, these benefits will need to be maintained, if not strengthened, and disadvantages must be minimized.

2.2.2 Determine an Alternative Planning Methodology

A significant body of research in the area of construction planning has focused on the improving the shortcomings of current planning system. Much of this research, therefore, focuses on the master planning level using the Critical Path Method (CPM) (Kelley and Walker 1959). Some researchers have proposed alternatives such as the Precedence Diagramming Method (PDM) (Hajdu 1997) or the Critical Chain Planning Method (CCPM) (Goldratt 1997) in order to overcome some of the shortcoming of CPM. Others have focused on improving the current system by using the latest computer tools and programming techniques to better capture and use scheduling knowledge. However, those alternatives focused on project planning and neglected production planning. In contrast, the present work is based on the realization that an alternate planning methodology is needed that encompasses both project planning as well as production management.

2.2.2.1 Analyze the advantages/disadvantages of the alternative methodology

An alternative planning methodology must have clear advantages over the widely accepted current practice of planning in order to survive the resistance of the industry. The Last Planner System (LPS) (Lean Construction Institute 1999), which specifically aims to improve planning reliability, forms the basis for the alternative methodology proposed in this research. The LPS is not described in detail, however, since it is the foundation of this research, a clear analysis of its advantages over the current planning method is spelled out.

2.2.2.2 Determine the most effective way to implement the alternative methodology

A sound methodology cannot reach its full potential if it is not accompanied by a sound implementation strategy. Project organizations are multi-tiered and involve participants from multiple entities that have different scheduling "philosophies." Each company has its own culture, competencies, and processes (e.g., "a way they have been doing scheduling)". Any other way enforced through contracts will be seen as additional work. Therefore, a sound implementation strategy is needed that minimizes participants' resistance to change by understanding each participant's needs while making sure that the objectives of the alternative planning method are achieved.

2.2.3 Develop a Methodology to Manage Interactive Planning

In order to maximize the benefits of the LPS, all participants involved in a project, and those doing production work, must adopt a new way of thinking. They must learn to interactively generate and provide reliable information to others involved in the production work. The term *interactive* refers to the exchange of planning information (1) between the owner and the designer, (2) between the owner and the general contractor, (3) between the general contractor and the specialty contractors, (4) among the specialty contractors, and (5) between the general or specialty contractors and supplier/vendors or shipping agents. Developing a methodology to manage interactive planning includes the following objectives.

2.2.3.1 Develop a methodology to coordinate project planning with production planning

Project planning and production planning need to work hand-in-hand in order to successfully execute a project. Accordingly, determining the relationship between the master schedule and lookahead, lookahead and weekly work plan, and weekly work plan and master schedule is a key in understanding the link between project planning and production planning.

2.2.3.2 Devise a scheme to coordinate project objectives and job-shop objectives

Project participants rarely work on a single project; rather, they work on several at once. Each of their projects has milestone dates and quality criteria that need to be met. At the same time, project participants have to make sure that the company is profitable, reputable, and efficient. Under the current contracting mechanism, they are constantly making tradeoffs between what is best for the project versus what is best for the company. In order to assist planners in making decisions regarding these tradeoffs, a multi-project planning scheme that allows the planners to see across constituent projects is mandatory.

2.2.3.3 Develop a measurement for assessing the quality of the coordinated schedule

How do we measure the quality of a schedule that has been created by multiple project participants in a distributed fashion? The space of possible solutions for developing a coordination schedule is too large to find the best solution. Therefore, a schedule is usually accepted as long as it does not violate the needs of the most powerful participants. If such a schedule cannot be developed, the needs of the participants are modified until a solution is found. Hindsight measurement can determine the quality of a schedule and can help improve the planning process, but that measurement does not help in making decisions to future actions. A method to gauge the quality of alternatives is, therefore, needed.

2.2.3.4 Devise a language for depicting the relationship between different scheduling units throughout the project organization

The schedule of a participant reflects the role that participant plays in the project organization and its view of the project. Each level will, therefore, have different scheduling units (e.g., time, space, contract, etc.) for describing the project. Relationships between these scheduling units must be maintained in order to facilitate interactive planning.

2.2.3.5 Articulate comparable level(s) of schedule detail to correspond to each level in the project organization

In order to compare and coordinate schedules from multiple sources, each source must provide a schedule with comparable detail. This level of detail can be specified in terms of the scheduling time unit (e.g., months, weeks, or days) and the scheduling window (e.g., one week, four weeks, two months, or whole project duration). Not all specialty contractors, suppliers/vendors or shipping agents can look into and reliably schedule work for the same amount of time into the future. That is, a specialty contractor, supplier/vendor, or shipping agent with a well defined work content and less interaction with other specialty contractors may be able to look three months ahead whereas one with changing work content and more interaction may be able to only look two weeks ahead. It is important to realize that there is no benefit to looking much farther than their scheduling reliability permits. Therefore, the scheduling window must allow for flexibility depending on the situation each trade is in. Nevertheless, an overall minimum scheduling window with acceptable reliability is mandatory, even if it is only a week, to ensure that all party's inputs are incorporated and the resulting coordinated schedule is reliable.

Understanding what limits the length of the scheduling window in current industry practice is essential in understanding how to minimize effects of uncertainties in order to extend the scheduling window. A standard will not guarantee the quality of the plan as that is set by the quality of information input by the planners. Nevertheless, it may help planners to focus on their scheduling responsibilities (i.e., scheduling windows and level of detail) and realize the role he/she is playing in the generation of a coordinated schedule.

2.2.3.6 Determine level of abstraction required at each level

Decisions are delayed when decision makers are faced with more information than they can process (Galbraith 1974). Thus, information must be screened and rolled-up, i.e., abstracted, when it flows from a source to a destination to minimize the recipients' effort in examining the gathered information and locating the problematic areas. This will also allow the source to maintain security of any information that must remain inaccessible to others. For example, the specialty contractors need to assign specific laborers to a work package in order to calculate the cost of executing this work package. This information, however, must not be exposed to the general contractor. An automatic screening and abstraction process may reveal only the name of the specialty contractor, start date, and end date.

2.2.3.7 Create a scheme to facilitate the detection of probable conflicts.

Using a coordinated schedule generated from multiple work plans, each planner can anticipate conflicts that may occur on site. By examining the relationship between the plans developed by multiple sources, conflicts can be anticipated that one planner alone could not detect. The planner can, then, take measures to avoid these conflicts before the work package is released for construction to minimize confusion, wasted labor and equipment time, and rework.

2.2.3.8 Devise methodology to represent resource use with regards to the work schedule

Often some material, equipment, or labor is available on-site before the start and after the finish of actual production. Whether or not these inventories are the result of deliberate planning, these resources usually take up holding space on site. Planners should have provisions to notify others of these space uses so as to diminish the likelihood of on-site conflicts. Associating these space uses with their activities will allow easy identification of space uses if the related activities need to be rescheduled. By allocating space use to start earlier or finish later than scheduled production work, the planner can represent actual space uses.

2.2.4 Develop a Computer Tool to Support Interactive Planning

A computer tool will assist production planners in developing schedules according to the planning process that is proposed in this research. The tool should guide planners throughout the planning process by providing only the necessary information and functionality at each step to promote prompt decision-making and minimize confusion. Development of the tool has occurred in two stages. The first stage of development focused on a single production unit in a construction and design environment. After the tool reached an acceptable level of development and validation, it was extended to include distributed planning and coordination capabilities.

2.2.4.1 Determine appropriate system architecture for the computer tool

One objective of the computer-based tool is to allow each production planner to develop a detailed production schedule by using their own resource uses. The tool also needs to maintain a large amount of data regarding tasks, resources, and their assignments. It also needs to function on-line and off-line, as the computers on construction sites do not usually have permanent Internet connectivity.

2.2.4.2 Apply the computer tool to construction and design

The application of the tool to construction and design provided user feedback regarding the planning process and tool use, which helped reshaping of the process and the tool. This was a very important development step as it pointed out the requirements of the tool seen from the industry's perspective. The main challenge is in designing the tool to reflect the industry's requirements, while at the same time not sacrificing the main objective of changing the planning process of the industry to reflect the LPS.

2.3 SCOPE

The distributed planning and coordination tool supports the generation of an execution schedule through trial-and-error by allowing all project participants to share their latest information.

For this research, implementation of the tool has been limited to coordination between the general contractor and specialty contractors (Figure 1), thereby allowing this research to focus on improvement the planning methodology of the project participants that are directly responsible for production. The implementation also is based on the assumption that the general contractor's schedule can represent the requirements and preferences of the owner and the specialty contractors' schedules can represent the delivery schedule of the supplier/vendors. Additionally, discussion will mainly explain about the planning process and the tool when used in construction.

2.4 CONCLUSION

The objective of this research is to develop a distributed planning and coordination method to support lean construction techniques. This objective consists of (1) understanding the advantages and disadvantages of the current practice with regard to planning and coordination of work done by specialty contractors, (2) developing an alternative planning method to increase plan reliability by allowing multiple planners to interactively create a coordinated production schedule, and (3) developing a tool to support the alternative planning method.

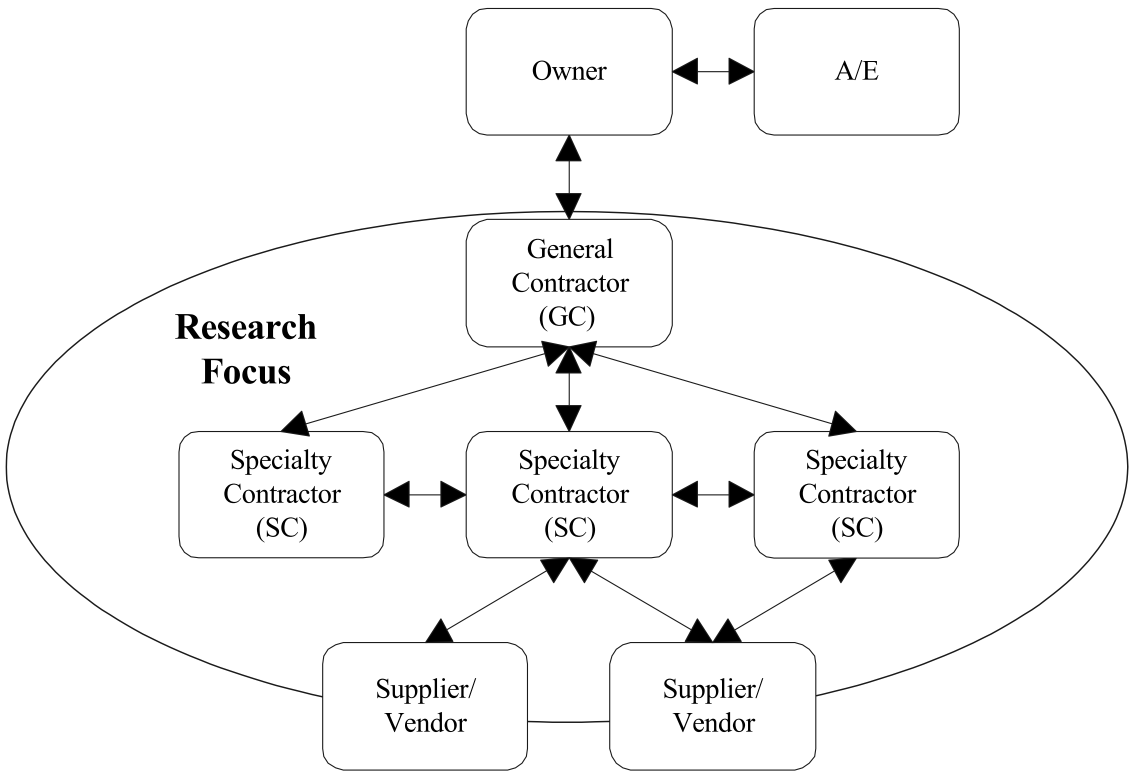


Figure 1. Research Scope

The research focuses on the construction phase of the project delivery process. Although the author has been and is currently developing a distributed planning method and a correspondingly suitable tool to support design and construction processes on several very large and complex projects, neither direct references to that work nor the projects will be given in this dissertation. This dissertation will, however, describe what the author has learned up to now, hoping it will generate additional research into relevant areas.

3 LITERATURE REVIEW

3.1 CONSTRUCTION PLANNING

Managing construction projects requires understanding of both project management and production management. Nevertheless, many publications on construction management focus solely on the project management aspects of construction and say very little, if anything at all, about the production management aspects of it. Many publications describe project management techniques including planning and scheduling.

"A Guide to the Project Management Body of Knowledge" (PMBOK) published by the Project Management Institute (PMI) (1996) captures many project management techniques. PMBOK contains the "generally accepted project management knowledge and practice" (Figure 2). It states, "many of the knowledge needed to manage projects is unique or nearly unique to project management (e.g., critical path analysis and work breakdown structure)" (Project Management Institute 1996, p. 8). For example, PMBOK specifically categorizes critical path analysis and the work breakdown structure (WBS) as project management-specific knowledge.

The construction industry uses PMBOK tools extensively in managing construction projects especially during the project schedule development phase. Figure 3 shows the whole project schedule development process based on the input and output lists of each step from PMBOK. To summarize the process, project schedule development is the sequencing of activities and the estimation of their durations. Groups of these activities constitute work packages, i.e., the lowest level in the WBS. The sum of all work packages constitutes the project scope, i.e., the product or deliverable to the owner.

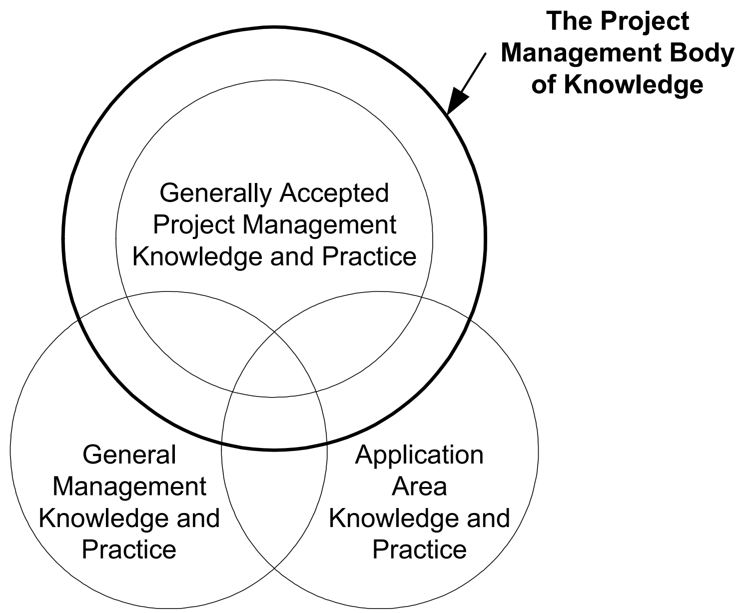


Figure 2. Scope of the Project Management Body of Knowledge (Project Management Institute 1996, p. 9)

PMI (Project Management Institute 1996, p. 54) defines a work package as

> "a deliverable-oriented grouping of project elements that organizes and defines the total scope of the project: work not in the WBS is outside the scope of the project."

The National Aeronautics and Space Administration (NASA 1997) defines WBS as

> "a top-level overview that provides the basis for monitoring a program or project by subdividing the work into successively smaller increments until a manageable element is reached. [The WBS] develops a program-team consensus on what the customer wants. Together with a make/buy determination, it can be a useful tool in deciding what elements are performed by civil servants and by contractors. A good WBS assures that significant tasks are not overlooked."

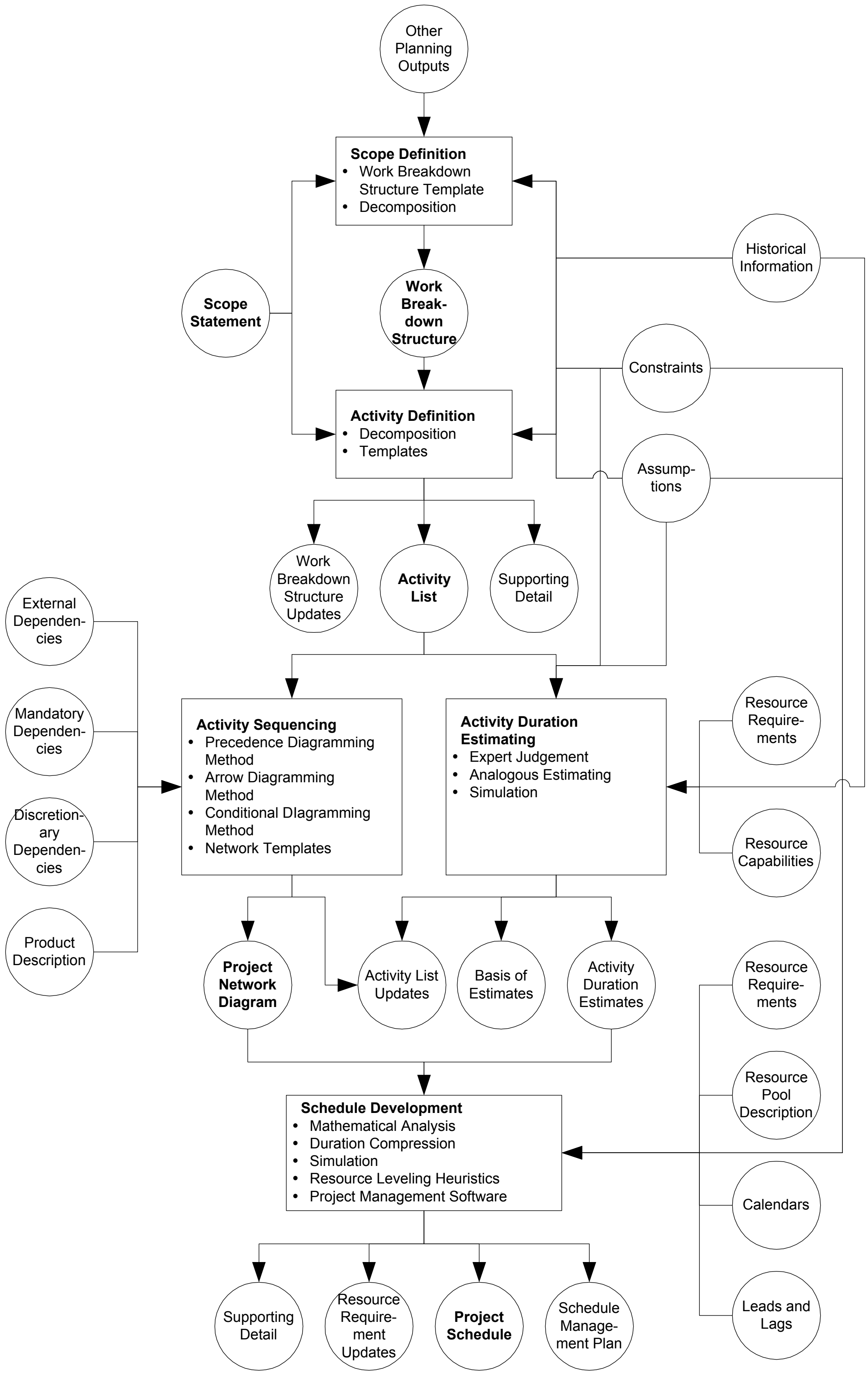


Figure 3. Project Schedule Development (derived from PMI 1996)

Note that this definition also contains a qualifying statement, which is

> "When used, the WBS must avoid stifling innovative ideas. Rigid control of every detail is neither necessary nor desirable. [The WBS] must not be so explicit that there is no room for creative thinking or individual empowerment, yet it must be sufficiently defined and all work elements identified to permit inspection and acceptance."

The document also gives a definition of Contract Work Breakdown Structure (CWBS), which is "a hierarchical diagram for a specific contract." Here the CWBS is qualified again: "It identifies the requirements to be satisfied, leaving the contractor free to determine how to achieve the desired result. … Remember, each level identified by the Government … will limit the innovation and creativity allowed to the contractor on that level."

The literature suggests that WBS must reveal and define the project scope in manageable pieces, while at the same time, not define it in such minute detail as to limit the creativity and empowerment of the participants that are going to carry out the work. In this view, "decomposition" is the main method of breaking the scope into work packages and eventually into activities. PMBOK defines decomposition as "subdividing the major project deliverables into smaller, more manageable components until the deliverables are defined in sufficient detail to support future project activities (planning, executing, controlling, and closing)" (Project Management Institute 1996, p. 53). This view adopts the transformation (or conversion) model, which decomposes the overall transformation, i.e., a project, into smaller transformations, i.e., activities and tasks (Koskela 1992). Consequently, the goal of control is to independently manage these smaller transformations in order to adhere to their original schedule and budget. Howell and Ballard (1996) refer this control model as the "thermostat model" as the outputs deviating from preset standards trigger actions and adjustments.

Howell and Koskela (2000) additionally point out that the current form of project management is a system for managing contracts based on the assumption that all coordination and operational issues reside within the contract boundaries. They list the deficiencies in the assumptions and the theory of current production management (Table 1).

Table 1. Deficiencies in Assumptions and Theory of Current Project Management (Howell and Koskela 2000)

Category	Assumption and Theory	Modern Projects
Uncertainty in Scope and Method	Low	High
Relationships between Activities	Simple, Sequential	Complex, Iterative
Activity Boundary	Rigid	Loose
Performance Criteria	Activity-based	Need to Consider Flow Between Activities
Production Management	Not Considered	Needs to be Considered
Model	Transformation	Needs to be Viewed as a combination of Transformation, Flow, and Value Generation

The Lean Construction research community (e.g., Lean Construction Institute, International Group for Lean Construction, etc.) has led the introduction of production management theory and techniques into construction, focusing especially on the theory and techniques of Lean Manufacturing.

3.2 LEAN CONSTRUCTION

The success of lean production in manufacturing (Womack et al. 1990, Womack and Jones 1996) has triggered the development of a lean production theory in construction, referred to as Lean Construction. Comparison against craft and mass production clearly distinguishes the characteristics of lean production (a term coined by International Motor Vehicle Program researcher John Krafcik, to denote that this production method uses less of everything compared to mass production) (Womack et al. 1990). Craft production produces a customer product one at a time using highly skilled workers and simple and flexible tools. The flexibility that craft production provides is an advantage, but it is achieved at a cost. Mass production produces large volumes of standardized products using unskilled or semi-skilled workers and expensive, single-purpose machines. In contrast, lean production combines the advantages of craft and mass production. It provides volumes of a variety of products at a relatively low cost by using teams of multi-skilled workers at all levels of the organization and highly flexible, increasingly automated machines (Womack et al. 1990).

Lean Construction views a construction project as a production system recognizing the dependences and variations along supply and assembly chains of construction projects and actively managing product and process uncertainties (Howell 1999). Tommelein (1997b, 2000) identifies the product uncertainties as (1) configuration, (2) dimensional tolerances, (3) dimensional variation, and (4) location and layout; and process uncertainties as (1) scope of work, (2) duration of timing, (3) quality, (4) resource assignment, and (5) flow path and sequencing.

Lean Construction thrives to achieve (1) a unique customer project, (2) delivered instantly, with (3) nothing in store (Howell and Ballard 1998). This goal is impossible to achieve. Nevertheless, this pursuit of perfection fuels continuous improvement in all aspects of project delivery process including supply chains.

Lean Construction criticizes the single view (transformation) advocated by the traditional project management model. Koskela (1992) first proposed a dual view (transformation and flow) to emphasize the flow perspective. He then included the perspective of value-creation and presented a tripartite view (transformation, flow, and value) on production (Koskela 2000).

Researchers have conducted a number of studies to date in order to refine the thinking process and the corresponding methods to implement lean production in construction. These efforts span across the entire project delivery system. Figure 4 shows the lean project delivery system developed by Glenn Ballard at Lean Construction Institute (LCI). Many of the current research projects focus extensively on lean supply and lean assembly. However, researchers are making advances into other areas as well. The author's research has been mostly focused on improving the area of lean assembly, namely detailed construction planning process and providing computer tools to support the process (Choo et al. 1998a, 1998b, Choo and Tommelein 1999a, 1999b, 2000a, 2000b). Hammond et al. (2000) and Choo et al. (2001) have extended this research methodology and the computer tool developed as part of this research to include the design process.

3.3 MULTI-TIERED PLANNING AND SCHEDULING

Mainly three tiers of schedules, formally and informally, exist on a construction project: a master schedule, lookahead schedules (also called progress schedule), and weekly work plans. Obvious differences among these schedules are the size of the scheduling window and the level of detail. Each type of schedule serves or should serve a different purpose.

Many existing computer tools for master scheduling adopt CPM (Critical Path Method), such as Primavera Project Planner (Primavera 2000b), SureTrak Project

Manager (Primavera 2000c), and Microsoft Project (Microsoft 2000c). These systems base themselves on a purely hierarchical top-down approach where every activity is broken down into smaller ones, i.e., they support the transformation view. For instance, Primavera Project Planner provides "fragnets" so that users can reuse past schedules for similar activities. Using any of these computer tools, general contractors prepare master schedules to cover the entire project duration. In turn, their superintendents create lookahead schedules that reveal more detail on upcoming activities in the near future (typically 3 or 4 weeks out). Specialty contractors then prepare their own schedules to meet the project's deliverables and milestone dates. In turn, their crew details their work in weekly work plans.

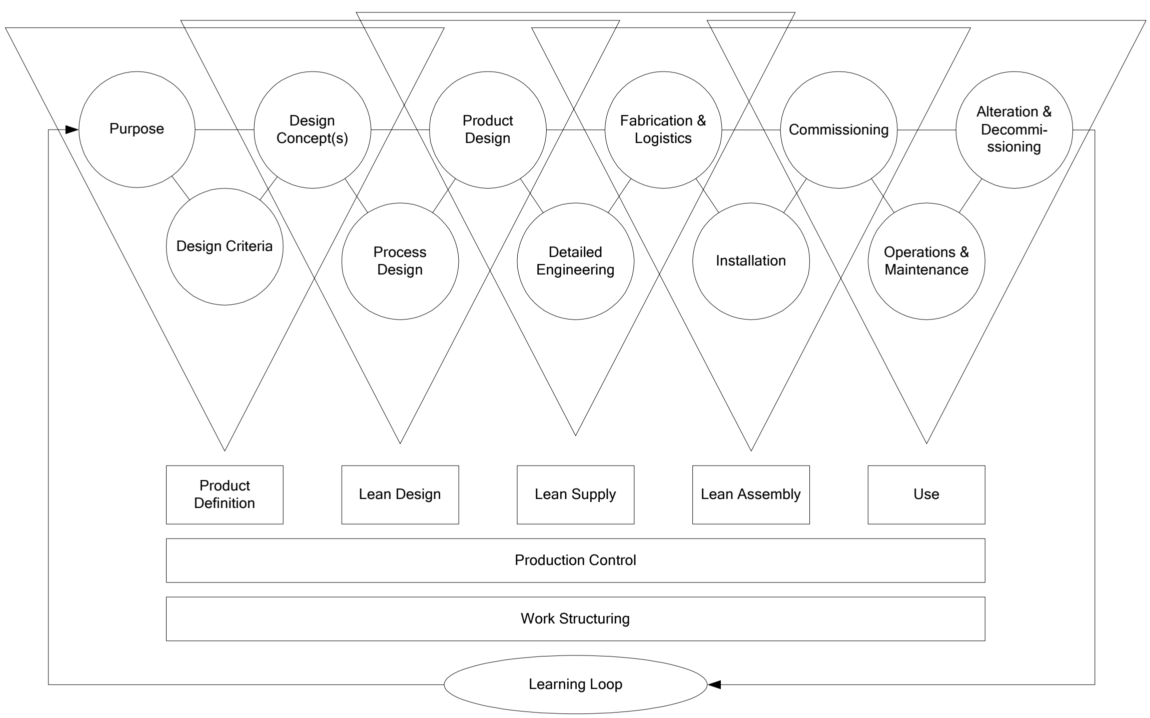


Figure 4. Lean Project Delivery System (Ballard 2000b)

The current planning model and the Last Planner System both use master schedule, lookaheads, and weekly work plans. However, the Last Planner System specifically aims to increase plan reliability. Accordingly, schedule development processes differ greatly. The following two subsections will describe these two planning models.

3.3.1 Current Planning Model

The current planning model reflects the widely-accepted methods and practices for developing a master schedule, lookaheads, and weekly work plans (Note that these terms may have a different meaning here than they do in the LPS due to a different conceptualization of the planning problem). This section describes the advantages and disadvantages of applying this model as found in past research and using field-collected examples.

3.3.1.1 Master Schedule

Activities, which are decomposed pieces of work packages, are the building blocks of the master schedule. Traditionally speaking, 'a work package is a sub-element of a construction project on which both cost and time data are collected for project status reporting. All work packages combined constitute a project's work breakdown structure' (Halpin 1985, p. 154). "A Guide to the Project Management Body of Knowledge" points out that work packages are often the lowest level items of a Work Breakdown Structure (WBS) (PMI 1996, p. 171). Figure 5 shows the relationship between a project, work packages, activities, and a part of the schedule developed using these activities.

The manual creation of a master schedule can require a complex process. Some have attempted to automate this process by adopting knowledge-based expert systems and artificial intelligence programming techniques to construction planning and scheduling resulting in several tools. CONSTRUCTION PLANEX (Hendrickson et al. 1987, Zozaya-Gorostiza et al. 1989) automatically generated a project network and the schedule.

The program suggests construction methods based on given soil and site information, resource productivity information, and other factors (such as weather); generates activities based on the determined construction method; determines the precedence between activities using physical relationship and resource information; estimates durations using estimated work quantity and resource productivity information; and estimates the cost using unit cost and scheduling information.

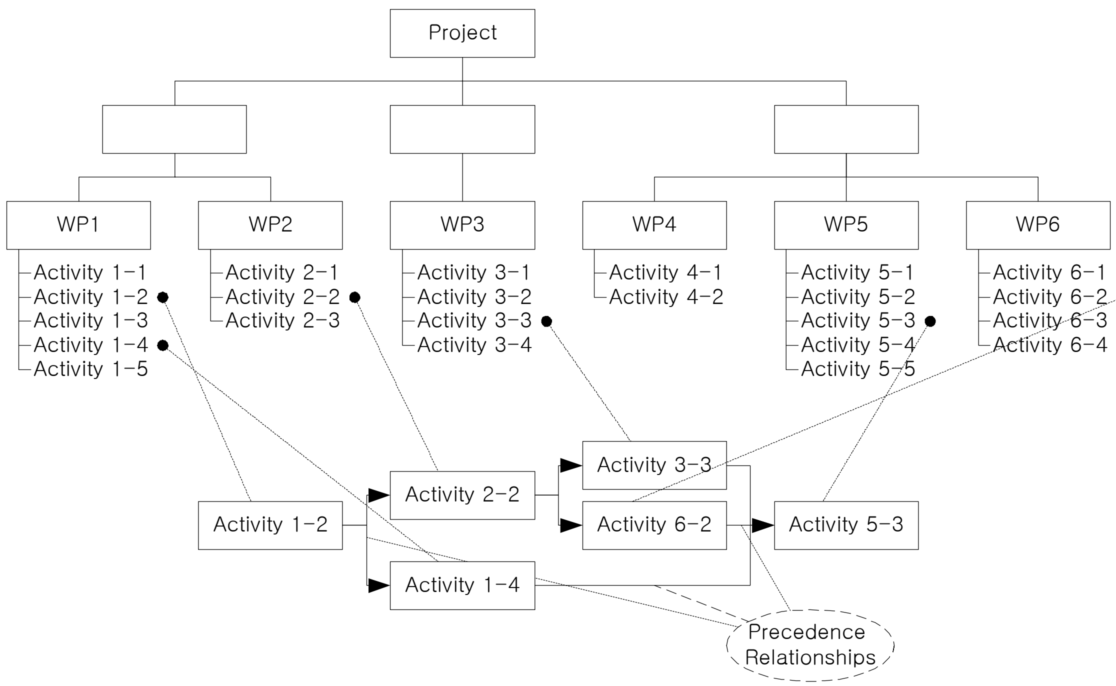


Figure 5. Relationship between Project, Work Packages, Activities, and Schedule (derived from PMI 1996)

Navinchandra et al. (1988) developed GHOST (Generator of Hierarchical networks for cOnSTruction), based on a blackboard architecture to determine precedence relationships between activities. The program uses knowledge sources to critique an optimistic and probably infeasible schedule in order to generate a feasible schedule. In this system, physical relationships among project components determine the precedence relationships between activities. GHOST implements subnetworks to detail work on each component.

Darwiche et al. (1988) developed OARPLAN (Object – Action – Resource Planning System), which produces a plan for constructing a facility based on a CAD model. The program determines activities and precedence between them using the physical CAD-derived relationships between project components. SIPEC (Kartam and Levitt 1990, Kartam 1995) applies the System for Interactive Planning and Execution (SIPE) to construction planning of a multistory building, where C refers to construction. SIPEC's activity sequencing was determined by (1) 'gravity support' (physical relationship) and (2) safety requirements (e.g., build decks to break falls). Cherneff et al. (1991) developed BUILDER, which uses knowledge about construction sequence, material costs, productivity rates and availability, and an estimating procedure to develop construction schedules. Whereas previous tools drew physical information from external CAD tools, BUILDER has a knowledge model that serves as both an enhanced CAD tool as well as the interpreter for the knowledge-based planner. PLANEX, GHOST, and BUILDER take a bottom-up approach to planning, starting from each component of the project model. In contrast, OARPLAN and SIPEC take a top-down approach starting from the overall project objective.

Some research focused on reusing experience from past projects to build a schedule for a new project. CasePlan (Dzeng and Tommelein 1993, 1995, 1997, Dzeng 1995) used case-based reasoning as a technique to develop a construction schedule by capturing experience from previous projects. By matching the product model of captured cases to the product model of the facility under consideration based on the facility's design, its construction schedule, and construction method and technology, CasePlan generates an appropriate construction schedule. Fischer and Aalami (1996) developed computer-interpretable construction method and resource models to formalize the assumptions of planners so that planners can automatically develop schedules from a CAD drawing. These models capture information about activity generation, sequencing, and resource requirements (Aalami 1998). Aalami (1998) developed a prototype system called Construction Method Modeler (CMM).

Other research focused on validating the sequence, assessing, or improving the quality of a construction plan, or comparing alternative construction plans. Know-Plan (Morad and Beliveau 1991) automatically generates a network and validates it through visual simulation of the construction process. CIPROS (Odeh 1992, Odeh et al. 1992, Tommelein et al. 1994) assesses the quality of a construction plan using discrete-event simulation. Whereas Know-Plan validates the activity precedence relationship by checking for geometrical conflict, CIPROS simulates the actual construction process by explicitly representing involved resources and uncertainties about activity durations.

Adeli and Karim (1997) formulated construction scheduling as an optimization problem with the objective of minimizing the direct cost given a fixed duration. They assume the relationship between the direct cost and the duration of a task to be linear or nonlinear. AbouRizk and Mather (1998) used an integrated CAD-based simulation system. The CAD model provided the geometrical information required for the simulations. They used the results from these simulations to compare different construction plans.

Sucur and Grobler (1996) describe a representational and computational framework for agent-based multi-project scheduling. The formulation of scheduling as a distributed constraint satisfaction problem results in the problem of solving intra-agent constraints and inter-agent constraints. The intra-agent is responsible for information exchange and negotiation between different types of resources whereas the inter-agent is responsible for information exchange and negotiation within a type of resource.

These models are well suited for developing a master schedule for a project in creating the list of required activities, as well as preferred precedence relationships between these activities under structural and safety constraints.

A large number of computer tools have been developed to assist project managers in manually developing and maintaining a master schedule, using CPM as implemented in Primavera Project Planner (Primavera 2000b), SureTrak Project Manager (Primavera 2000c), or Microsoft Project (Microsoft 2000c). These computer tools are widely accepted by project managers as tools for planning and overseeing construction projects in the process of administering contracts. They also serve as tools for generating a common representation which depict predecessor relationships between activities where each activity has a given duration and unit resources allocated to it. This representation facilitates communication between different participants involved in a construction project regarding who should be doing what work and when.

However, these tools are inadequate in terms of expressiveness when it comes to supporting production planning and control, that is, to support those who are performing construction work in the field. The productivity of field workers depends on the actual availability of resources, and this availability is governed by resource flow prior to installation, including the timely generation or procurement, release or delivery, and allocation of their resources (Tommelein and Ballard 1997a). Nevertheless, these tools do not take into account the availability, skill level, or productivity of the crew that is actually going to carry out the work.

Tools to support production scheduling, that is, to support those that perform construction work on site, must (1) be able to efficiently generate schedules that reflect the actual constraints and objectives of the construction [or manufacturing] environment, and (2) allow these schedules to be incrementally revised over time in response to unexpected executional circumstances (Smith and Ow 1990). CPM provides no mechanism for explicitly checking resource availability, maintaining resource continuity, etc. Moreover, the resources that are relevant to field workers, namely erection drawings, materials, equipment and tools, and methods specifications, rarely—if ever—are explicitly described in CPM schedules. Not only is it tedious to add them, but it also requires a different mindset. Howard et al. (1989) point out that CPM and PERT are good for early planning stage, but are seldom used as activity control tools once projects start because on-going, high-planning requirements are too high to justify use when conditions rapidly change. Project management's schedules are therefore almost useless for those doing the work.

3.3.1.2 Lookahead Schedules

A big problem field workers face is coping with discrepancies between anticipated and actual resource availability. Numerous uncertainties (e.g., ambiguities in design drawings, errors in take-off, fabrication errors requiring rework, delays in shipment, damage during handling, etc.) affect the flow of resources prior to their application.

Accordingly, field workers have developed their own, special-purpose planning methodologies, but they have done so with varying degrees of success. Existing field-level planning methodologies vary considerably from one construction superintendent or foreman to the next. Figure 6 and Figure 7 are samples of two lookaheads that are used on different building projects.

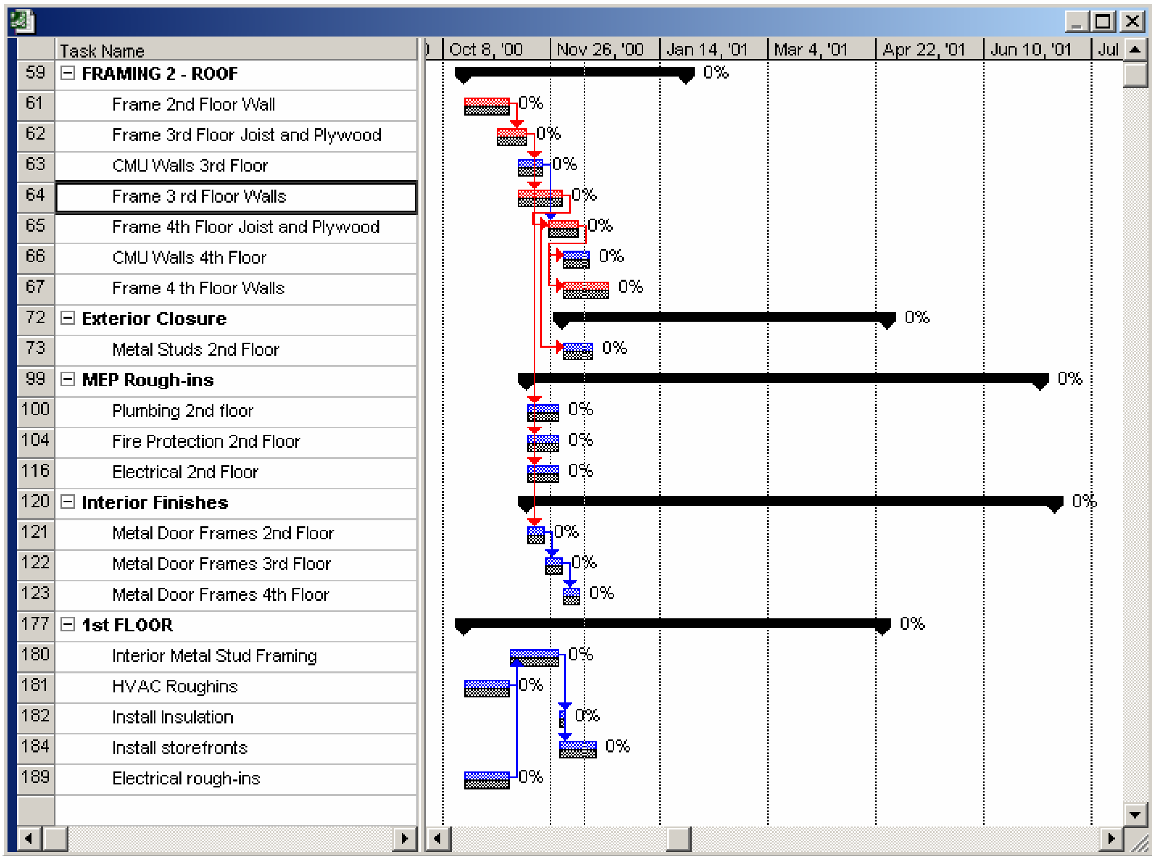


Figure 6. Sample of a Bar Chart-based Lookahead

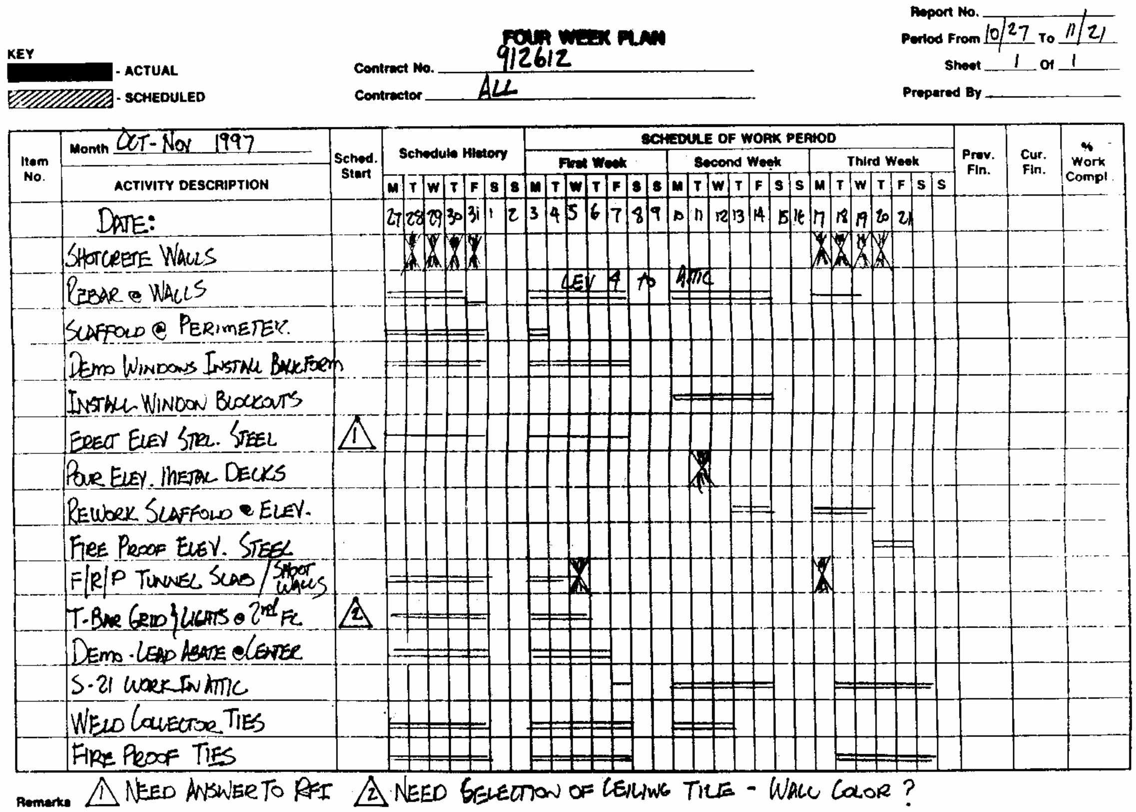
The project engineer for the first project used master scheduling software to develop his lookahead (Figure 6). He selected only the activities that started or finished within a certain time frame, here a lookahead window spanning 6 weeks. In this case, the lookahead is simply a dropout from the master schedule. The planner can choose to detail the plan, as necessary, but would have to adhere to the representation of the CPM bar chart.

Using a computer tool to create lookaheads facilitates the editing process and automates the recalculation process. The planner can also maintain a history of the schedule changes by archiving, either digitally or maintaining a hard copy of the schedules before and after each change. However, the history of schedule changes depicts the results of decisions made, not the logic behind the decision. The history, therefore, is "knowledge-poor" (Howard et al. 1989).

Figure 7 shows a sample of a lookahead filled out by hand. This form allows the planner to freely input the necessary information and does not limit the planner to a CPM-based format. Note that the planner used a "Remarks" section to specify the tasks that needed to be done before the work could start, which is referred to as "make-ready work" by Ballard (1997).

When superintendents produce lookaheads in non-CPM format (as in Figure 7) using a computer, they most typically use a word processor or spreadsheet software. The software-generated resulting schedules are no better than those generated by hand in terms of the schedule data being isolated from other relevant data in the company. A database where all other relevant and related data can be stored together provides a much better platform to implement production scheduling tools (Choo et al. 1998a, 1998b, and 1999).

Regardless of the format of lookaheads, existing planning tools appear to have no mechanism for screening scheduled activities against criteria such as definition, soundness, sequence, sizing, and learning (Ballard 1997).


KEY
- ACTUAL
- SCHEDULED

FOUR WEEK PLAN

Contract No. 912612

Contractor ALL

Report No.

Period From 10/27 To 11/21

Sheet 1 Of 1

Prepared By

Month OCT-NOV 1997

Item No.	Activity Description	Sched. Start
	DATE:	
	SHOTCRETE WALLS	
	REBAR @ WALLS	
	SCAFFOLD @ PERIMETER	
	DEMO WINDOWS INSTALL BACKFORM	
	INSTALL WINDOW BLOCKOUTS	
	ERECT ELEV STRL. STEEL	⚠1
	POUR ELEV. METAL DECKS	
	REWORK SCAFFOLD @ ELEV.	
	FIRE PROOF ELEV. STEEL	
	F/R/P TUNNEL SLAB / SHORT WALLS	
	T-BAR GRID & LIGHTS @ 2nd FL.	⚠2
	DEMO - LEAD ABATE @ CENTER	
	S-21 WORK IN ATTIC	
	WELD COLLECTOR TIES	
	FIRE PROOF TIES	

Remarks ⚠1 NEED ANSWER TO RFI ⚠2 NEED SELECTION OF CEILING TILE - WALL COLOR ?

Figure 7. Sample of a Hand-drawn Lookahead

3.3.1.3 Weekly Work Plan

Weekly work plans are the most detailed plans[2] developed by the foremen of specialty contractors who will actually carry out the work. These specialty contractors can provide knowledge regarding (1) development of creative solutions, (2) space needs associated with construction processes, (3) fabrication and construction capabilities, and (4)

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[2] There may be more detailed plans in the form of methods of procedure, which are presumably known to the members of the team that receive assignments via the weekly work plan. Casten et al. (1995) recommended the use of first run studies to develop these work methods or methods of procedure.

supplier's lead-times and reliability (Gil et al. 2000). The information regarding construction capability includes availability of labor, equipment, and tools. In terms of labor, they know the skill level, productivity, and availability of each worker. This allows the foremen to estimate the duration of each activity more realistically as compared to durations developed for the master schedule, that had to be based on an assumed process using a certain number of people with average skill level and productivity. Thus, the quality of plans is better when the planning authority is pushed down (e.g., suggested by Laufer (1992)).

However, as done for lookaheads, foremen usually develop weekly work plans using forms filled out by hand, or spreadsheet or word processing software. Some foremen create weekly work plans in their head and never formalize and share them with anyone else, or — if at all — communicate them vaguely in meetings. The opportunity for supervisors or management to receive feedback and learn is thereby lost. Ballard (2000a) points out that coordination meeting times often are spent more on collecting data from participants rather than on brainstorming to find creative solutions. Although weekly work plans are a very important source for schedule development and control, they are rarely included in a formal planning system. Crew supervisors usually discard paper-based plans after they have served their purpose: crew supervisors use them as 'crib sheets' to sequence work, assign work, and mobilize resources. Russell and Froese (1997), thus, referred to them as "throw-away" schedules. Creating a weekly work plan to determine the work to be done by one's crew is important. It also is important to share such plans with other participants for coordination purposes.

3.3.2 Last Planner System (LPS)

Lean production concepts support the development of a methodology for managing construction planning, by emphasizing process efficiency and focusing on achieving objectives (e.g., Faniran et al. 1997). The Last Planner System (LPS) refers to the process of creating a master schedule, a lookahead, and a weekly work plan through front-end planning, lookahead planning, and commitment planning, respectively, using Lean Construction Planning techniques (Ballard and Howell 1994a). "Front-end planning" and "lookahead planning" are terms that are also used in other planning systems. However, "commitment planning" is a very different term. Weekly work planning is referred as "commitment planning" because, at this stage, specific resource assignments need to be made so that work can actually be performed.

Ballard and Howell (1994a, b) point out that the traditional construction management approach is to define activities and schedule work to be done, prior to the start of construction, in terms of what SHOULD be done. In this approach, resources simply are assumed to be available when needed, so that SHOULD presumably is do-able and guaranteed to result in DID. It is then up to production crews to gather what resources they have on hand and to adhere to the schedule as well as they can. It is generally expected that these production crews CAN DO the work regardless of the resource availability.

The CAN-DO attitude has its root in the fact that the person or organization responsible for producing the schedule does not have a clear understanding of the work to be performed. Because they do not have the hands-on experience, they cannot clearly define the full scope or assess the real nature of the work to be done, the methods to be used, and the required capacity of the resources to be applied. Also, specific circumstances of work execution are not predictable. Thus, the work cannot be planned in far advance at the level of the detail that is required to optimally perform it and control production. Therefore, the work force has traditionally been told what goals to accomplish and it was left up to them to determine how to accomplish those goals (as there are usually many ways to accomplish the same goal under the same time and resource constraint), even though the means to achieve them may be beyond their control. The reality is that the schedule reflects only anticipated resource availability, but actual resource availability can differ substantially from it, so crews are bound to deviate from that original schedule.

To alleviate this situation, Ballard and Howell (1994a, b) proposed the LPS, which focuses on injecting reliability in planning by stabilizing workflow at the production level. The main purpose of the LPS is to shield workers from the uncertainties they do not control. They also propose that weekly work plans are effective when assignments[3] meet specific quality requirements for:

1. **Definition:** Are assignments specific enough so that the right type and amount of materials can be collected, work can be coordinated with other trades, and

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[3] Assignment is defined as "a directive or order given to a worker or workers directly producing or contributing to the production of design or construction." (Lean Construction Institute 1999)

it is possible to tell at the end of the week if the assignment has been completed?

2. **Soundness:** Are all assignments workable? Are all materials on hand? Is design complete? Is prerequisite work complete? Note that make-ready work will remain for the foremen to do during the week, e.g., coordination with trades working in the same area, movement of materials to the point of installation, etc. Nonetheless, the intent is to do whatever can be done to get the work ready before the week in which it is to be done.
3. **Sequence:** Are assignments selected form those that are sound in priority order and in constructability order? Are additional, lower-priority assignments identified as workable backlog, that is, are additional quality tasks available in case assignments fail or productivity exceeds expectations?
4. **Size:** Are assignments sized to the productive capability of each crew or sub-crew, while still being achievable within the plan period?
5. **Learning:** Are assignments that are not completed within the week tracked and the reasons for deviation identified?

Having a plan meet the LPS quality criteria (Ballard 1997) does not guarantee that there will be no plan failure at all. A plan could always fail upon execution. However, the purpose of the LPS is to help minimize plan quality failures in order to avoid unnecessary execution failures. Ballard and Howell therefore advocate that only assignments that meet these quality criteria be put on a weekly work plan.

The LPS, which has started as a methodology for generating quality assignments in weekly work planning, has been extended to the current form of LPS, which includes front-end planning (Lean Construction Institute 1999, Ballard 2000a) and lookahead planning (Ballard 1997, Tommelein and Ballard 1997b) (Figure 8).

According to the Lean Construction Institute, each level of the LPS has a very specific purpose (Lean Construction Institute 1999, p. 42).

The purpose of master schedule is to:

1. Demonstrate the feasibility of completing the work within the available time,
2. Display an execution strategy that can serve as a basic coordinating device, and
3. Determine when long lead items will be needed.

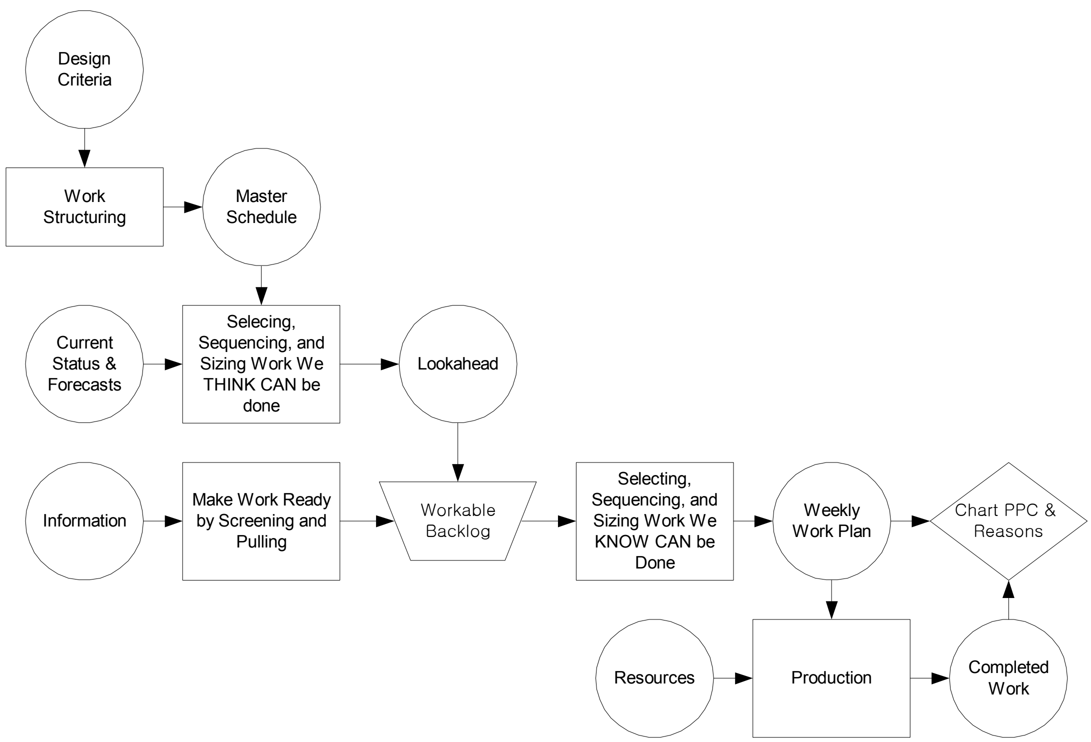

Figure 8. Last Planner System (Lean Construction Institute 1999)

The purpose of the lookahead schedule is to:

1. Shape work flow in the best achievable sequence and rate for achieving project objectives that are within the power of the organization at each point in time,
2. Match labor and related resources to work flow,
3. Produce and maintain a backlog of assignments for each frontline supervisor and crew, screened for design, materials, and completion of perquisite work at the CPM level,
4. Group together work that is highly interdependent, so the work method can be planned for the whole operation, and
5. Identify operations to be planned jointly by multiple trades.

The purpose of the weekly work plan is to:

1. Identify make ready actions and assessing their feasibility prior to making assignments so as to shield production units from uncertainty.
2. Make best use of the production unit's capacity and acknowledge individual's differences in light of the schedule loads.

Ballard and Howell also propose a new metric, PPC (Percent Plan Complete), for gauging the reliability of the planning system. Unlike other project performance criteria or variance analysis (e.g., earned value method) that measure whether the project is on schedule (e.g., schedule index or schedule variance) or on budget (e.g., cost index or cost variance), PPC measures whether the planning system is able to reliably anticipate what will actually be done. Determining whether an assignment was completed or not according to the plan is mandatory in calculating PPC, but elaborating on reasons for failure to complete the work as planned is even more important. These learned reasons will serve as valuable knowledge in elaboration of constraints in future planning efforts.

3.3.2.1 Front-end Planning

In the LPS, the master schedule is developed based on the design criteria using work structuring (Figure 9). Work structuring is defined as “a process of breaking work into pieces, where pieces will likely be different from one production unit to the next, so as to promote flow and throughput” (Lean Construction Institute 1999, p. 54). These pieces are termed “work chunks”, which are “the unit(s) of work that can be handed off from one production unit to the next.” Work chunks may change as they move from one production unit to the next (Ballard 1999b). The notion “breaking work into pieces” is consistent with “grouping work” or “subdividing” as is done in the development of a WBS. The main difference however is the goal of the breakdown. Currently, the contracts, the history of the trades, and the traditions of the craft are the determining criteria for work structuring practices (Tsao et al. 2000). In work structuring, a conscious effort is made to structure the work to facilitate throughput with a goal to “make work flow more reliable and quick while delivering value to the customer” (Ballard 2000b).

The relationships between work chunks are defined by deliverables, i.e., when, how much, in which sequence, and what the other chunks need. These deliverables do not conclusively determine sequencing, as relationships might be reciprocal. However, in the current methodology, activities are linked by precedence relationship, which presumes that as long as the sequencing of those activities is right, the output of the predecessor will be compatible with the requirement of the successor. This is not necessarily the case. For example, Tommelein (1997b) demonstrated the importance of timing and sequencing of handoffs by simulating a given sequence of activities with different handoff scenarios, i.e., pull vs. push.

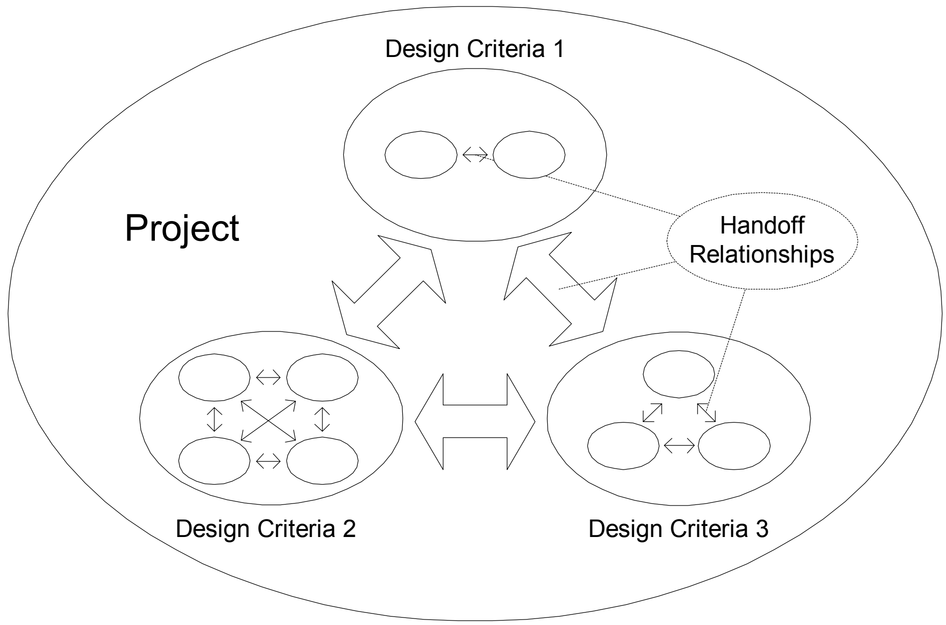

Figure 9. Work Structuring

However, as the definition of work structuring suggests, work structuring is not limited to only developing master schedules, but it extends to developing operations and process designs in alignment with product design, the structure of supply chains, the allocation of resources, and the design-for-assembly efforts (Lean Construction Institute 2000).

3.3.2.2 Lookahead Planning

Ballard (2000c) defines "control" as "causing a desired future rather than identifying variances between plan and actual." In this regard, the LPS differs greatly from traditional planning and control practices. In LPS, control consists of workflow control and production unit control. Lookahead planning is mainly responsible for workflow control whereas weekly work planning is mainly responsible for production unit control (Ballard 2000b).

During lookahead planning, (1) explosion, (2) screening, and (3) make ready occur (Ballard 1997). Explosion is detailing master schedule activities using the Activity Definition Model (ADM)[4] before they enter the lookahead window (Lean Construction Institute 2000). Screening is "determining the status of tasks in the lookahead window relative to their constraints, and choosing to advance or retard tasks based on their constraint status and the probability of removing constraints (Lean Construction Institute 2000).

As the definition suggests, an important tool in screening is constraint analysis, which consist of identifying constraints that prevent activities from starting and ending without unplanned interruptions. For example, one constraint might pertain to procurement of material. Having some unspecified amount of this material available to start work does not automatically satisfy the constraint. The constraint is satisfied only when the crew has the required, predetermined amount of material at hand to finish the predetermined amount of work, or when it has a reliable schedule of material delivery to support continuous installation.

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[4] Activity Definition Model (ADM) is "an input-process-output representation of design tasks or construction processes. The model depicts the specification of directives, prerequisites, and resources. It also shows an inspection process resulting either to redo or release to the customer process. The model is used as a guide to exploding scheduled tasks into a level of detail at which their readiness for execution can be assessed and advanced." (Lean Construction Institute 2000)

Constraint lists are not necessarily simple and single-tiered. Constraints can be multi-tiered which means that a constraint can be exploded into multiple constraints which in turn constrain other constraints and activities. The same logic can be extended to constraints regarding equipment, labor, and information.

Make ready is (1) confirming lead-time, (2) pulling, and (3) expediting (Ballard 2000b). Lead-time is the duration of time required from order to delivery (Lean Construction Institute 2000). Confirming lead-time allows the planner to determine whether certain materials, equipment, labor, or information can be pulled. Pulling is "instantiating the delivery of input based on the readiness of the process into which they will enter for transformation into outputs" (Lean Construction Institute 2000). This is counter to pushing, which is "releasing materials, information, or directives possibly according to a plan but irrespectively of whether or not the downstream process is ready to process them" (Lean Construction Institute 2000). It is a lean production ideal to pull all input to site, just in time for installation. Advantages of pulling input to site are (1) it eliminates the need to stock items on site and therefore alleviates site congestion, (2) it minimizes the impacts of design change, (3) it minimizes misuse (material being used for something that it was not intended for), vandalism, and wear and tear of material, (4) it eliminates additional handling and supervision, and (5) it alleviates cash flow problem by minimizing tied-up cost.

However, not all input can be pulled. In order to pull, the status of the consuming activity at the time of delivery should be reliably estimable at the time of ordering. This requires that the lead-time be reliably estimable as well. In other words, the order date and consumption date should both appear within the lookahead window, i.e., the lookahead window has to be larger than the lead-time. If the lookahead window is smaller than the lead-time, the lookahead window has to be increased or the lead-time has to be decreased in order to effectively pull (Lean Construction Institute 1998). If this cannot be achieved, one has to resort to pushing.

One disadvantage of a push strategy is that pushed input usually ends up being piled up until the consumption process consumes them. The inability to reliably estimate the start date of a consumption process and its desired input sequencing is often a reason for the pile up. However, one might deliberately allow for additional time and quantity when pulling input in order to decouple consumption from procurement (Howell et al. 1993). Additional time and quantity can be used as a buffer to minimize the effect of variation in the duration of procurement, procurement sequencing, and productivity of the consumption activity.

Tommelein and Ballard (1997b) discuss the application of screening and pulling on lookahead planning and commitment planning. The difference between the advancement of the lookahead window as traditionally viewed in CPM versus the LPS can best be explained using an example. Figure 10 (a) shows a sample CPM schedule. Six activities (hatched rectangles) and the precedence relationships between them (arrows) are shown. Note that “activity F” does not have any precedence relationship with other activities. Figure 10 (b) and (c) show the result of applying the traditional CPM vs. the LPS to updating the schedule one week later, provided all work in week 1 was completed as planned.

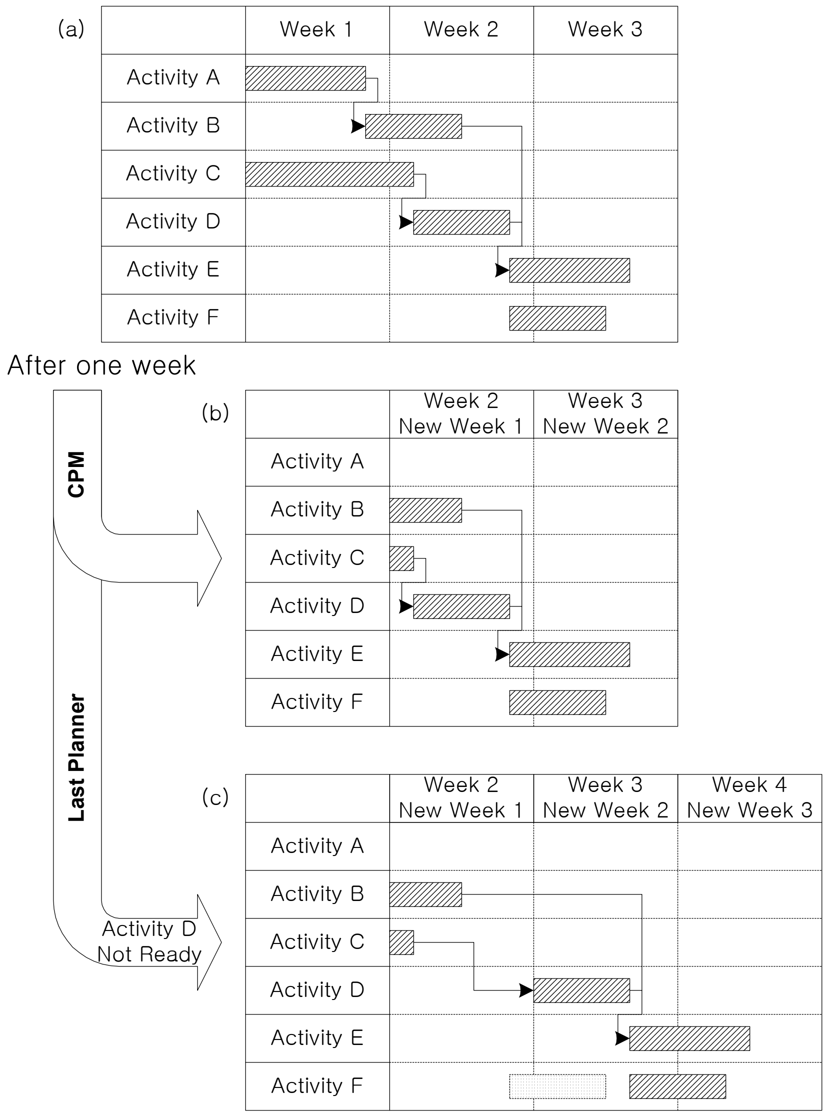


Figure 10. Advancement of Lookahead Window

Now assume that site management is told that the material for "Activity D" won't arrive on site to meet the original schedule. Since CPM does not have any mechanism to prevent an activity from advancing in the lookahead schedule, "Activity D" remains in its scheduled position to be done in week 2 (new week 1). With the LPS, "Activity D" cannot advance due to the screening mechanism. The question arises: When will it be reasonably certain that the materials for activity D will be on site? Assume this to be in week 3 (new week 2). Accordingly, “Activity D” is rescheduled to start then. This is a very good and *mandatory* decision because “Activity D” will not be workable in the second week due to lack of material, so it should not be scheduled for that week. There is no use to pretending it will.

The decision to delay the start of “Activity D” may have created more problems than what Figure 10 could describe. For instance, if the space freed up by the completion of “Activity D” was to be used by “Activity F”, rescheduling of “Activity F” now also is required. This schedule delay cannot readily be seen using a regular CPM schedule because the (precedence) link that describes the space relationship is usually not explicitly shown. Precedence relationships due to need of labor and equipment are not readily shown in regular CPM schedules either.

3.3.2.3 Commitment Planning

Commitment planning in the LPS differs from the traditional weekly work planning in that it explicitly recognizes uncertainties (as is done throughout the planning hierarchy) and tries to shield (Ballard and Howell 1994a, b) construction crew from these uncertainties that they do not control. It is also important to note that commitment plans have to meet specific quality requirements as well, i.e., (1) definition, (2) soundness, (3) sequence, (4) sizing, and (5) learning (Ballard and Howell 1997).

3.4 Relationship between PDCA cycle, Current Planning System, and Last Planner System

The Plan, Do, Check, Act (PDCA) Cycle (also called the Control Circle) is often used to show continuous learning and improvement effort in a process. Although Deming (2000, p. 88) named it The Shewhart cycle, it came to be known as The Deming Cycle. Each step in the PDCA cycle can be related to each step of the current planning and control system (middle circle in Figure 11) and to each step of the LPS (inner circle in Figure 11). However, there are many differences between these planning systems. The goal, approach and tools in “Plan” are very different for the two systems, as was explained in earlier sections. The more important differences in terms of continuous improvement can be seen in “Check” and “Act”.

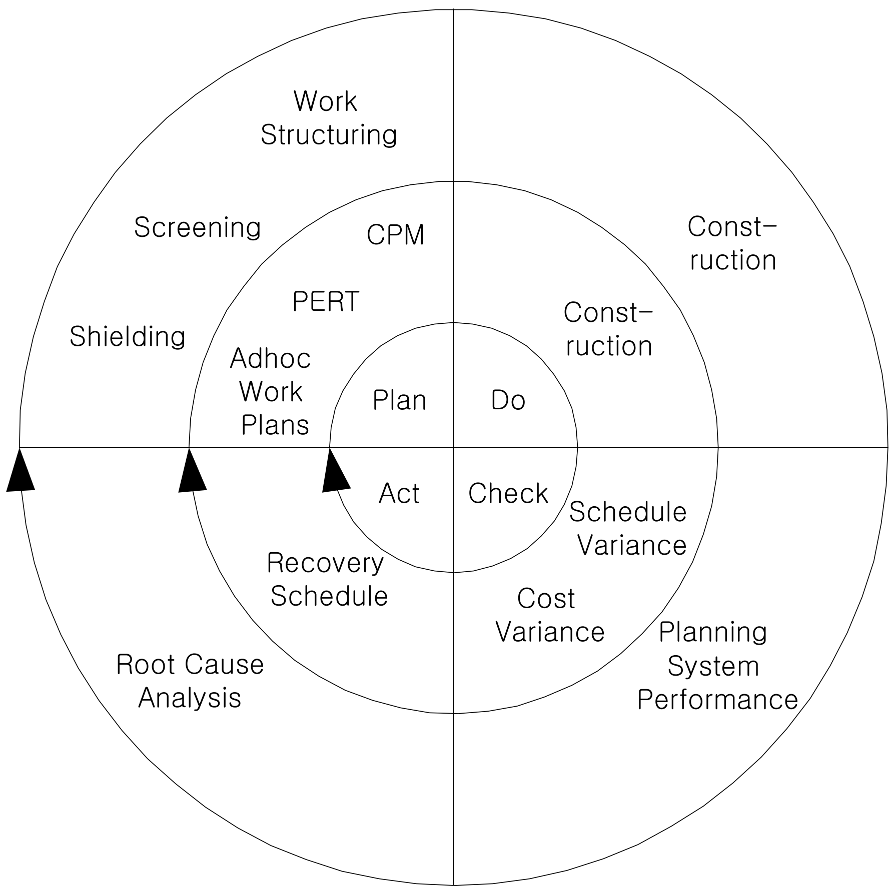


Figure 11. Relationship between PDCA Cycle, Current Planning System, and Last Planner System

The current planning system focuses on continuous learning and improvement of the “project” whereas the LPS focuses on continuous learning and improvement of the “planning system”. The current planning system “checks” how much the project is deviating from its original target using schedule variance and cost variance and “acts” on the project using a recovery schedule in an effort to bring the project to conform to its original or re-determined target. “Check” and “act” are done every day, week, or month depending on how often the project status data is collected and analyzed, thus, the notion of cycle exists. This, arguably, supports “continuous learning and improvement of the project”.

In contrast, the LPS “checks” how reliably Last Planners are able to plan their work using PPC and “acts” on the root causes to prevent the same planning failure from reoccurring. Frequency of “Checks” in LPS is the same as the frequency of planning. For example, if the planning is done every week then “Check” is also carried out every week and if planning is done every day then the “Check” is also carried out every day. “Act” in LPS is a never-ending exercise as the LPS pursues “perfection”. By setting an almost unachievable target, the LPS drives continuous learning and improvement. However, the current planning system does not provide a target suited for continuous learning and improvement but rather suited for recovery when necessary.

Another notable difference is in what is “learned.” The current planning system can “teach” who delayed which activity, or whether the duration or the resource requirement was over/under-estimated. Performance may be assessed using an earned value analysis. Kim and Ballard (2000) explain how the current “check”, i.e., the earned value analysis, might be a hindrance to planning to promote flow. This “learning” can either be useful or useless depending on the characteristics of the future activities and projects. However, the

LPS improves the performance of the planning system, which will benefit all future activities and projects; thus truly promoting continuous learning and improvement.

3.5 Plan Reliability

Dealing with uncertainty has always been and will remain a major issue for the construction industry. The first step toward minimizing the effect of uncertainty is to acknowledge its existence and explicitly represent it. A planner would be able to plan work and possibly minimize the effect of uncertainty if at least a representation of uncertainty were easy to create and understand.

Many types of uncertainty exist throughout the life cycle of a project, that is, from the conceptual phase of the project to the handoff to the owner for commissioning. Many of these uncertainties bring about changes to the schedule. Uncertainties in project scope and design changes may increase or decrease work shown in the original schedule. Planners can represent these changes as an addition/deletion of one or several activities, increased/decreased duration of one or several activities, or changes in the dependencies. Uncertainties involving resources (availability of material, space, and information and variability in productivity of labor and equipment) can also influence the schedule. Uncontrollable factors such as weather can also force the schedule to change.

Planners can employ two different approaches to minimize the effect of uncertainty. One approach is to minimize the effect of uncertainty by identifying the causes of the uncertainty and eliminating these causes as much as possible. Another approach is to explicitly represent uncertainty using a probabilistic distribution, thereby planning uncertainty into the plan and setting completion dates according to an acceptable level of likelihood or confidence.

The LPS, developed to improve the reliability of the planning system uses the first approach. The LPS as explained earlier is not a tool to explicitly represent uncertainty but a tool to shield the production units from it thereby reducing to build time and resource buffers into the schedule. The Project Evaluation and Review Technique (PERT) (Malcolm et al. 1959) developed by the United States Department of Navy, is a method that uses the second approach. It allows planners to explicitly represent uncertainty by assigning probabilistic distributions to activity durations. It, then, allows planners to associate a probability with a completion date. In the PERT methodology, all uncertainty regardless of its cause(s) translates into duration variability of the affected activity. This approach is not very popular in construction although its graphical representation is widely used. One impediment to wide acceptance is that it is hard to assign a probabilistic distribution to each project activity. Another impediment is that it is hard to describe variability due to uncertainty in a text/graphical format that is easy for planners to understand.

The Critical Chain Planning Method (CCPM) (Goldratt 1997) is a complementary planning method to PERT in that it also uses the second approach. Strategically placed time and resource buffers at merging points of an activity network prevent local variation from affecting the whole network.

3.5.1 Automated Simulation of CPM Schedules using Stroboscope

Choo and Tommelein (unpublished 1998) created a graphical representation to depict uncertainty in start/finish time and duration. As done in PERT, the duration distribution of an activity represents all uncertainties that can increase or decrease the duration of an activity. This research employed the Monte Carlo simulation tool, Stroboscope (Martinez

1996), to model the effect of uncertainties associated with construction activities. Stroboscope, being a generic process simulation tool, has many capabilities and is higly flexible. It allows the programmer to analyze construction operations in detail although it requires time to learn, build simulation models, and decipher the output generated by simulating these models.

To minimize the user's hardship in building simulation models yet to allow the user the benefits of simulation, Choo and Tommelein developed an automated simulation tool, StroboCPM. StroboCPM consists of a standalone front-end (Figure 12) developed in Visual Basic, which is used to input CPM information. It automatically generates the simulation code for the given CPM and executes it in Stroboscope to collect data on the start and the end dates for each activity. The simulation model takes advantage of the CPM add-on dynamic link library in Stroboscope. Once the data are collected, StroboCPM automatically represents the collected data in Visio.

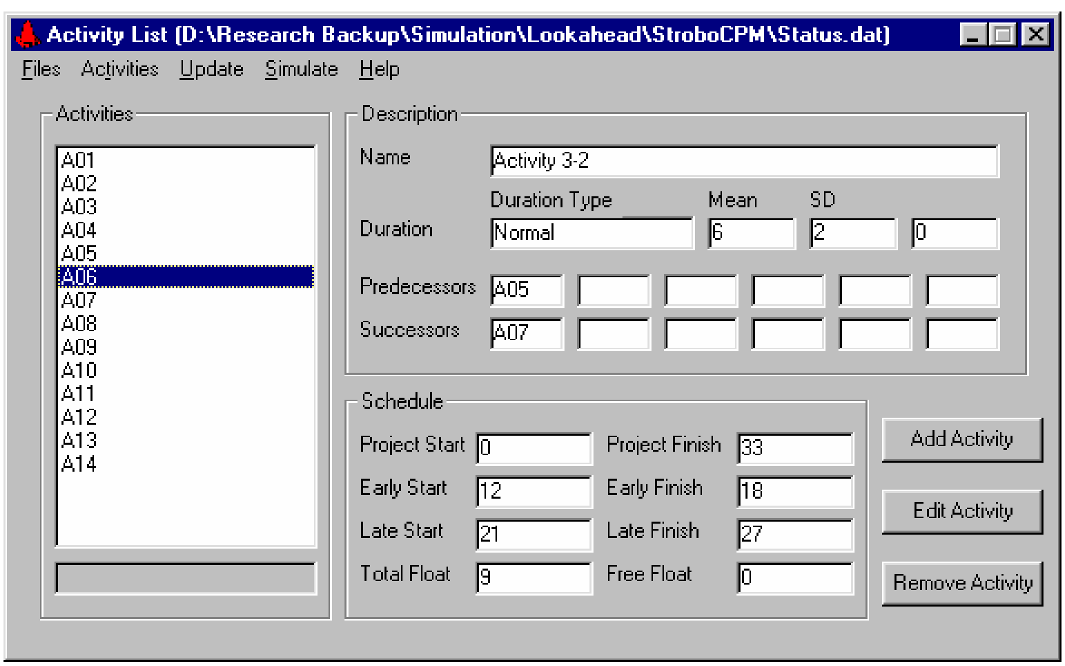


Figure 12. Front-end of StroboCPM

A year after the author developed StroboCPM, the author learned that Martinez had developed Stroboscope Prbschd (Martinez 1998), a program similar to StroboCPM, which automatically generates a CPM bar chart from the collected data.

StroboCPM, like any other CPM tool, requires as input the list of activities including their duration and the precedence relationships among them. In StroboCPM, however, the planner can specify durations by means of a deterministic, normal, or PERT distribution (specified in the CPM add-on dynamic link library). The program, then, automatically develops Stroboscope source code and executes the simulation. The planner can review or adjust the generated source code file if required. After simulation, the program saves the output for review and represents the data by a simple graph. Figure 13 illustrates a sample CPM schedule and Figure 14 shows the sample's simulation result. Each activity as shown in Figure 13 is represented by means of five arrows in Figure 14.

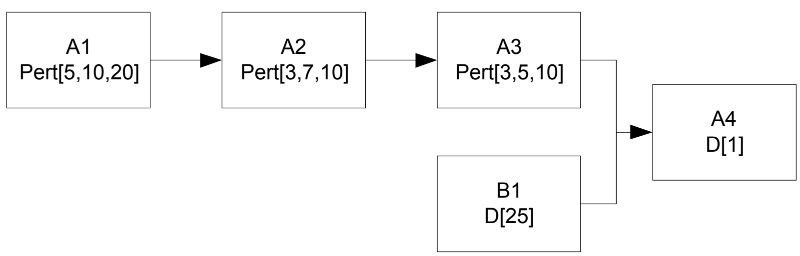


Figure 13. Sample CPM Schedule

The tail of the first arrow represents the mean value of the start date less twice the standard deviation of the start date. The head of the first arrow represents the mean value of the end date less twice the standard deviation of the end date. Similarly, the tail and head of the second arrow represent the mean less the standard deviation of the start and end date. The tail and head of the third arrow represent the mean of the start and end date. The tail and head of the fourth arrow represent the mean plus the standard deviation of the start and end date. The tail and head of the fifth arrow represent the mean plus twice the standard deviation of the start and end date. The slope of the line connecting the arrows' tails (or heads) represents the degree of uncertainty in start (or finish) of an activity. The steeper the slope is, the smaller the uncertainty is.

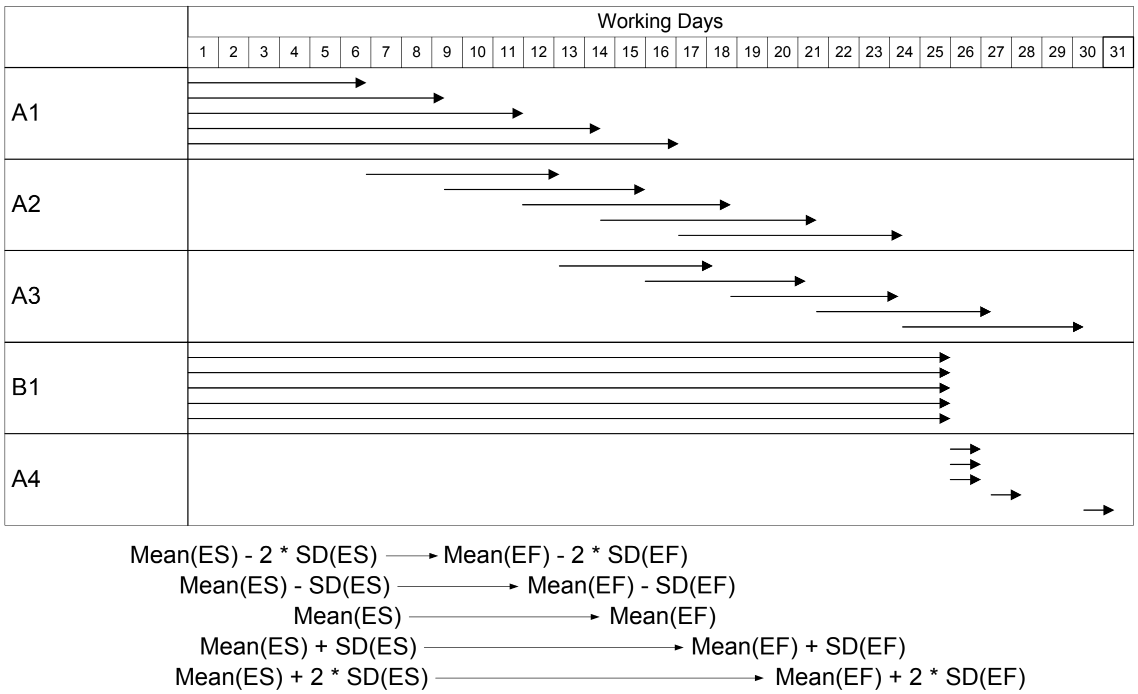


Figure 14. Sample StroboCPM Chart

Using this graph, a planner can associate probabilities with dates. For instance, the planner is able to set up a milestone based on the anticipated chance of meeting it. In a deterministic schedule, assuming the durations of activities are averages of normal distributions, meeting a milestone date set on a finish date of an activity has 50% or less chance. If the planner wants to increase the chance of meeting the milestone date, a deterministic schedule does not provide any guidance. The StroboCPM chart shown in Figure 14 can guide the planner to set the milestone date with a desired probability of meeting it.

For example, assume Activity A4 represents an important milestone date, e.g., an inspection day that requires an outside inspector to visit the project. In order to determine the needed lead-time to finish activity A1 through A3 to get ready for inspection, the planner can introduce a fictitious activity B1 to set the date for the inspection. The planner can then adjust the duration of Activity B1, which represents the lead-time, until the date for inspection is within acceptable certainty.

If the duration of B1 is 25 days, then there is a 50% chance that the project will be ready for inspection on the 26th day, as can be seen from Figure 15. If the chosen duration results in the top four arrows representing activity A4 having the same start and end date, then there is an 84.13% chance that the site will be ready. As shown, the planner can adjust the duration of B1 so that the chance of meeting the inspection date is acceptable.

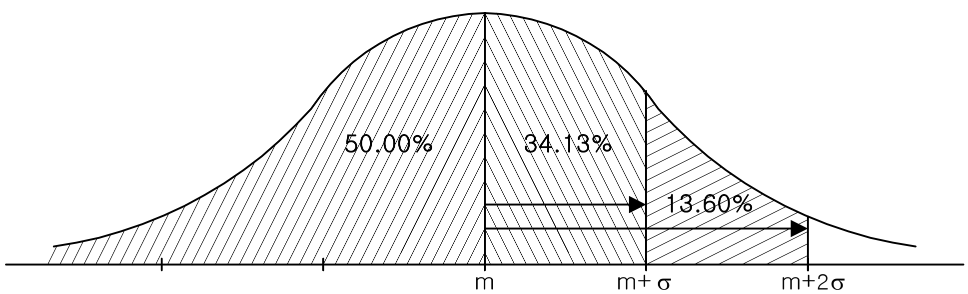


Figure 15. Percentages of Normal Distribution

The StroboCPM approach assists the planner in visually recognizing uncertainty associated with activity starts and finishes in the schedule. My creating this graphical representation brought out important questions. What is an acceptable level of uncertainty? How much better is 70% than 65%? How can we reduce uncertainty? The answers to these questions depend on numerous variables. However, StroboCPM does not have the capabilities to explicitly represent these variables.

As StroboCPM adopts the CPM representation of a project, limitations of this representation are also inherent in StroboCPM. For example, it assumes that the start/end dates and duration of an activity represent all governing uncertainties of an activity regardless of their sources. My research, therefore, shifted to a schedule with shorter time span and more definition.

3.5.2 Planning Performance Criteria

In the construction industry, the term "reliable planning" is a relatively new one. Kaplan and Norton (1992) point out that the existing project performance measurements are based on financial measures. Kartam et al. (1995) point out that available models and performance criteria are insufficient for analyzing and improving the performance of a construction planning system. They also add that many project managers use project performance criteria to control and punish poor performers rather than to improve project performance. Lantelme and Formoso (2000) assert that managers regard measurement only as a tool for controlling project participants' behaviors and that it should be used to communicate goals, share responsibilities, and promote learning in organization. Therefore, in order to promote reliable planning, adequate measurements are necessary.

Kartam et al. proposed an alternative approach that uses a system model (workmap (Ballard 1994)) and process models (interaction process model, and communication process model). This approach also uses the responsibility matrix to show the participants involved in the communication process model. The workmap depicts inputs, outputs, directives, and feedback loops of a process and interactions with other processes. The interaction process model and communication process model distinguish value adding from non-value adding processes.

This approach adopts the LPCS system to weekly work planning in order to measure and improve planning system reliability. They categorized the Percentage Assignments Missed (PAM), which is equal to 100%-PAC (Percentage Assignments Completed), into Percentage Assignments Execution Failure (PAEF) and Percentage Assignments Selection Failure (PASF). PAC, PAEF, and PASF are termed PPC, Execution Failure, and Plan Failure by Ballard (1994b), respectively. They also developed criteria for evaluating the performance of the LPS. These criteria are listed in Table 2.

Table 2. Measurements Proposed by Kartam et al. (1995)

Measurement	Equation	Note
% Improvement in Assignments Executability	$\frac{(PAM)_{t_1} - (PAM)_{t_2}}{(PAM)_{t_1}}$	PAM: Percentage Assignments Missed
% Improvement in Assignments Selectability	$\frac{(PASF)_{t_1} - (PASF)_{t_2}}{(PASF)_{t_1}}$	PASF: Percentage Assignments Selection Failure
% Improvement in Assignments Practicality	$\frac{(PAIP)_{t_1} - (PAIP)_{t_2}}{(PAIP)_{t_1}}$	PAIP: Percentage Assignments ImPractical
% Improvement in Resource Planning	$\frac{(PRPF)_{t_1} - (PRPF)_{t_2}}{(PRPF)_{t_1}}$	PRPF: Percentage Resource Planning Failure
% Improvement in Assigning the Right Work	$\frac{(PAW)_{t_1} - (PAW)_{t_2}}{(PAW)_{t_1}}$	PAW: Percentage Assignments Wrong
% Improvement in Assigning the Right Amount of Work	$\frac{(PAIT)_{t_1} - (PAIT)_{t_2}}{(PAIT)_{t_1}}$	PAIT: Percentage Assignments missed due to Insufficient Time

Production managers can use these measurements to gauge the status quo of their planning system. However, these measurements do not gauge how sensitive each schedule is to the manifestation of uncertainty. Too sensitive a schedule can very easily become obsolete when it faces even the smallest uncertainty. The planner then has to adjust the schedule to reflect changes brought by the uncertainties. The more sensitive the schedule is, the more often the planner has to reschedule. Thus, one desirable characteristic for a schedule is that it would be able to absorb a certain level of uncertainty without bringing failure to the whole schedule. The term “robustness” denotes this characteristic.

3.5.3 Robustness

As explained in earlier chapters, scheduling is an on-going effort. This effort consists of two complementary scheduling approaches, i.e., predictive and reactive scheduling. Predictive scheduling is “the task of finding a legal sequence and assigning start times to operations before the actual production takes place” (REFRESH 2001). Reactive scheduling is “the problem of updating schedules in the most effective way when the constraints or assumptions on which they are based are changed or invalidated” (Aigner et al. 2000).

One means to increase the robustness of a schedule is to have contingency plans that can be followed without disturbing the whole project. In the LPS, workable backlogs are used to increase the robustness of the weekly work plans. By having workable backlog, the production units can create a “reactive schedule” by selecting one of the “interchangeable” assignments when one of the assignments in a “predictive schedule” cannot be executed. If the substituted work is truly “interchangeable”, then the failed assignment can be executed when it is possible to do so without causing a major change to the project schedule. Major changes occur when a disturbance in a weekly work plan is passed up to the project schedule. Girsch (2000) points out that attempts to specify production in too much detail can result in a schedule that is too nervous, which in turn increases the reactive scheduling effort. Therefore, as pointed out earlier, a master schedule needs to stay at a high level of abstraction to build robustness into the plan as well as to promote the creativity and empowerment of the participants that are going to carry out the work.

Another means to increase robustness is to build capacity and time buffers into the schedule. Queuing theory, reiterated in the context of construction planning by Ballard (1999a) suggests that the production units should be loaded less than 100% of their capacity. They should have a capacity buffer, when developing detailed production plans, i.e., weekly work plans, in order to promote work flow reliability. By having a capacity buffer, the production units are able to recover from unforeseen uncertainties so that the effects of these uncertainties do not carry over to the following weeks. CCPM, explained earlier in Section 3.4, is one method that consciously builds time and resource buffers into the plan.

3.6 CONSTRUCTION COORDINATION

3.6.1 Coordination vs. Scheduling

The successful delivery of a project does not only depend on a single contractor's ability to deliver but also on the whole project team's ability to deliver. Currently most of the coordination decisions are made during general coordination meetings. These meetings are usually carried out once or twice each week and last from one to three hours. The frequency and duration of these meeting depend on the level of complexity and urgency. They are led by either a project engineer or a superintendent. During the meetings the work to be carried out until the next meeting is discussed including milestones to be met, special permitting issues, site logistics, and clarification of directions from other project participants. However, not all issues are dealt with during the meeting, especially those that relate to only one or a few specialty contractor(s). Trying to solve these issues during the general coordination meeting will lengthen the meeting and would not be an effective use of other contractors' time.

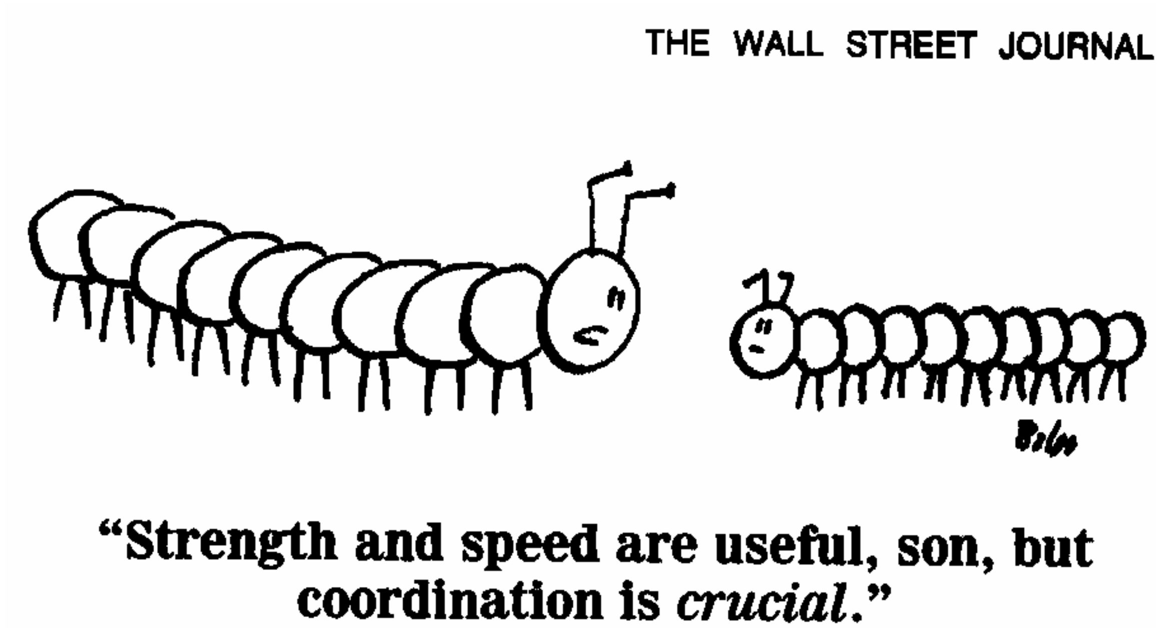


Figure 16. Importance of coordination. (Wall Street Journal)

The complexity of production work can be categorized into complexity caused by (1) technicality of the production work itself and (2) necessity for multiple trades to work at the same time. Most of the general coordination is focused on issues related to the second category, on simultaneity, while the dedicated coordination meeting is focused on the issues belonging to the first category, on technicality. As more activities are carried out simultaneously, the complexity due to simultaneity increases exponentially. The coordination problem arises when one or more activities need the same resource, especially labor, equipment, or space, at the same time, or when these activities are performed out of sequence preventing or making it difficult for any successive activity to be carried out. Simultaneity also poses the problem of balancing work flow and appropriate spacing between trades. In order to provide a solution to this problem, the list of activities to be carried out as well as the required and available resources for these activities must be specified. The coordinator can make a general assumption to develop a preliminary long-term plan. However, in developing an actual execution schedule, input from each contractor regarding their preferred way of carrying out their portion of work is mandatory. As each subcontractor is making an effort to minimize their own duration as well as cost (which is rarely captured in a CPM-based master schedule), they will try to create as many critical paths for their own crew as possible (Birrell 1980). They will load their resources according to their own schedules as long as it does not violate the contractual arrangement and milestone date set by the prime contractor. The coordinated execution schedule must therefore account for each contractor's schedule and preferences, and take priority into consideration. As these schedules become building blocks for the coordination schedule, they must be able to represent the actual work that can be carried out (as proposed by the LPS) rather than work "wished" to be carried out. This is especially important when successive trade(s) depend on predecessor trades to provide output of the production work or release resources (labor, equipment, and space), which usually is the case in a construction environment. The predecessor therefore must be able to provide an accurate depiction of what and how much of it can be released to successors.

Tommelein (1997b, 1998) describes the effect of dependency and variability in terms of what is released to successive trades and Tommelein et al. (1998) describe the effects in terms of quantity released by simulating the "Dice Game" using discrete event simulation with Stroboscope (Martinez 1996). Tommelein et al. coined the term "Parade of Trades" from Gus Sestrup, a superintendent with Turner Construction, to represent construction environments where multiple trades follow each other in a linear sequence and work output by one trade is handed off to the next trade. Choo and Tommelein (1999a) have created the "Parade of Trades" computer software to allow users to simulate the "Dice Game." Alarcon and Ashley (1999) used @Risk (1997) to simulate a slightly modified Dice Game and analyzed the impact of variability on project cost and schedule.

As can be seen from the results of these different studies and implementations, it is important for each schedule to contain reliable and explicit information regarding resource assignments, specifying who or what will be used, and when and where each activity will take place and occupy other supporting space. Since each contractor develops its own work schedule based on the work content and productivity as well as availability of crew and equipment, it is impossible for one planner to develop a detailed, reliable schedule. An old saying, "the chain is only as strong as its weakest link," best explains the importance of each input schedule having to be reliable. Only when input schedules are sound, can they be collected and compared to anticipate conflicts and developed into an overall sound schedule. The coordinated schedule can be reliable only if the individual schedules provided by all participants are reliable and well defined.

While schedules provide one means to show where coordination has to take place (which work will be carried out simultaneously and where) one might argue that the problem of simultaneity is not best solved through scheduling at all, but rather through some type of mutual adjustment mechanism as advocated by Mintzberg (1973). A time dated sequence of activities is needed less than a common plan of action (who goes first, handoff criteria, etc.), rules for use of shared resources (e.g., the crane will be tied up for placing concrete every morning, and it can load specialty contractor materials in the afternoon), plus constant coordination and adjustment (A slows down to let B get a little further ahead, D sends some people back to help C catch up, etc., as is needed when partners are dancing). Coordination becomes more like how a single crew works together with others, with each knowing what needs to be done and doing it. The requirements for mutual adjustment are not captured in schedules, which pretend that work is sequential and non-interfering, and that team boundaries are impermeable.

3.6.2 Space Coordination

Based on past research and the lack of available commercial tools, it can be inferred that the management of space as compared to the management of other resources, i.e., labor, material, equipment, time, money, is currently least well defined and supported in construction. Nevertheless, a considerable amount of research has been done on space allocation and scheduling. In industrial engineering, there are mainly two approaches, i.e., optimization algorithms and heuristic algorithms, for designing a facility layout (Heragu 1997). The heuristic algorithms can be further divided into construction algorithms, improvement algorithms, and hybrid algorithms. The same categorization applies to construction layout planning.

Artificial intelligence that mimics the site layout planning process performed by human engineers has also been applied to layout planning and space scheduling (Tommelein 1998, Tommelein et al. 1991, Tommelein et al. 1992a). Space scheduling focuses on “the problem of allocating space to resources governed by a construction schedule, and conversely, changing the schedule when space availability is inadequate”

(Tommelein and Zouein 1993). Another approach is heuristic-based optimization (Zouein and Tommelein 1994, Zouein 1995).

Yeh (1995) formulated a construction site layout problem as a linear programming problem and applied the simulated annealing technique to solve it, with as objective to minimize the total cost of the layout, based on the user's assessment of value of individual locations.

Cheng and O'Connor (1996) developed a system called ArcSite that uses a travel frequency matrix and an attract/repel relationship matrix in locating temporary facilities. ArcSite uses a constructive placement procedure in generating a layout, placing one temporary facility at a time. Travel frequency ratings were categorized as "very frequently" (5+/day), "frequently" (3-4/day), "regularly" (1-2/day), "infrequently" (3-4/week), "occasionally" (1-2/week), and "never" (0). The attractive relationship rating ranged from -3 (strongest) to 0 (weakest). The site location for each facility was determined by the solution that minimizes an objective function that incorporated the travel frequency rating and attractive relationship rating.

Special-purpose layout planning tools have also been developed. Bohinsky and Fails (1991) developed the Computer Aided Rigging (C.A.R.) system, which aids the rigging superintendent in selection of crane equipment by simulating the rigging process. Williams and Bennett (1996) describe the Automated Lift Planning System (ALPS) developed to assist in the crane selection process. ALPS assist the user in selecting a crane best suitable for the given lift situation from a library of cranes by considering the capabilities of each crane. Lin and Haas (1996) developed an interactive critical operations planning environment (COPE). COPE assists in planning construction operations involving large semi-stationary equipment by considering the capabilities of the equipment as a criterion for selection of the location. COPE integrated three software components: (1) a CAD platform (MicroStation), (2) a database management system (Oracle), and (3) a programming language (MDL).

Tommelein (1999) used the Stroboscope (Martinez 1996) discrete event simulation system to evaluate the location and sizing of support facilities on a construction site. Whereas traditional methods relied on heuristic methods and average values to determine the support facilities, Tommelein modeled the variability in travel times using simulation.

The main purpose of these tools has been to support the planning process and decision-making ability of a site engineer. Although most of these tools allowed a user to modify the solution provided, the main focus of control resided with the computer.

SightView (Tommelein et al. 1991) and MovePlan (Tommelein and Zouein 1993) actually brought the focus of control to the planner. SightView, which is the interactive display system for SightPlan (Tommelein et al. 1987), allows the user to limit possible positions of an object. This information is then input to SightPlan to propagate constraints and regenerate the site layout. MovePlan tied layout planning to CPM scheduling. The user of MovePlan is responsible for selecting layout time frames, generating alternatives, and picking candidate solutions whereas the computer provides the calculation, solution graphical and temporal representation and modeling capabilities. Simulation tools that link a 3-D CAD model with a CPM schedule, i.e., 4-D CAD (McKinney et al. 1996) and 4D-Planner (Williams 1996) have been developed to validate the constructability of construction schedules prior to construction.

Thabet (1992) applied the technique of blocking out rooms in a building for the exclusive use of a trade to solve the space scheduling problem. Tommelein et al. (1993) looked at the schedule implications of space conflicts. Akinci et al. (1998) created a framework for predicting the behaviors of space-interfering activities and their schedule impact given these time-space conflicts once the space-interference is detected. The same methodology will be applied to the site layout tool developed in this research.

3.7 EXISTING TECHNOLOGY

Before the movement toward on-line integration and collaboration, the construction industry has been working mostly with dedicated computer tools. Each of these tools supported one or several functions needed to successfully carry out a project, e.g., estimating, drawing, scheduling, cost management, communication, etc. Howard et al. (1989) reported that these tools exacerbated the fragmentation in planning, financing, designing, constructing, and managing projects. They also reported that project management tools were "knowledge-poor" because they store the decisions not the decision making processes.

3.7.1 Internet-based Tools

With the advancement of communication technology especially the proliferation of the Internet, many companies provide integrated on-line tools to assist with collaboration on construction projects, e.g. ProjectNet (Citadon 2001), Team Builder (E-Builder 2001), ProjectPoint (Buzzsaw 2001), Constructw@re (Constructware 2001), ProjectTalk (Meridian Project Systems 2001), Buildpoint (Buildpoint 2001), Project|Center (Bricsnet 2001), etc. Most of these tools, listed above, provide similar functions, that is to support document distribution and tracking. These documents can either be text files, pictures, or drawings.

Many traditional standalone tools also were extended to have on-line capabilities, e.g., Primavera Project Planner (Primavera 2001), Microsoft Project 2000 (Microsoft Corporation 2000c), Prolog Website (Meridian Project Systems 2001), etc. So far, no one clear standard-setting winner exists. Rose (2001) points out that traditional companies may have an advantage over newcomers as they understand the needs of the customer better and have proven technology. O'Brien (2000a) points out that the current generation of websites is not designed to fully support the daily activity of the users. They are mainly based on the concept that sharing information is beneficial and that the current existing technology allows this data to be centrally maintained.

3.7.2 Information Exchange

Current on-line collaboration tools allow for real-time sharing of project related information between different participants. By managing project-related information at a single source, these tools alleviate the problem of information exchange between different programs and platform. However, project participants still rely on many standalone tools to carry out un-integrated project management functions. Scheduling is one of these un-integrated functions. Most of the on-line tools allow project participants to share schedule information by attaching the schedule data file to an email or the tool's internal message system as an attachment or by posting a static snap-shop of the schedule. However, these tools do not provide an explicit means to support distributed planning, i.e., creation of a coordinated schedule through collaboration of multiple participants at multiple level of project hierarchy, because the schedule information is communicated only in one direction.

Using a one-directional communication system, a central planner (coordinator) must update the schedule with coordinated information after viewing or receiving schedules from each participant. The coordinator must figure out which schedules result in conflicts and then notify the corresponding participants to figure out ways to overcome these conflicts without creating new conflicts with other participants' schedules. Once all conflicts have been detected and dealt with, the coordinator needs to update the original schedule. Since the coordinator is responsible for making sure that the latest information is made available to others, all participants are not guaranteed the latest information.

The schedules can be collected and compared automatically if communication takes place in both directions. A participant's schedule can automatically be incorporated into the latest updated schedule and if a conflict is detected, it can automatically notify the participant. In distributed planning, each participant is guaranteed the latest information and consistency among the participants because everyone is working from a single source of information.

A few scheduling-dedicated tools allow project participants to collaboratively create project schedules. For example, Microsoft Project Central (Microsoft 2000c), which extends the capabilities of a standalone Microsoft Project (Microsoft 2000c), allows multiple project participants to collaboratively create a project schedule. However, it remains to be seen how a tool based on a project-centric view, such as in Microsoft Project Central, will be integrated into daily management of each project participant.

Currently, the construction industry uses many different scheduling tools. It is common for project participants on a single project to use different tools, which vary from scheduling-dedicated tools to generic spreadsheets. Therefore, it is critical for the exchange of scheduling data to be flawless. Although many of these tools currently support data exchange through import/export functions, not all the data can be yet transported from one tool to another because all tools are based on proprietary formats. These formats have different ways, e.g., of representing resource assignment, critical information about resource assignments, which increases the likelihood of information loss when schedule data is transferred from one tool to the next.

On some projects, the owner chooses a commercial scheduling tool and imposes its use on all participants of the project. However, this does not necessarily guarantee a smooth exchange of information because a contractor might be using some other tool to support its internal planning effort while using the selected tool only for reporting purposes. The simultaneous use of two or more tools for related purposes will invariably lead to data being captured in one but not in the other. This makes it more difficult to achieve the original purpose of making realistic information available to others.

Lack of standards is a key barrier to effective information exchange and perpetuates the fragmentation of the construction industry (e.g., Arnold and Teicholz 1996). Efforts are under way to develop standards for information technologies in the construction industry. Examples of such efforts are STEP (Standard for the Exchange of Product Model Data, ISO Standard 10303, Product Data Representation and Exchange) by ISO (International Organization for Standardization) (see Froese 1996), EDI (Electronic Data Interchange) standards by the United Nations EDIFACT organization (United Nations

Electronic Data Interchange for Administration, Commerce and Transport (UN/EDIFACT) 2003), CALS (Continuous Acquisition and Life Cycle Support) by the US Office of the Secretary of Defense (Naval Surface Warfare Center 2003), and IFC (Industry Foundation Classes) by IAI (International Alliance for Interoperability) (International Alliance for Interoperability 2000).

The U. S. Army Corps of Engineers has created a standard for exchanging scheduling data: Standard Data Exchange Format (SDEF) for Project Scheduling (East and Kim 1993, U. S. Army Corps of Engineers 1996). This standard is, again, to support master schedules only and there is no information on resource allocation. Additional data fields are needed to convey material, labor, equipment and space allocation. Also, standards for lookaheads and weekly work plans remain to be developed so that the information they contain can be exchanged without losing data in the process.

Research also has been conducted on developing information classification systems and automating communications. Luiten and Tolman (1997) automated communication for constructability checking using a STEP model. Kang and Paulson (1998) proposed a construction information classification system (CICS) to promote consistency of representation in all phases of a construction project. By dividing the construction project into four facets: facilities facet, spaces facet, element facet, and operations facet, they provided a classification scheme that can be used for both cost estimating and network scheduling.

3.8 OTHER AREAS OF RESEARCH IN DISTRIBUTED PLANNING AND COORDINATION

Although distributed planning and coordination is a fairly new concept, it has been implemented in tools that are currently being used in many areas. Most of these tools belong to the groupware class. Groupware is “a class of software that helps groups of colleagues (workgroups) attached to a local-area network. Typically, groupware supports the following operations: scheduling meetings and allocating resources, e-mail, password protection for documents, telephone utilities, electronic newsletters, and file distribution. Groupware is sometimes called workgroup productivity software” (INT Media Group 2001).

One implementation of groupware that can be used for distributed planning is electronic calendaring and scheduling. Calendaring focuses on managing data input and manipulation on a calendar, while scheduling focuses on communication and negotiation between calendars (Crosswind 2001). By sharing schedule information with others in the workgroup, electronic calendaring and scheduling tools assist participants to collaboratively schedule meeting times. These tools usually do not make any decisions for the users but they assist them in identifying and communicating conflicts. One major disadvantage of using such a tool is that the solution can never be guaranteed as optimal because it is very difficult, if not impossible, to enumerate and compare all alternatives in a complex situation.

Thus, researchers in artificial intelligence have done extensive research to develop agents to mimic or to assist a human’s decision making process in complex situations. In many cases, several types of agents are involved in distributed planning problems.

Many academics and industry practitioners are using agent-based planning and coordination technology to support entities in complex situations. In construction, Kim (2001) developed agent-based compensatory negotiation approach for construction projects in order to assist project participants in choosing the schedule alternatives that minimize cost.

A distributed planning system using artificial intelligence has also been implemented in battlefield simulations. Baxter and Hepplewhite (2000) depict a hierarchical distributed planning framework to coordinate movement of tanks and troops. The scenario they describe bears much resemblance to construction projects. Resemblances are:

1. Hierarchy of planning: multiple levels of planning and corresponding planning horizons exist.
2. Short life of plans: No one can create a plan at the start of a campaign (war or a project) and expect it to be valid throughout the campaign.
3. Self-managing resource: No matter how well the plans are laid out, soldiers on battlefields or project participants can make decisions with no regard to existing plans, thereby making these plans obsolete (Hughes et al. 1995).

A major difference is the level of command and control imposed on the lower level participants and plans. In a battlefield, disregarding command is viewed as act of disobedience and is treated with heavy penalty. It is, thus, less likely to have self-management that results in obsolescence of plans in a battlefield. Despite this difference, learning can be shared.

Large geographically distributed organizations also have been developing distributed planning systems to support their own projects. Johnson Space Center and Lockheed-Martin, for example, have been developing a distributed planning system for the International Space Station (ISS) (Hagopian et al. 1994, Maxwell 2002). Maxwell (2002) points out that a major lesson learned from his experience is to involve as many stakeholders in design of the system early on and expect change. This is very consistent with the author's experience in developing a distributed planning and coordination system. Backes et al. (2000) have developed an Internet-based task sequencing system to coordinate the daily operational request of the Mars Polar Lander (MPL).

Zelewski and Siedentopf (1999) advocate that multiagent system research be a multi-disciplinary research effort that combines the fields of "distributed artificial intelligence" and "coordination science." Closer observation into past and on-going research reveals that two different coordination scenarios of distributed planning mainly exist. First is the coordination of interactions or movements of multiple objects, usually people or equipment, where a user or group of users has dedicated and/or shared control over one or more of these objects. Second is coordination of actions for movements of a single object, usually equipment, where a number of users have shared control over this object. This dissertation discusses the first scenario where the goal is to co-create a plan of action for multiple crews who have shared resources, such as special personnel (e.g., inspectors, managers, administration staff), space (e.g., laydown area, work area, access path, etc.), and equipment (e.g., cranes, elevators, scissor lifts).

3.9 CONCLUSION

Fragmentation between project planning and production planning in current construction management practice impedes reliable execution of construction work. As a project gets more complex, dynamic, and fast, it is virtually impossible for a single entity to detail out the schedule for the total project and the schedule to remain valid for a majority of the project duration. Project schedules become invalid as soon as unforeseen conditions are encountered. Unforeseen conditions, by definition, refer to conditions that the planner did not account for at the time of schedule construction. The severity of the effect on the schedule varies according to the conditions. Nevertheless, the underlying condition will continue to change throughout the project. Therefore, there is a need to develop a formal means of predictive and reactive project and production scheduling that promotes reliability. This research adopts the LPS in order to increase plan reliability through an explicit predictive and reactive scheduling process.

Research in construction planning and scheduling until recently has focused mainly on improving the effectiveness of project schedules or efficiency of the project schedule creation processes. Since 1993, the Lean Construction research community led by Ballard and Howell has specifically shifted their efforts to improving reliability of the production schedule in order to promote better workflow. This proactive approach to uncertainty was exactly what the author was seeking for. The author, therefore, adopted their approach to uncertainty. During the author's research, LPS evolved from the earlier form (Ballard and Howell 1994a, b) to the current form of the LPS as discussed in this dissertation. However, the author believes this system will continue to advance as several planning challenges remain to be tackled.

Applying the LPS process alone to each project participant, however, does not guarantee a realistic plan. Achieving a realistic plan involves communication among all project participants. The communication between project participants regarding resource use (including space use), activity sequencing, and hand-offs from one to the next must accompany the planning process to succeed.

The current planning (PLAN) and control (CHECK and ACT) model assists production units in conforming to the predetermined schedule assuming that it remains valid during the project. In contrast, the LPS's planning and control model guides the production units to improve the reliability of their planning system in pursuit of perfection. The author's distributed planning and coordination model adopts the LPS model.

Distributed planning and coordination currently is being researched in many areas and in different forms of application. Current technology suggests that the technological barriers to implement such tools are low. The challenges in implementing distributed planning and coordination lies mainly in changing mental models of participants from command and control as well as traditional organizational boundaries and work structuring models.

4 APPLICATION OF LAST PLANNER SYSTEM TO DESIGN AND CONSTRUCTION

The author has applied the LPS to construction and design and accordingly developed two computer tools, namely WorkPlan (Choo et al. 1998a, 1998b, 1999) and DePlan (Hammond et al. 2000). The main objective of these tools is to guide a production unit in creating reliable schedules, mainly weekly work plans, using the LPS. The principles that guided the design of WorkPlan and DePlan, and these program's implementation and functionality are described in this chapter.

WorkPlan and DePlan were developed for managing production units within a multi-project environment rather than within a single project. Figure 17 illustrates an example where a specialty contractor can be working on two projects simultaneously; thereby requiring the specialty contractor to manage their production units across two projects.

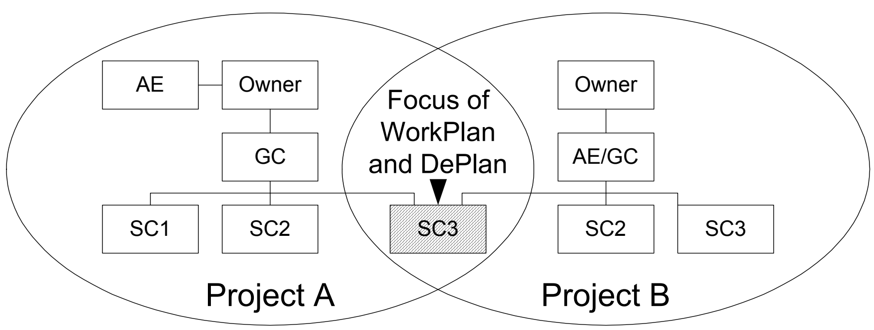


Figure 17. Focus of WorkPlan and DePlan

A single project view and a multi-project view each come with their distinctive objectives that sometimes require trade-offs. The single project view represents project-centric objectives such as meeting a predetermined level of quality while minimizing project cost and duration. The multi-project view represents production unit centric objectives such as meeting a predetermined level of quality while making a profit on each job, maintaining a continuous work flow, maintaining steady employment, maintaining or gaining a solid reputation, and improving process efficiency.

4.1 Jobshop Scheduling vs. Project Scheduling

Most commercially available computer programs for construction scheduling present a model for project scheduling, since most of the products construction companies produce are one-off (Allam 1988). These tools are useful in master-level scheduling but they tend to break down when detail is added to the schedule as needed to describe day-to-day work on site. However, scheduling for construction also can be viewed as job-shop scheduling (Allam 1988, Tommelein and Ballard 1997a). Especially for the production units doing the work, such as specialty contractors, scheduling requires an on-going effort as new contracts are awarded continuously. Scheduling newly awarded projects influences other ongoing and future projects in the company.

Schmenner (1993) proposes a spectrum of manufacturing processes that contains five major manufacturing processes, i.e., project, job-shop, batch flow, line flow, and continuous flow.

Figure 18. Spectrum of Manufacturing Processes

The project, which is at the left end of the spectrum, is characterized by (1) a unique product, (2) a jumbled flow, and (3) loosely linked process segments. The continuous flow, which is at the other end of the spectrum is characterizes by (1) high volumes of standard products and (2) continuous, automated, and rigid flow, and (3) tightly linked process segments. Job-shop is described as the most flexible process for creating variety of products in large volumes. He points out that the job-shops viability is heavily depends on information regarding costs, times (run times, set up times, labor content times), routings, and process steps. He also points out that job-shops are hardest to schedule as the flow processes are so disjointed and independent.

The goal of job-shops scheduling is to schedule a set of jobs on a limited number of resources. These jobs have operations that need to be performed in certain order. These operations may be different for each job. Job-shop scheduling problems are usually formulated as Constraint Satisfaction Problem (CSP) (Montanari 1971, Dechter and Pearl 1988) or Constrained Optimization Problem (COP) (Papadimitriou and Stieglitz 1982, Dechter et al. 1990). These problems are then generally solved using a backtrack search. The solution is then measured based on four prevailing metrics.

- Tardiness: The amount of time a job completes past its due date. The total (average) tardiness of a schedule is the total (average) job tardiness in that schedule.
- Flowtime: The time spent by a job in the shop while being processed. It is the length of the time interval that spans from the release of the job to its completion. The total (average) flowtime of a schedule is the total (average) job flowtime in that schedule.
- Earliness: The amount of time a job completes before its due date. The total (average) earliness of a schedule is the total (average) job earliness in that schedule.

- Makespan: The length of the time interval that spans from the start time of the first released job to the completion time of the last completed job. This measure is appropriate in project scheduling, where there is a finite number of jobs to be carried out.

The similarity between job-shop scheduling and production planning is more apparent in specialty contractor organizations where resources may be shared and alternate being used on multiple projects. A specialty contractor's resource-loaded schedule may contain information about two types of resources, i.e., dedicated resources and shared resources. Dedicated resources are committed exclusively to a single production unit on a single project. Shared resources are committed to more than one production unit or to more than one project. Some shared resources may serve multiple production units on multiple projects, which complicates the coordination problem even more. Shared resources may be project-shared or company-shared.

Project-shared-resources can be equipment such as cranes, elevators, site trailers, etc., personnel such as project management staff (project manager, project engineer, superintendents, building inspectors, etc., and space such as material storage areas, pre-installation and installation working areas, access paths, etc. Company-shared-resources can be equipment such as expensive hoisting equipment, large plotters, etc., and personnel such as a project manager, inspectors, laborers, etc. The scheduling effort for multiple projects is further complicated as involvement of specialty contractor in any one project tends to be intermittent and relatively short as compared to the total project duration. General contractor organizations tend to have—relatively-speaking—more dedicated resources for each project.

Tommelein and Ballard (1997a) point out that each specialty contractor's detailed design, fabrication, procurement, and construction process tends to take on the form of a job-shop. All offsite work may be done in a shop, but construction takes place each time at a site. This job-shop view is very different from the project view that general contractors adopt and that is reflected in existing CPM software. CPM focuses on the project itself, which has a definite start and finish date. In contrast, job-shop scheduling focuses on the continuous flow of work (jobs), where job execution may be interwoven so that there is no clear start or finish for the shop's operation as a whole (Figure 19).

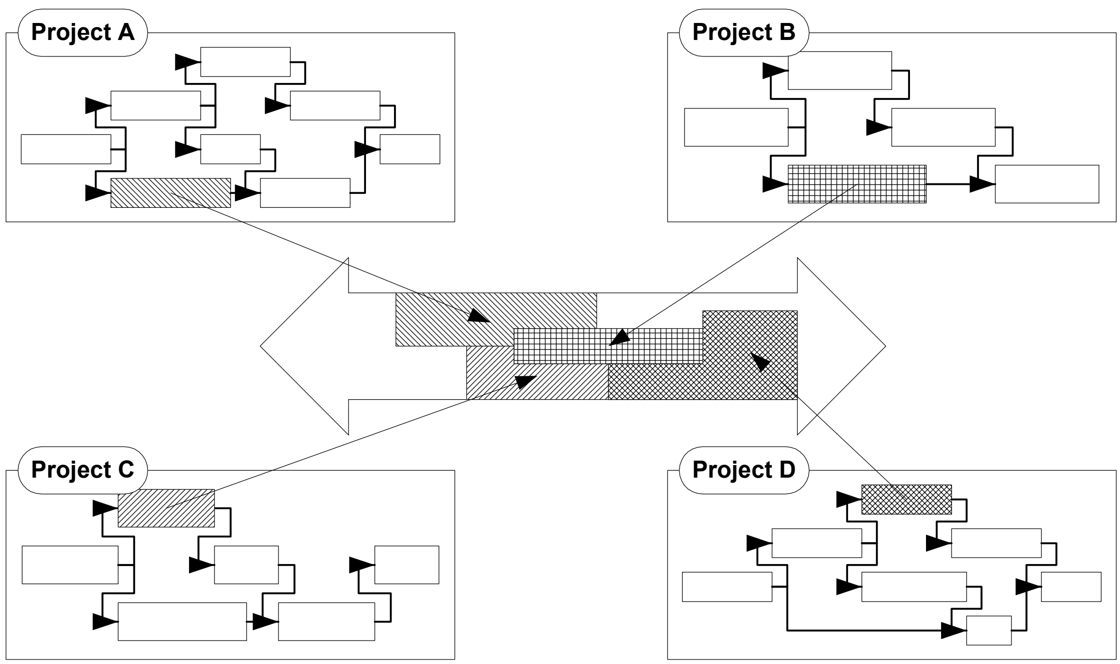


Figure 19. Job-Shop View vs. Project View

These different perspectives result in differences in (1) the calculation methods for activity dates and (2) the types of relationships one may express between activities. In the project scheduling view, a definite start and end date for the project exist. Therefore, the early start date, early finish date, late start date, late finish date, total float, and free float for each activity can be calculated. Primarily the physical dependence between building components determines precedence relationships between activities. Planners then use resource constraints to determine whether the plan is doable. If not, the precedence between activities can be changed by changing construction methods or by delaying one or more activities.

In the job-shop scheduling view, the planner can schedule each job to start as early as possible as long as the required material is available, and as late as possible as long as it does not delay its due date. The relationships between jobs are primarily determined by resource constraints although activities in each job are primarily determined by physical dependencies. Therefore, in a job-shop scheduling view, it is critical to maintain a steady flow of work for all resources so that fluctuation of resource utilization, i.e., overload and downtime, can be minimized. Resource overload (which is usually satisfied by overtime or additional resources) and downtime result in additional costs.

In order to achieve a steady flow of work, foremen include in their schedule tasks that are critical to following tasks and those that are used as 'fillers' (Senior 1996). These fillers may be chosen from workable backlog, which is work that can be scheduled to begin as soon as the required labor, equipment, and space become available.

Another way to achieve a steady flow of work is to move resources around to different projects. This is inefficient because it requires movement of resource and increased setups, which are non-value adding activities. It also impedes the learning process, which could result in deterioration of productivity of the crews, the safety of the work environment, or the quality of the product.

O'Brien (2000) discusses the implications of (re)allocation of subcontractors in a multi-project environment. He points out that dynamically moving crews or equipment from one site to another will result in added cost and time for the movement, plus the additional cost and schedule impacts incurred by lost productivity. Regrettably, these costs may be unavoidable in cases where the involvement of a specialty contractor is intermittently required on a project. The impact of these cases can be minimized if the need for involvement is predictable.

Another way to achieve a steady flow of work is to keep all resources busy by varying their capacity, e.g., the number of workers in a crew or the number of equipment. This is probably the worst case because, in addition to the problems of the previous case, finding resources, especially people, at the required time might not be feasible.

Figure 20 shows CPM schedules of two projects, each presumably performed by a different general contractor, but a single specialty contractor (shown by the cross-hatched activity) involved for part of the work in both. Even though a specialty activity may be unique in each project (activity “a” in “Project A” and activity “b” in “Project B”), the work requires the repeated application of a specialty for specialty contractor “SC 1.” To optimize performance, the specialty contractor is likely to try to schedule work in a continuous flow, whereas the general contractor primarily must schedule a sequence of dissimilar pieces of work in order to get them done within project time and budget constraints. These two scheduling methodologies differ significantly from one another so that different computer support tools are in order.

The job-shop view shares some traits with program management in that both adopt a multi-project perspective and consider resource usage across those projects. Program management is defined as “The effective implementation of change through multiple projects to realize distinct and measurable benefits for an organization” (Becker 1999).

Programs are relatively long-term and may consist of several relatively short-term projects (Roman 1986). A difference between the two is that the constituent projects in a program usually are (1) aimed at achieving a short-term goal that will eventually lead to a long-term goal (usually business goals) and (2) internally-initiated. The projects in a 'job-shop' construction company are not necessarily focused on a single goal but rather aim at achieving different goals for the different project customer(s). Nevertheless, the job-shop and program management both require considerable coordination and planning efforts including detailed resource planning and persuasion (Becker 1999) in order to integrate and manage the constituent projects. Accordingly, WorkPlan's and DePlan's designs are to adopt a job-shop scheduling view and include a detailed resource planning process.

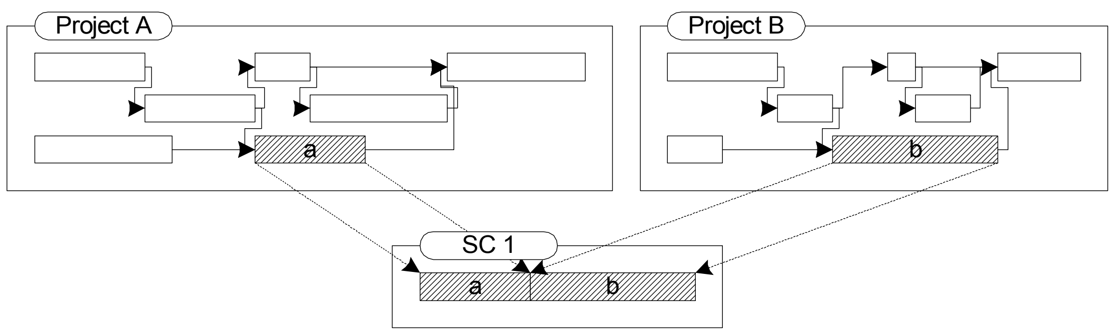


Figure 20. Relationship between Projects and Subcontractors

4.2 COMMON DESIGN CHARACTERISTICS

WorkPlan and DePlan share many design characteristics. They embed a very similar planning procedure as well as build on similar assumptions and choices made during implementation.

The scheduling unit in WorkPlan and DePlan is a work package. A work package is defined as "a definite amount of similar work to be done (or a set of tasks) in a well-defined area, using specific design information, material, labor, and equipment, and with prerequisite work completed" (Choo et al. 1998a). The work package defined here differs from the work package developed from WBS (Project Management Institute 1996). As the goal of the WBS is to provide a common system that can be applied at various levels for both cost estimating and scheduling (Barrie and Paulson 1992), the work packages at the WBS-level are created mainly for project control purposes. Therefore they tend to be inadequate in terms of use and expressiveness when it comes to supporting production planning and control, that is, supporting those who are performing construction work in the field. Stanoevska-Slabeva et al. (1998) point out that traditionally planning was based on quantitative knowledge but due to "increasing complexity and dynamics of quantitative information, related qualitative information like additional explanation, description premises are becoming more important." WorkPlan and DePlan are designed to capture and provide qualitative scheduling information as well as quantitative scheduling information.

Work packaging is a planning process that requires detailed understanding of the scope of work and the constraints that impact them. Without proper consideration of constraints, work packages would not be an effective means of managing the job (Kim and Ibbs 1995). Constraint analysis is a key component in the LPS and thus in WorkPlan and DePlan.

Since constraint analysis entails detailing of constraints for each work package, software designed to support this process must allow all records to be structured in function of what may constrain the execution of a work package. This requires editing, storing, and retrieving information regarding constraints as well as projects, work packages, and production unit's assignable resources (examples of such resources are labor and equipment in WorkPlan, and designer and administrative services in DePlan). This information usually already exists in electronic format in the company whether it is in spreadsheets or word processor files. This information can be captured and used throughout the project—a technique "capture information once and at the source" recommended by process reengineering (Hammer 1990). Therefore, a database, namely Microsoft Access (Microsoft Corporation 2000a), was selected as the platform to develop WorkPlan and to develop the extended WorkPlan portion of DePlan.

Quite a few commercial database packages exist to track RFIs, submittals, drawings, etc. Examples are Expedition (Primavera 2000) and ProLog (Meridian 2000). WorkPlan and DePlan differ from these packages in terms of their primary objective, which is to systematically check all constraints and prerequisite work before work packages are released to construction, so that one can avoid making low-quality assignments, thereby providing stability in the workflow of the construction process. Stability is a key aspect of lean production theory (Howell and Ballard 1994).

WorkPlan and DePlan focus on some lean production techniques (Womack and Jones 1996) such as "stopping the assembly line to immediately repair quality defects" in that they try to locate defective assignments early on before the assembly process (i.e., construction) and prevent them from being passed down (which corresponds to stopping the assembly line). They also support "pulling materials through the production system to meet specific customer demands" in that they help pull required resources (namely, material, labor, equipment, space, information, etc.) by guiding the Last Planner in developing resource constraints and then meeting these constraints. WorkPlan and DePlan also support "synchronizing and physically aligning all steps in the production process” in part by guiding the planner to carry out constraint analysis through work structuring. They also support “clearly documenting, updating, and constantly reporting the status of all process flows to all involved” at least in part by describing the status of all planning process flows to all involved. Although is not explicitly supported, “reducing overall process cycle time by minimizing each machine’s change-over time” is consistent with the job-shop scheduling objective of supporting continuous work flow. By assisting the planner in a multi-project scheduling environment, repeat efforts of mobilization and demobilization can be detected and possibly avoided.

The main difference between WorkPlan and DePlan is that WorkPlan is designed to support planning during construction and DePlan is intended to support planning during design. The planning process is very similar in both cases. However, the difference in intended use results in differences in external programs that the programs rely on for front-end planning. It also results in differences in vocabulary and in some domain specific views of data in the database.

4.3 WORKPLAN

WorkPlan is developed for managing a production unit working on multiple construction projects, usually a specialty contractor or a general contractor with it’s own work force.

4.3.1 Design of WorkPlan

WorkPlan guides the planner through the process of (1) inputting required information to support the Last Planner process, (2) carrying out the Last Planner process, and (3) generating reports and charts from the actual construction schedule data. Figure 21 shows the detailed planning procedure supported by WorkPlan. WorkPlan maintains detailed information regarding laborers and equipment. Thus planners can make explicit resource assignments by selecting specific resources from the list of resources maintained in the database.

Important features in the design of WorkPlan included support for (1) explicit resource assignment, (2) automatic cost calculation for alternative resource loading analysis, timesheets, and total direct cost, and (3) generating reports to show PPC and reasons for non-completion.

4.3.2 Implementation of WorkPlan

WorkPlan's graphical user interfaces (GUI) are sequenced so as to guide planners according to the procedure shown in Figure 21. The first two screens of WorkPlan (Figure 22 and Figure 23) show the program authors' names, the version of the software, and copyright information. Early versions of WorkPlan were documented on several occasions (Choo et al. 1998a, 1998b, 1998c and 1999). WorkPlan in its current form is detailed next.

Once the planner agrees to the copyright information, which only appears the first time WorkPlan is executed, the first page of the Navigator screen (Figure 24) automatically appears. The Navigator serves as the main interface to WorkPlan. There are four pages to the navigator; "Information", "Scheduling", "Reports", and "Etc." Each page contains related functions, some of which must be done in a sequence. A detailed description follows of the functions belonging to each page.

The first page of the Navigator is the "Information" page. The main purpose of this screen is to maintain information regarding undertaken projects and company resources. There is no sequential procedure to follow when inputting information regarding project and work packages information, laborer information, and equipment information.

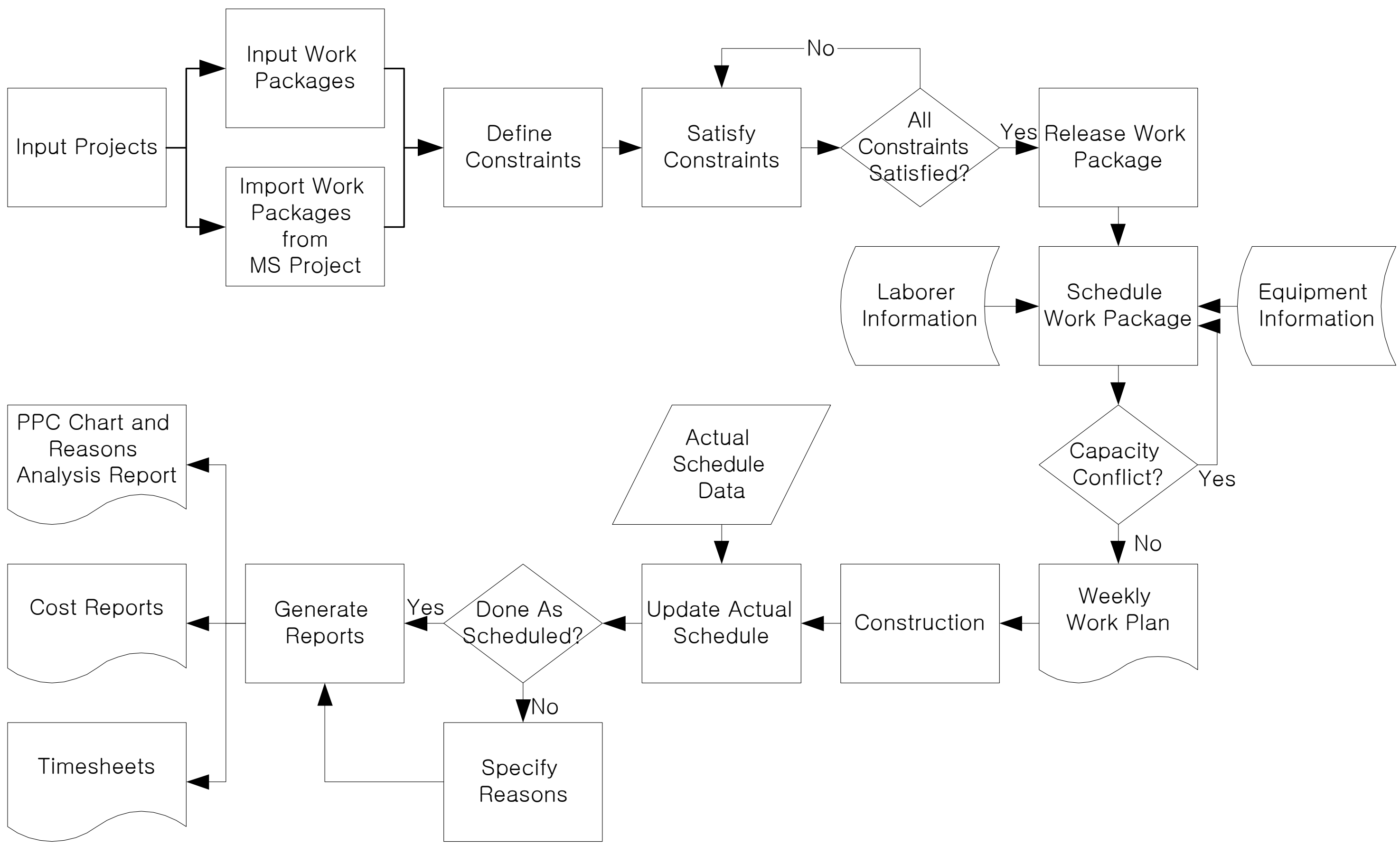


Figure 21. WorkPlan Procedure Diagram

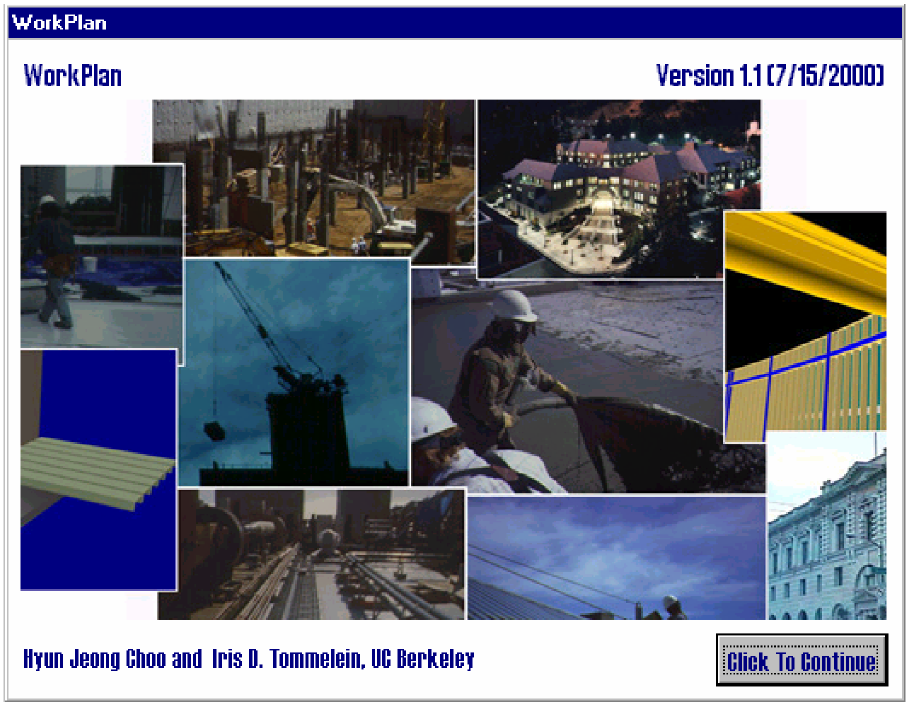


Figure 22. Startup Screen

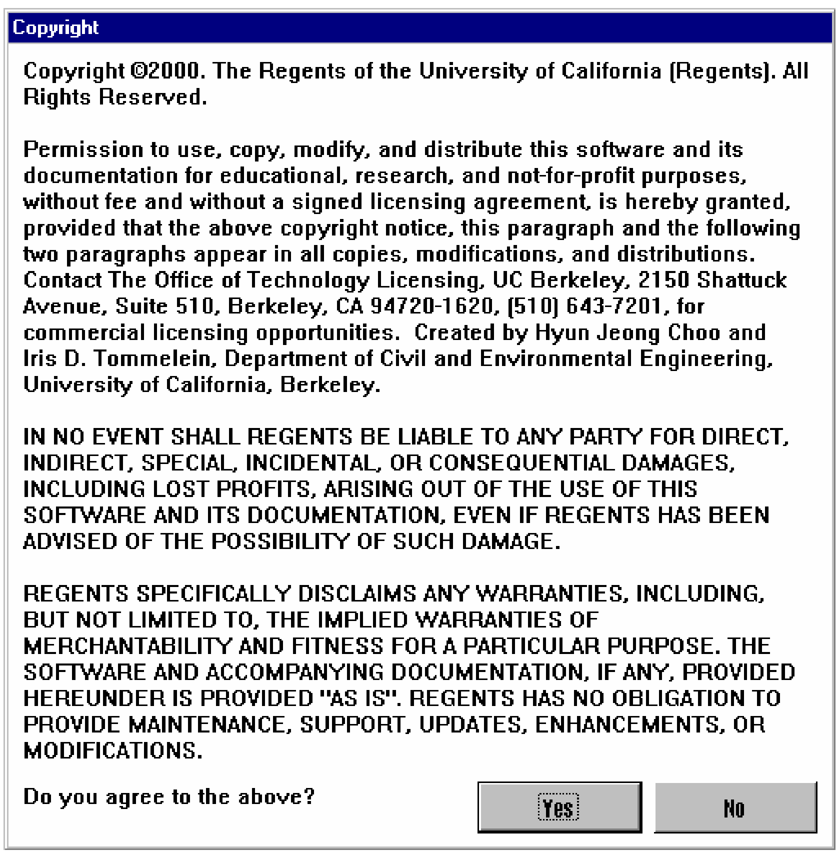


Figure 23. Copyright Screen

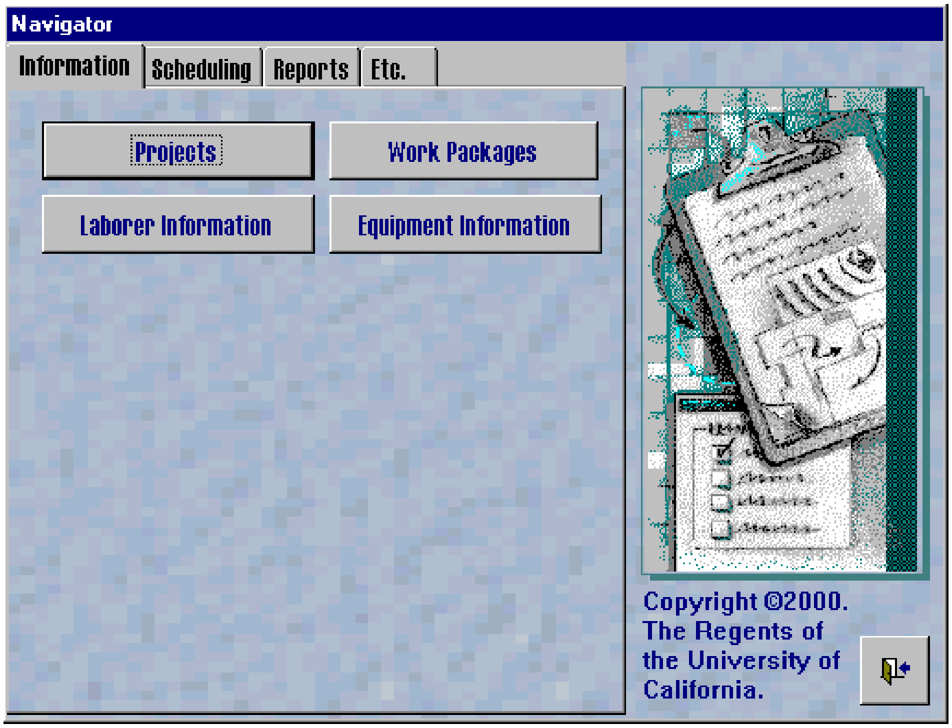


Figure 24. Navigator Screen Page 1

However, project information must be entered before work packages belonging to that project can be entered. Information regarding laborers and equipment is used during the resource allocation phase of scheduling. Cost information of laborers and equipment is also used to (1) compare different resource allocation schemes, (2) calculate the direct cost each week, and (3) total direct cost-to-date.

By clicking "Projects" in the Navigator Page 1, the "Project Information" screen (Figure 25) can be accessed. This screen allows the planner to input information for new projects and edit information for existing projects. The "Project No" and "Project Name" fields are required. "Project No" field is the unique key, i.e., it is used to differentiate one project from another. Other fields are optional.

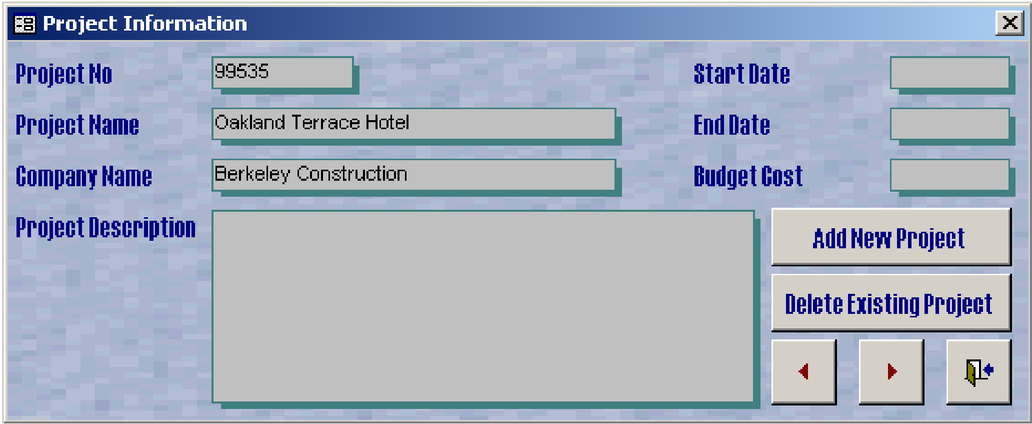


Figure 25. Project Information

Once the project information is entered into the database, the information regarding the work packages can be entered into WorkPlan using the "Work Package Information" screen (Figure 26). The project information has to be entered before work packages can be entered for that project. The "WP Code" field is the unique key. Value for the "Project No" field can only be selected from a list, which shows all projects that have been entered through the "Project Information" screen (Figure 7), in order to enforce data integrity. The "Budget" field is optional and not used in any of WorkPlan's calculations. The "Go To" combo box is used to locate work packages that have already been entered into WorkPlan

This implementation assumes that work packages to be entered are single-tiered. In other words, all work packages in WorkPlan are defined and sized so that the Last Planner process can effectively be carried out. This assumption is eliminated in WorkMovePlan (Choo and Tommelein 2000a, 2000b), as described in Section 6.1.1.

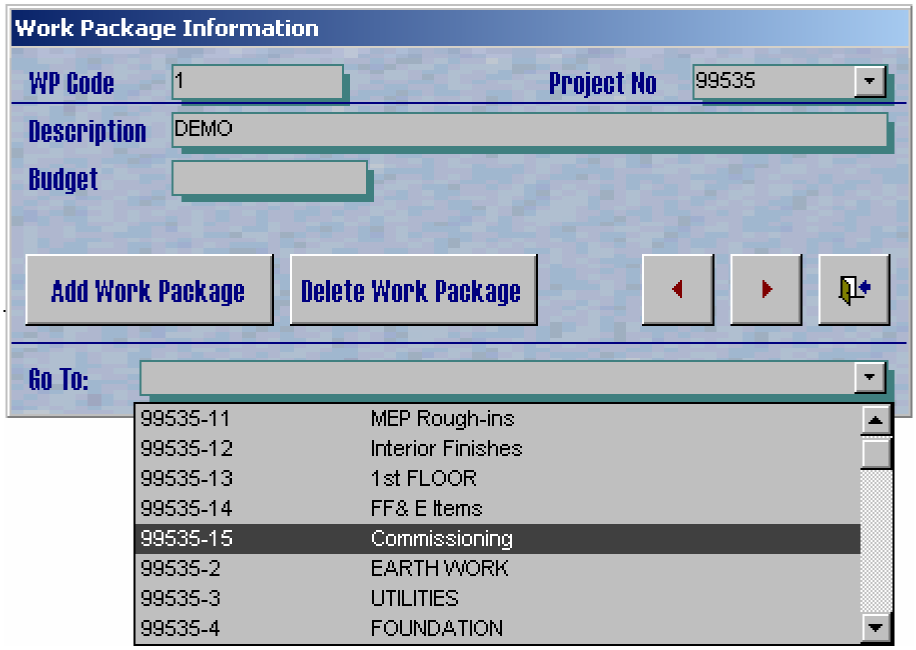


Figure 26. Work Package Information

Two distinct production unit resources are managed with WorkPlan. Information about laborers can be entered using the “Labor Information screen” (Figure 27). The “ID” field is the unique key. However, the value for the “Name” field is required so that the planner can specify laborers by their name rather than their ID. The “Group” and “Position” fields are optional. The “Trades” section is used to enter all trades that a laborer is capable of performing (or skills that the laborer has) and the pay rates for performing each may differ. This information is used during the scheduling process in specifying what trade each laborer is expected to work on. This form can also be used to enter information regarding crews, rather than individuals, or specialty contractors that are working for the production unit (e.g., subcontractors). For each crew, the sum of the rates for all crew members can be used, and for each specialty contractor, their unit cost or “0” can be used depending on the contract.

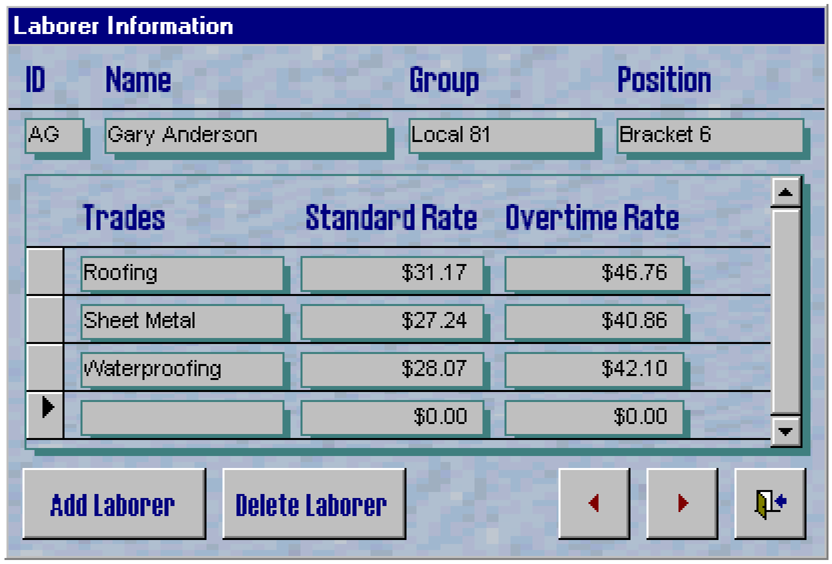


Figure 27. Laborer Information

Information about equipment can be entered using the "Equipment Information" screen (Figure 28). The "ID" field is again the unique key. The "Name" field is mandatory but other fields, such as "Power", "Weight", "Reach", "Depth", and "Bucket", are optional.

The second page of the Navigator screen (Figure 29) is used in scheduling and recording the actual progress (as-built). The "For Planning Phase" section of the screen allows the planner to schedule the work crew and equipment whereas the "For Updating Phase" section allows the planner to input the as-built schedule.

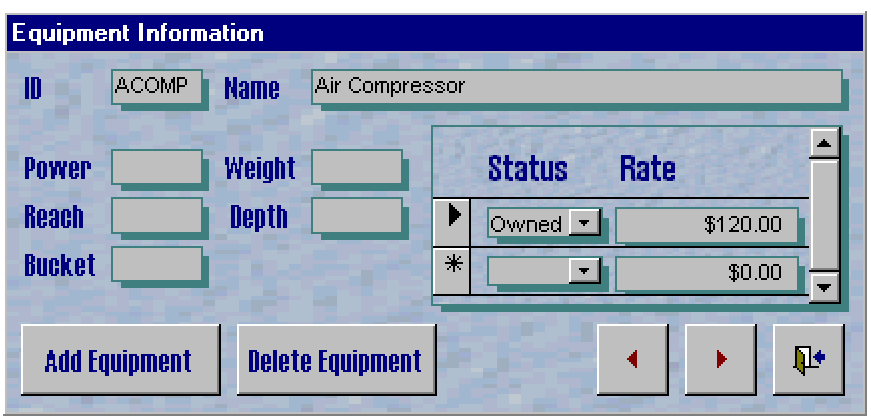


Figure 28. Equipment Information

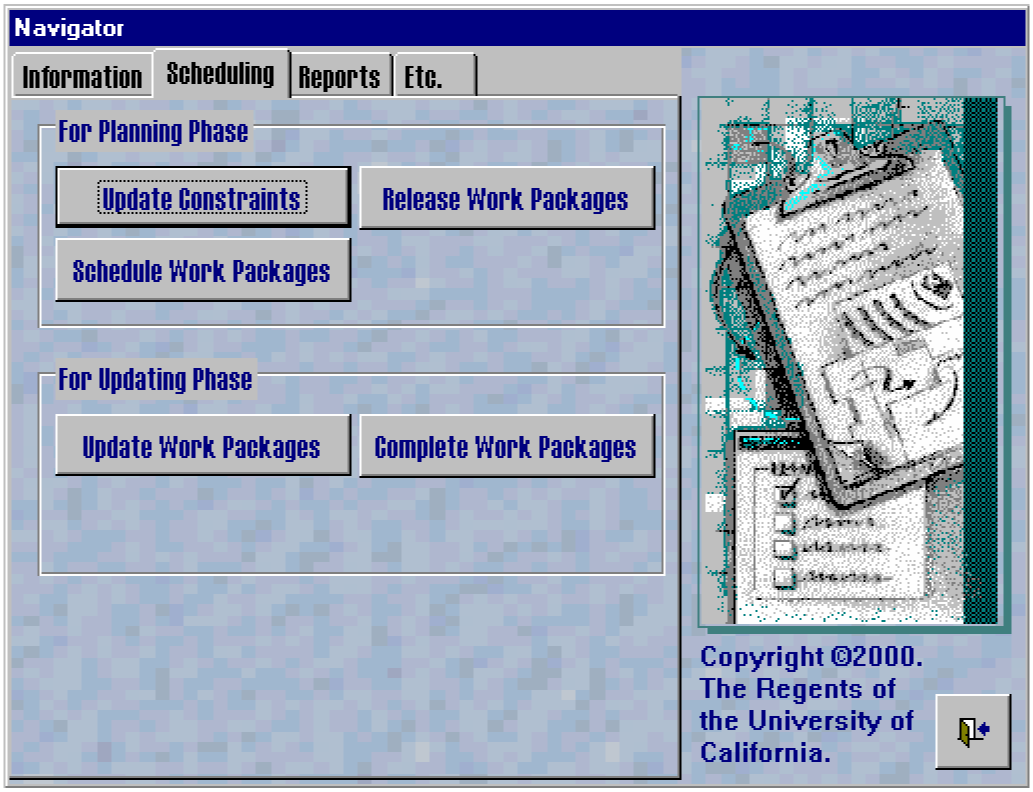


Figure 29. Navigator Screen Page 2

The planning phase starts with describing the constraints for each work package, which is part of the lookahead planning process. Constraints for each work package can be maintained using the “Work Package Constraints” form (Figure 30 or Figure 31).

Two different user interfaces have been implemented and modified as requested by beta testers (use of WorkPlan by industry practitioners is further described in Section 4.5 and in Choo and Tommelein (2001)). The first implementation (Figure 30) allows the planner to see constraints belonging to each work package. A project engineer who thought that seeing too many constraints at once actually was confusing favored this implementation. The second implementation (Figure 31) allows the planner to see constraints across all work packages. A project manager who preferred to see relationships between all constraints favored the second implementation. Both implementations proved to have merits and demerits. Therefore, including both implementations proved to best in terms of serving the needs of a broad range of planners.

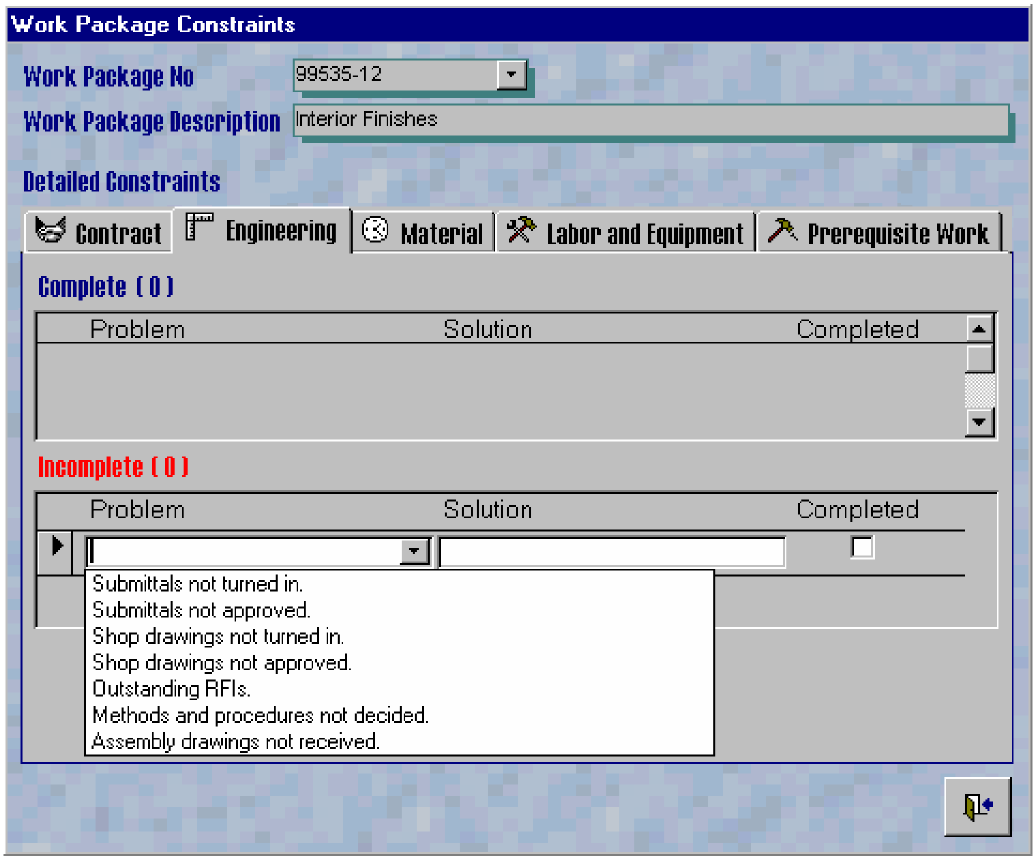


Figure 30. Work Package Constraints Implementation I

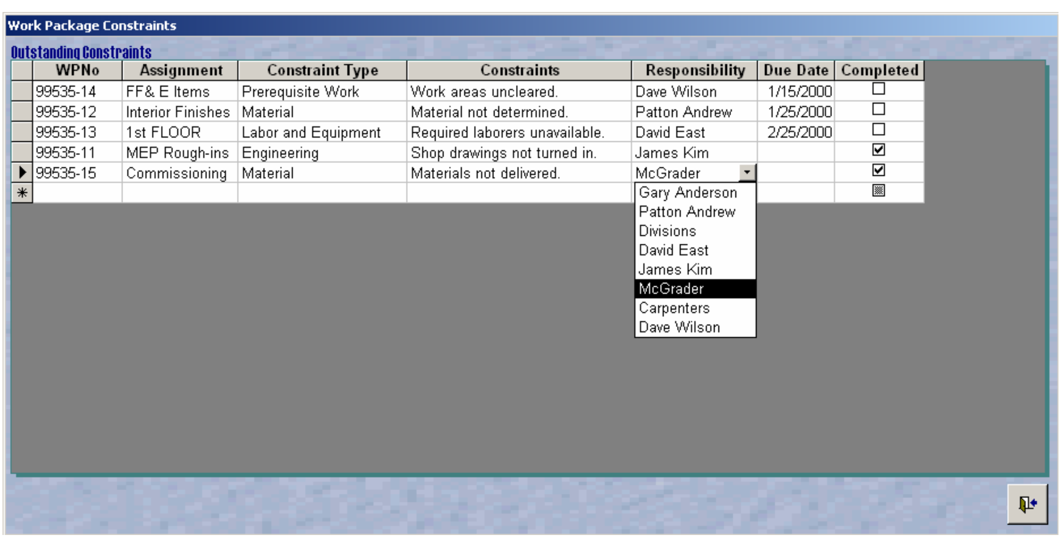


Figure 31. Work Package Constraints Implementation II

In both implementations, constraints can be categorized in one of five categories. Each category contains a preloaded set of general constraints that appear to occur on projects over and over again. These categories of constraints and preloaded examples are:

1. Contract
   - Is this work package in the contract? Is it the result of a newly-issued change order?
   - Has all coordination information been confirmed?
   - Has the subcontract been issued?
2. Engineering
   - Have all submittals been turned in? Have all submittals been approved?
   - Have all shop drawings been turned in? Have they all been approved?
   - Are there any outstanding requests for information (RFIs)?
   - Have all methods and procedures been decided?
   - Have assembly drawings been received?
3. Materials
   - Have all fabrication drawings been produced?
   - Have all material requirements and sources for procurement been established?
   - Have all requests for quotation (RFQs) been sent?
   - Have all materials been purchased?
   - Have all materials been fabricated?
   - Have all materials been delivered?
   - Have all the materials been allocated?

4. Labor and equipment

- ♦ Has the work package been scheduled?
- ♦ Are the required laborers available for the duration of the work?
- ♦ Is the required equipment available for the duration of the work?

5. Prerequisite work

- ♦ Has all prerequisite physical work been completed?
- ♦ Have all work areas been cleared so that the work package can begin?

The constraints may be selected from this preloaded list or be written in by the Last Planner if they are not yet included or other wording is found to be more appropriate.

At the bottom of this screen are constraints that are still outstanding; at the top those that have been solved. Once an outstanding constraint has been solved (checked), it automatically moves up to the top. Solved constraints are not deleted from the database even though they require no further attention. Keeping them serves two purposes, i.e., (1) it confirms these constraints have been attended to, and (2) solved constraints can be used to construct a knowledge base of constraints to help anticipate problems with similar work in case of change orders or in the future on other projects.

Once all constraints for a work package are satisfied or are expected to be met by the time the actual work starts, the work package can be released for construction. Released work packages by default are considered "workable backlog," which are "assignments that have met all quality criteria, except that some must yet satisfy the sequence criterion by prior execution of prerequisite work already scheduled" (Lean Construction Institute 2000). In WorkPlan, only released work packages can be scheduled to appear in weekly work plans. 'Unreleased' work packages are prevented from being scheduled. If execution of a released work is expected to cause difficulties or rework downstream, it should not be scheduled weekly work plan.

The releasing can be done using the “Work Package Release” screen (Figure 32). It lists ‘unreleased’ work packages at the top of the screen and released work packages at the bottom of the same screen. By pressing the down-arrow button, an ‘unreleased’ work package can be released; by pressing the up-arrow, a released work package can be ‘unreleased.’ There is no strict rule that prevents a work package from being released even though there may still be outstanding constraints. Release is allowed because it should be possible to schedule work with outstanding constraints as long as these constraints are expected to be met by the time the actual work starts. The nature of planning is such that it is done ahead of execution, so there will always be a need to forecast, and correspondingly, uncertainty exists as to whether or not the forecast will prove to be correct. ‘Unreleasing’ should occur in circumstances whenever the conditions assumed in release are determined to be unavailable, for example if a previously unidentified constraint crops up at the last minute or if a constraint is not satisfied to the extent it was anticipated.

The work packages in the workable backlog can be selectively resource loaded to create weekly work plans. Creating the weekly work plan starts by selecting a week to be scheduled using the “Scheduling Week” screen (Figure 33). Clicking any day of the week will result in that same week.

Two different resource-loading schemes have been implemented, i.e., a two-step (Figure 34 and Figure 35) vs. a one-step scheme (Figure 36). In the two-step implementation, a work package to be scheduled is first selected using the “Schedule

Work Packages" screen (Figure 34). The work packages that have been released but remain to be scheduled are listed on the left side in this screen. The right side of the screen lists work packages that have been scheduled.

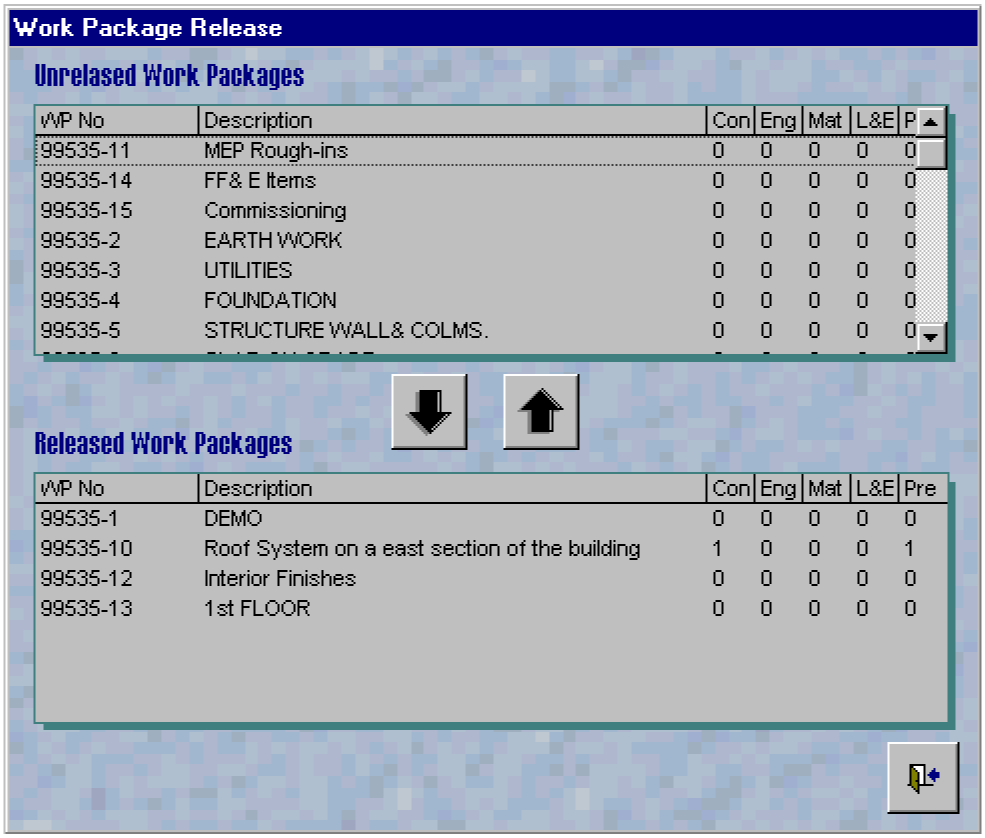


Figure 32. Work Package Release

In WorkPlan, a resource's day can be shared across multiple work packages. The ability to check for over-allocation is therefore required. Every time a work package is scheduled, WorkPlan checks the total number of hours committed for each resource across all work packages of all projects. It notifies the Last Planner in the "Assignment Conflict" section if any resource is assigned for more than eight hours per day, which is assumed to be a full working day. If overtime is intended, then WorkPlan will apply the corresponding hourly charges. If overtime is the result of oversight, the Last Planner must revisit the work packages involved and reassign resources to balance them more evenly.

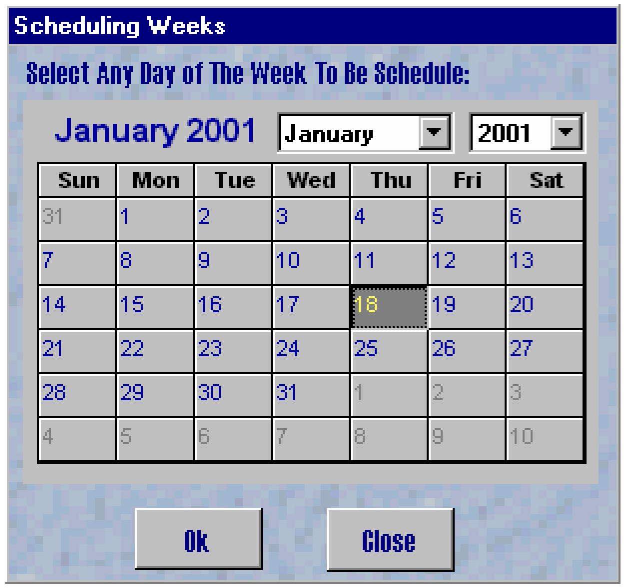


Figure 33. Scheduling Week Selection

The "Resource Assignment" screen (Figure 35) allows the Last Planner to explicitly assign resources to a released work package. As shown in this screen capture, the names of laborers and equipment to be assigned to a specific work package are selected from a drop-down list using data stored in the database. The hours represent the time each resource will work on the specific work package. Laborers and equipment can be shared among multiple work packages in a day by dividing their workday into multiple work packages. No differentiation is made between working on multiple work packages in a day sequentially or simultaneously.

Studies have confirmed that multitasking is less efficient than working on a single job (Arbulu and Tommelein 2002). However, it cannot be prevented in some cases, e.g., foremen overseeing multiple work packages, very specialized laborer (welder, riveter, etc.), and intermittently used shared equipment (elevators, cranes, etc.).

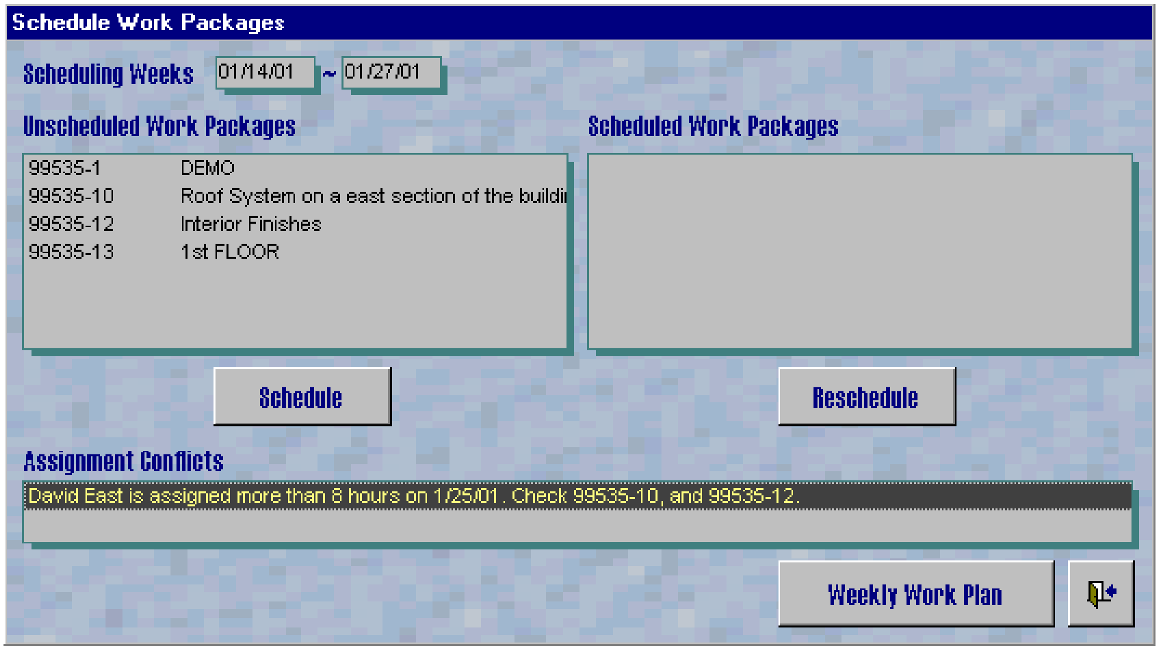


Figure 34. Schedule Work Packages Type I

"Remaining work" is used by the Last Planner to estimate the total cost of the work package based on the expected unit cost and quantity of work that is left to be done. Every time the schedule is modified, the Last Planner has the option of updating the estimate of the remaining work. This information is not automatically generated within the database. It is based on the Last Planner's estimate, which is in turn based on the amount of work remaining. By estimating the total cost of each work package, a realistic target cost can be set. In WorkPlan, this target cost is not compared with budget for this work package as this comparison does not realistically provide status of the work. Budgets for work packages are not developed based on specific resource assignments. They are usually based on industry or company average resource assignments. While aggregate of these budgets might allow the financiers to plan ahead for cash flow, it does not provide Last Planners with an accurate picture of the status of each work package.

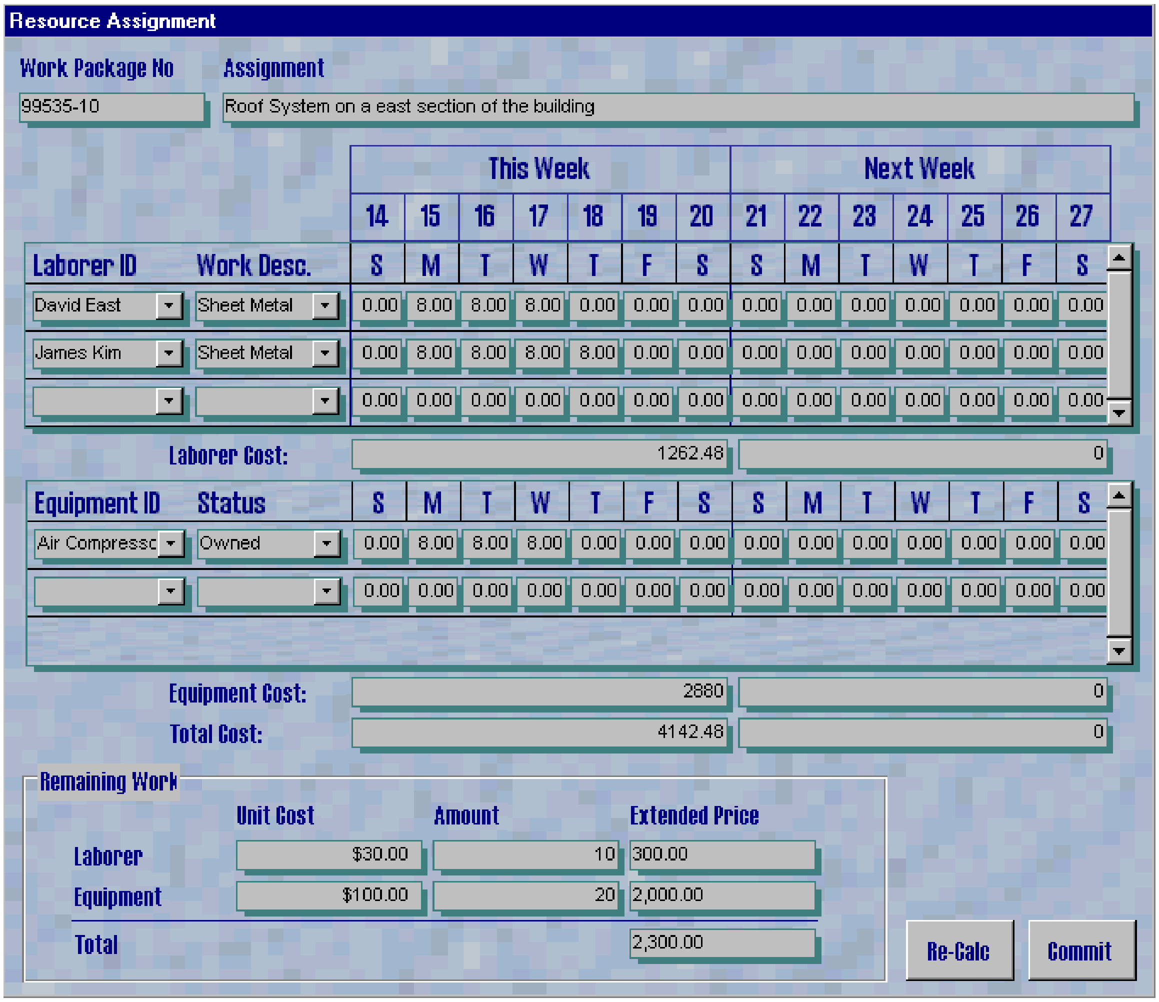


Figure 35. Resource Assignment

In the one-step implementation, the selection of a work package and resource assignment is done using a single screen (Figure 36). This implementation allows the planner to see all resource assignments regardless of the project or work package to which they belong. Thus, it truly provides a view of a job-shop schedule.

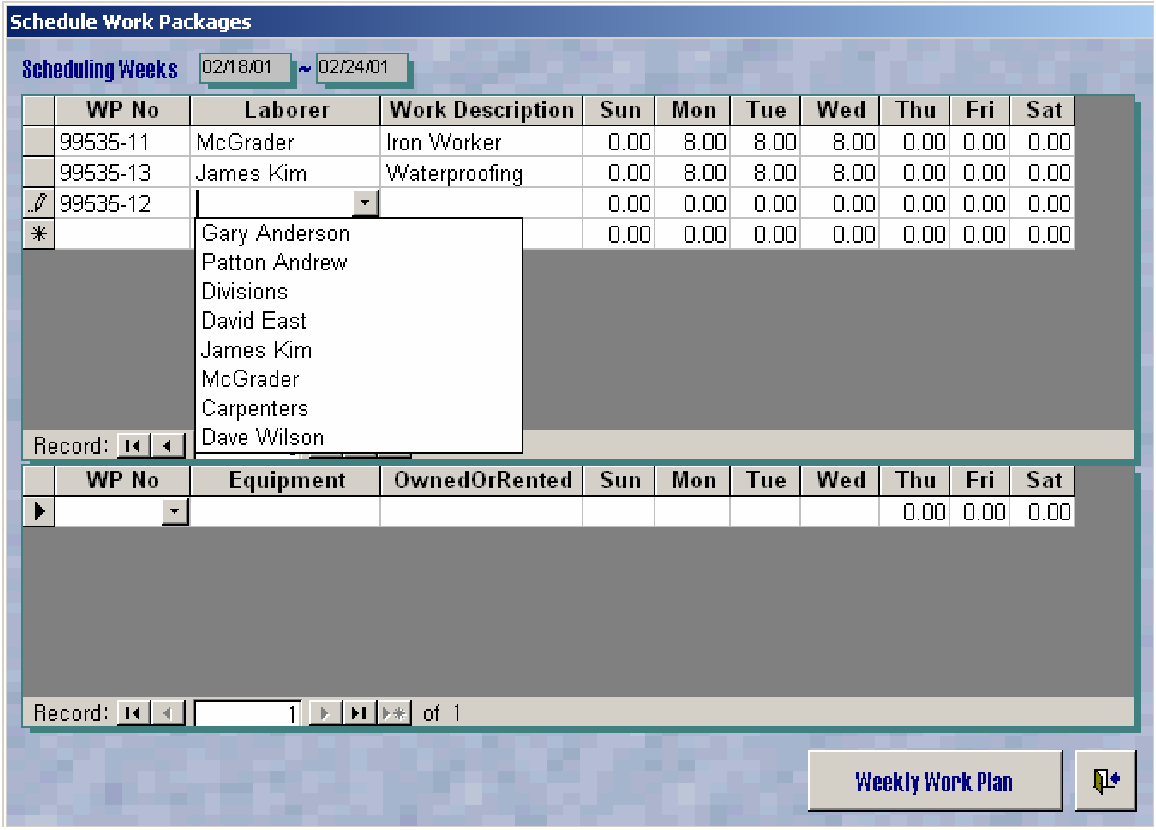
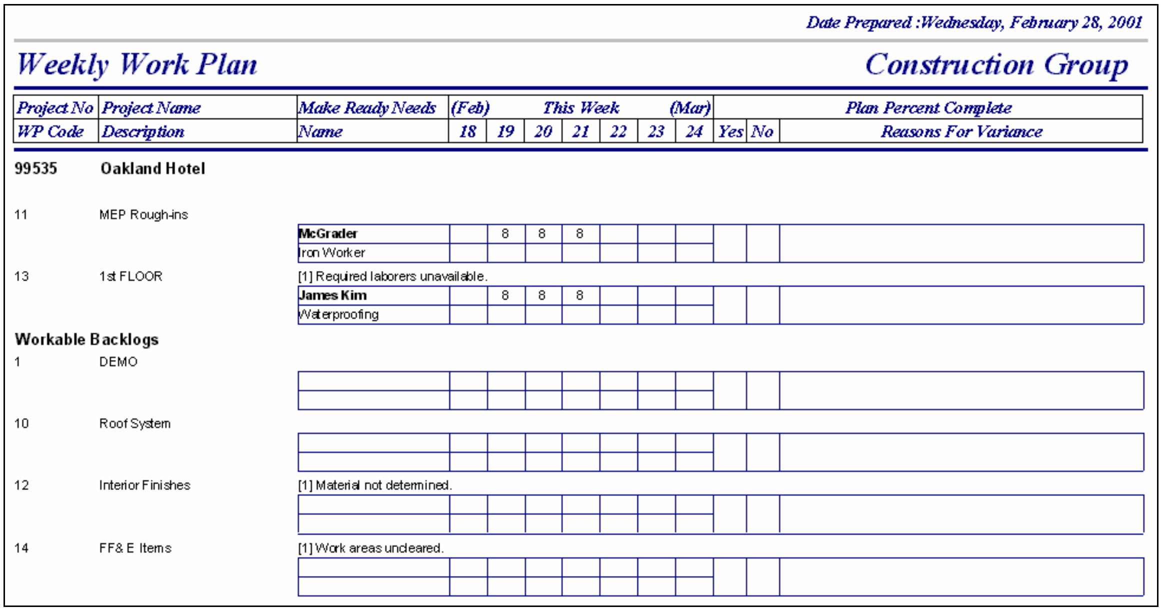


Figure 36. Schedule Work Packages Type II

In either the one- or two-step implementation, the resource assignments can then be printed in the format of a weekly work plan (Figure 37). This consists of two parts, the top part shows the scheduled work packages and the bottom part shows the workable backlog. The workable backlog serves as a guideline for field crew in selecting replacement work when scheduled work cannot be performed for any reason. This plan can be developed by a crew foreman, then printed out and handed to the field crew. Once a work package has been completed, the crew is expected to fill out the actual number of hours they worked on each specific work package for reporting purposes. They must check whether or not the work package was completed as planned, and if not, provide reasons for variance. This data is then entered into the computer to calculate the PPC and create a detailed reasons report (explain later).



Date Prepared :Wednesday, February 28, 2001

Weekly Work Plan — **Construction Group**

Project No / WP Code	Project Name / Description	Make Ready Needs / Name	(Feb) 18	19	20	21	22	23	(Mar) 24	Yes	No	Plan Percent Complete / Reasons For Variance
99535	Oakland Hotel											
11	MEP Rough-ins	McGrader / Iron Worker		8	8	8						
13	1st FLOOR	[1] Required laborers unavailable. James Kim / Waterproofing		8	8	8						
Workable Backlogs												
1	DEMO											
10	Roof System											
12	Interior Finishes	[1] Material not determined.										
14	FF& E Items	[1] Work areas uncleared.										

Figure 37. Sample Weekly Work Plan

After execution of a weekly work plan, that is, at the end of the week, "**how** each work package was done" and reasons for variance (the difference between "**what** was **listed** to be done within a week" and "**what** was **actually** done within that week") are input, if there are any. WorkPlan uses the "how" data to create timesheets and the "what" data to create the PPC Report that represents the reliability of the current planning system (explained in detail later). PPC is calculated by dividing the number of completed assignments by the total number of assignments each week (Ballard and Howell 1997). This recording procedure was created to allow for learning. It starts by selecting the week to be updated using "Updating Week" screen (Figure 38). As done in "scheduling week", clicking any day of the week will result in the same week.

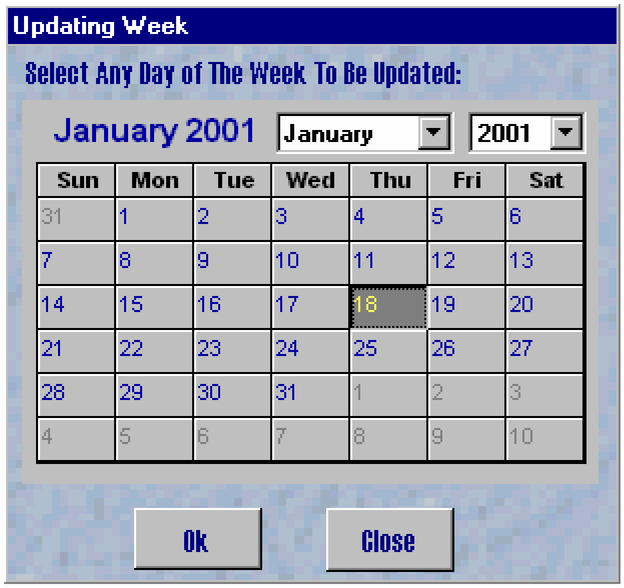


Figure 38. Updating Week

The work packages to be updated (to record what actually happened) are selected using the "Update Work Packages" screen (Figure 39). The work package that had been scheduled is shown on the left list and the workable backlog in the right list. The workable backlog is provided just in case the crew worked on another work package than the one scheduled or performed additional work because (1) they could not start a scheduled work package(s), or (2) they finished all scheduled work in a shorter time than was anticipated.

After selecting a work package to be updated, the planner can enter the actual resource usage using the "Resource Assignment Update" screen (Figure 40). The screen represents "scheduled" work at the left side and allows for user input of the actual schedule at the right side. The default value of the right side is "as scheduled". Changes can be made by selecting resources from the drop-down list and typing the number of hours worked. The update can be used to generate timesheets (shown later), if needed for accounting purposes. Tracking this information provides the basis for the cost calculation and, more importantly, allows for measurement of the reliability of the current scheduling system. Here again, the Last Planner has the option to update the estimate of remaining work.

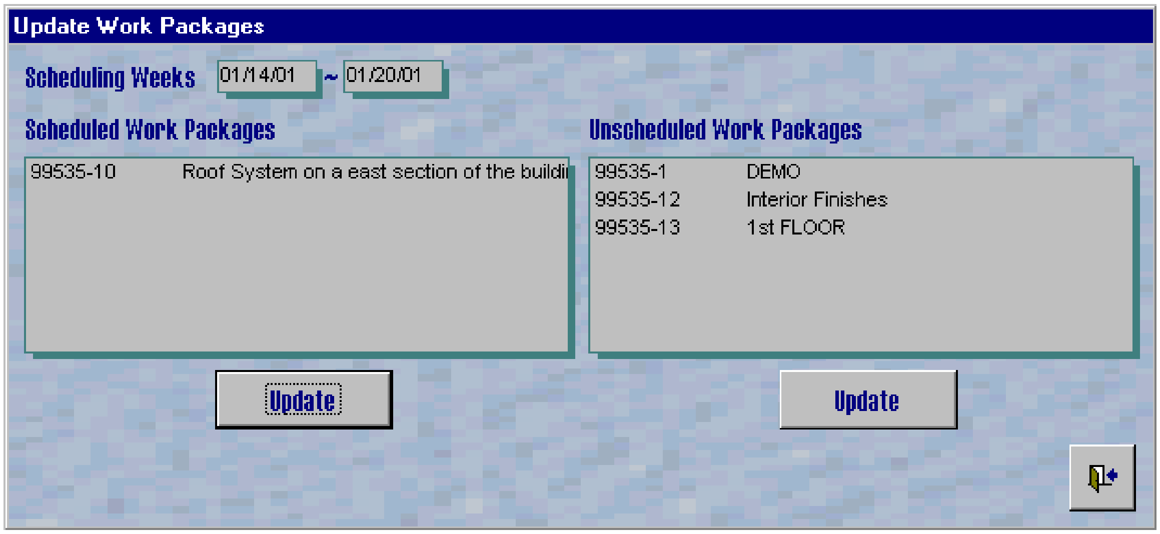


Figure 39. Update Work Packages

In order to finish updating the work package, the Last Planner has to answer the question "Was this week's work for [Work Package No] completed as scheduled?" If the answer is "Yes", the process is finished. If the answer is "No", the "Reasons for Incompletion" screen (Figure 41) will appear. As long as the scheduled work is completed within the week that it was scheduled for, the answer is "Yes", even if it wasn't completed exactly as scheduled. This allows each production unit to have the flexibility to resolve uncertainties that arise during the week. This flexibility suggests that the hand-offs between production units are managed on a weekly basis. However, this flexibility may not be ideal if it generates uncertainty for other production units that are closely related by predecessor/successor relationship or resource dependency.

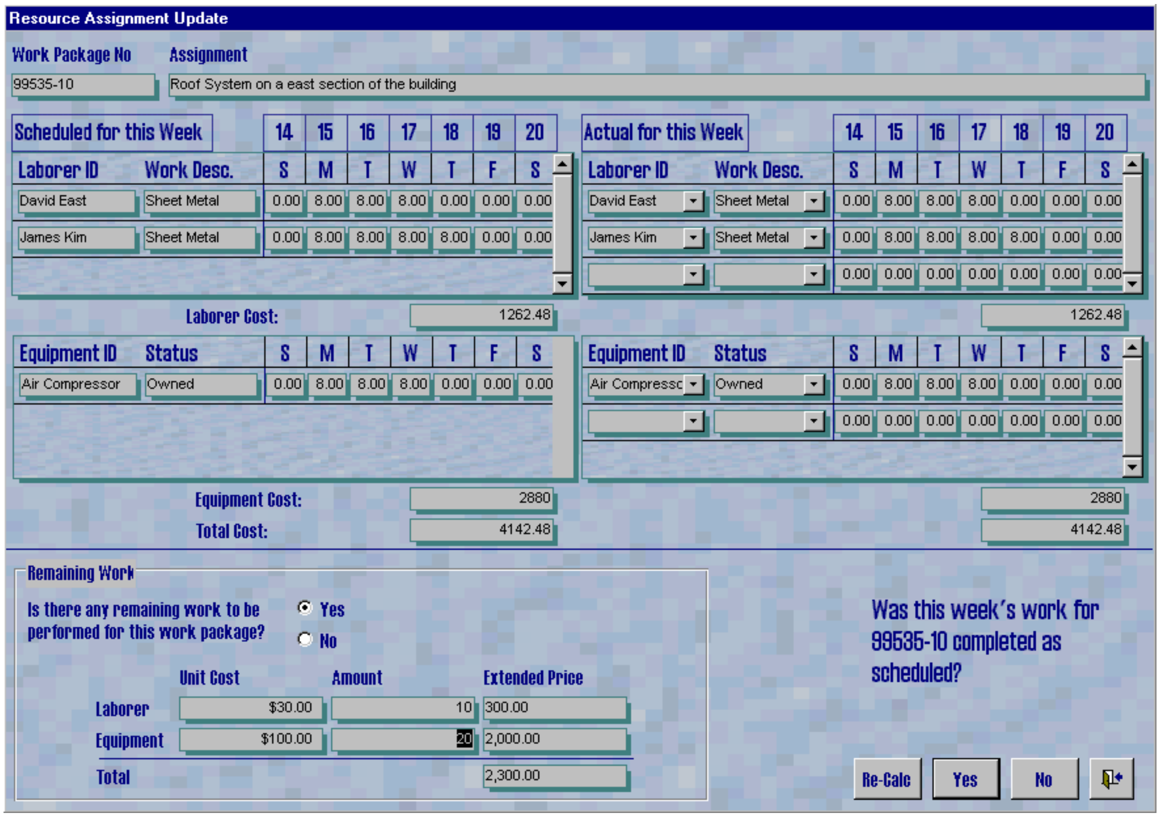


Figure 40. Resource Assignment Update

The "Reasons for Incompletion" screen allows the planner to enter the reasons for not being able to execute the work packages as scheduled. Whereas the PPC report can be used to measure the reliability of the planning system, the reasons provide insight and direction into how to improve the planning system. The planner should try to describe the root cause of the reason rather than simply describing what might be a superficial reason. Acting on superficial reasons does not necessarily guarantee that the same failure will not happen again. Only eradication of root causes will prevent the same failure from happening again. 5 Why's (asking 5 times in a row to get to the root cause) is a continuous improvement technique that can be used to reveal the root cause for failure (Ohno 1988, Womack et al. 1990).

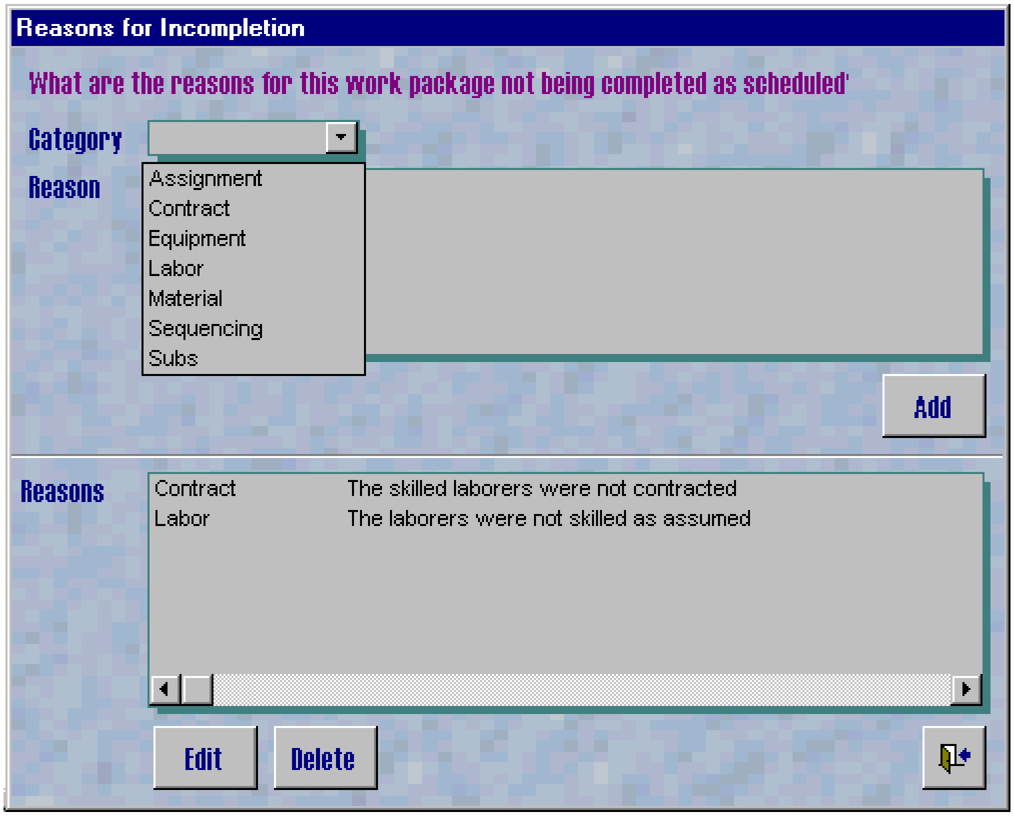


Figure 41. Reasons for Incompletion

The third page of the Navigator screen (Figure 42) is used to generate reports from the data in WorkPlan. All reports WorkPlan can generate (except the Weekly Work Plan) can be generated using this screen. Clicking any report button opens up the “Report Manager” screen (Figure 43). Reports belong to one of two categories. The “Project Listing”, “Work Package Listing”, “Laborer Listing”, “Equipment Listing”, and “Trades Report” allow the planner to generate reports on information, as they exist in WorkPlan. The “Constraint Analysis Report”, “Timesheet”, “PPC Report”, and “Detailed Reasons Report” are reports of schedule-related information.

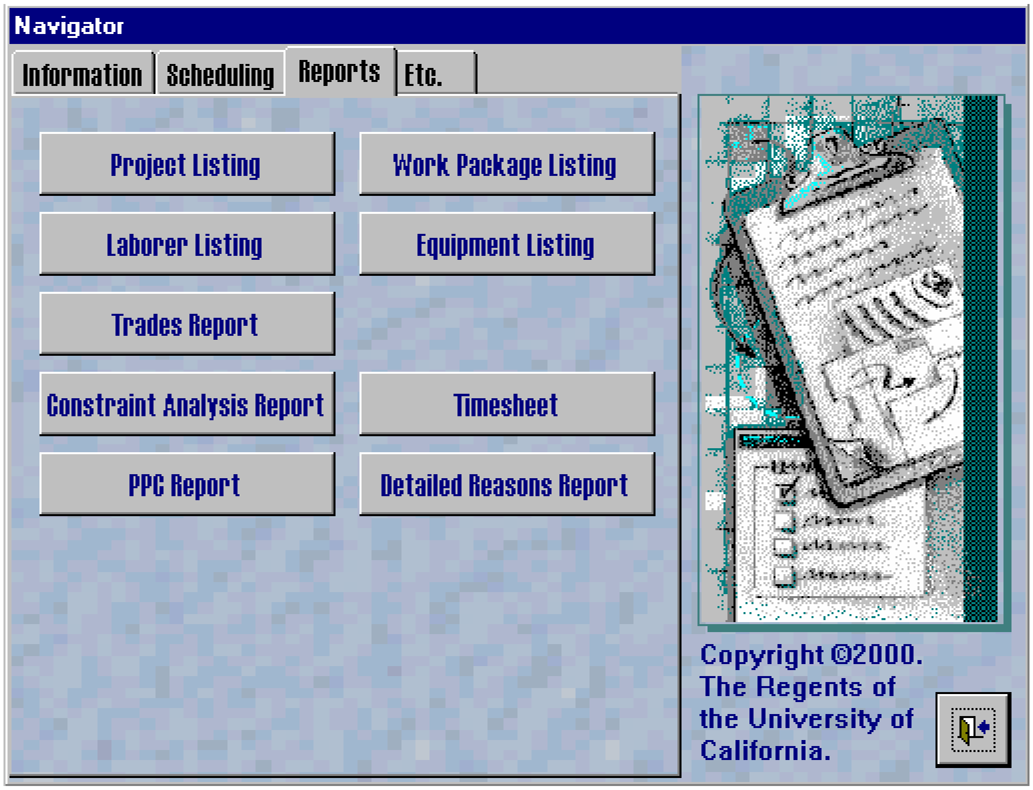


Figure 42. Navigator Screen Page 3

The report manager allows the planner to (1) preview a report, (2) e-mail a report, (3) print a report, and (4) export a report in rich text (.rtf), as a snapshot, Microsoft Excel (Microsoft 2000b) (.xls), HTML (.htm), and MS-DOS text (.txt) format. The exporting function allows the report to not only function as a static report but also as a means for passing information to other programs or other company or project personnel.

The "Project Listing", "Work Package Listing", "Laborer Listing", and "Equipment Listing" (screen shots not provided) reports describe information entered using the "Navigator" page 1 (Figure 24). The "Trades" report (Figure 44) allows the planner to see what laborers can perform a given trade at what cost. This information is valuable when the Last Planner needs to trade off

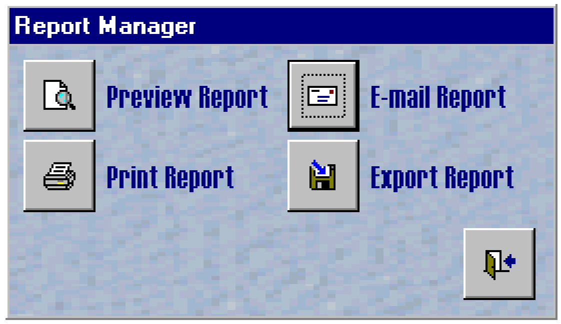


Figure 43. Report Manager

Date Prepared : Thursday, March 01, 2001

Trades

Trades	ID	Name	Standard Rate	Overtime Rate
Carpenter				
	NLB	NLB	$0.00	$0.00
Earthwork				
	Div2	Division 2	$0.00	$0.00
Iron Worker				
	Mcg	McGrath	$0.00	$0.00
Roofing				
	AG	Gary Anderson	$31.17	$46.76
	ED	David East	$44.66	$66.99
	KJ	James Kim	$14.51	$21.76
	WD	Dave Wilson	$44.66	$66.99
Sheet Metal				
	AG	Gary Anderson	$27.24	$40.86
	ED	David East	$37.35	$56.03
	KJ	James Kim	$11.44	$17.16
	WD	Dave Wilson	$37.35	$56.03

Figure 44. Trades Report

The “Constraint Analysis Report” (Figure 45) allows the Last Planner to pass the constraint information to other project participants in a hardcopy or electronic format. As satisfying constraints is a very important procedure in making work packages ready, the ability to pass constraint analysis information to related participants is very important.

Date Prepared : Thursday, March 01, 2001

Constraint Analysis Report

Due Date	WP No	Responsibility	Assignment	Type	Problem	Complete
1/15/00	99535-14	Dave Wilson	FF& E Items	Prerequisite Work	Work areas uncleared.	☐
1/25/00	99535-12	NLB	Interior Finishes	Material	Material not determined.	☐
2/25/00	99535-13	David East	1st FLOOR	Labor and Equipment	Required laborers unavailable.	☐

Figure 45. Constraint Analysis Report

The updated schedule information can be used to generate a "Timesheet" report (Figure 46). WorkPlan automatically groups the actual work completed by each laborer and calculates the total direct cost for each work package.

Date Prepared : Monday, July 13, 1998

Timesheet

Laborer Name	Work Desc.	WP No								
Gilbert Atlas										
	Sheet Metal									
		97-309-C-1000	$968.24							
			06/28	06/29	06/30	07/01	07/02	07/03	07/04	
						4.5	8	5.5	8	
	Waterproofing									
		97-309-C-110	$609.12							
			06/28	06/29	06/30	07/01	07/02	07/03	07/04	
				8	8					

Figure 46. Timesheet Report

The information collected during the schedule updating process is used to generate the "PPC with Reasons" report (Figure 47) and the "Detailed Reasons Report" (Figure 48). The "PPC with Reasons" report shows PPC computed on a weekly basis for the last seven weeks. The vertical axis on the left shows the PPC computed on a weekly basis. The solid line in the graph represents PPC. The axis on the right depicts the number of occurrences of reasons for each category. The bars in the graph correspond to the number of occurrences for each category as listed. The "Detailed Reasons Report" with occurrences in the PPC chart can help decide where to focus management attention in order to improve the reliability of the planning system.

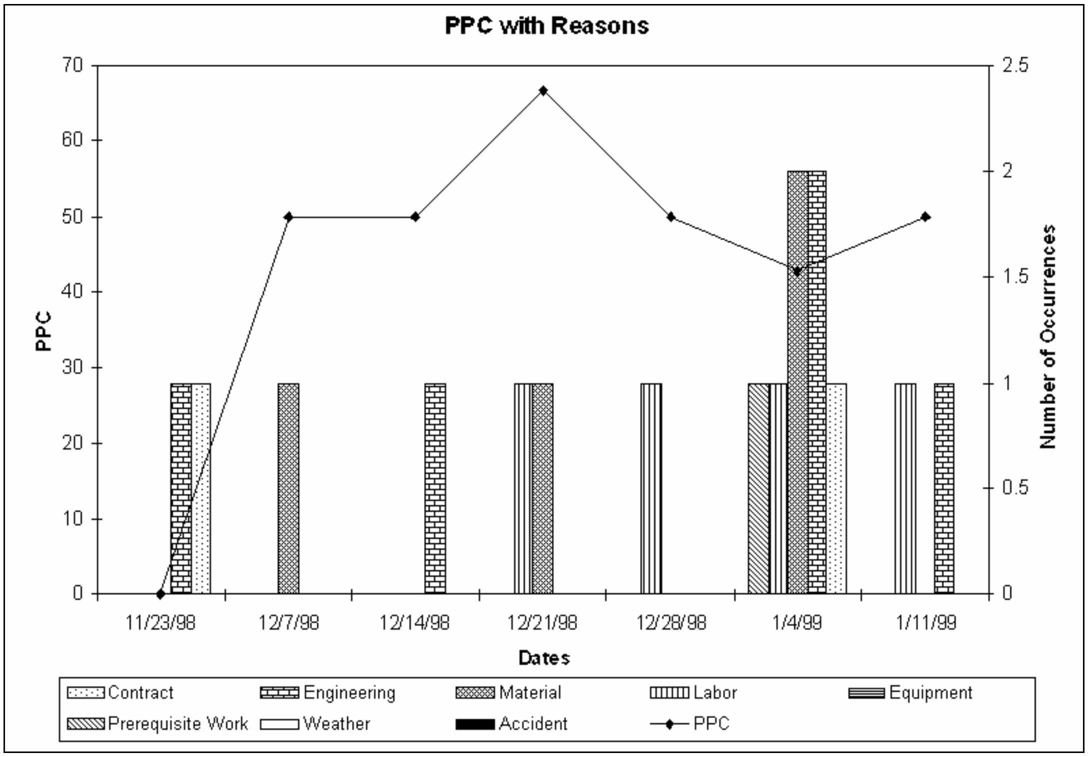


Figure 47. PPC with Reasons Report

Detailed Reasons Report

Category	*Assignment Date*	*Work Package No*	*Reason*
Assignment			
	7/30/00	99535-10	Assignment too big.
Contract			
	1/14/01	99535-10	The skilled laborers were not contracted
	1/21/01	99535-10	East didn't have a contract
Equipment			
	7/30/00	99535-10	Didn't have the equipment.
	12/3/00	99535-1	Not available
Labor			
	7/23/00	99535-12	Wasn't productive as assumed.

Figure 48. Detailed Reasons Report

The fourth page of the Navigator screen (Figure 49) is used to change options for WorkPlan and to migrate data to a newer version of WorkPlan.

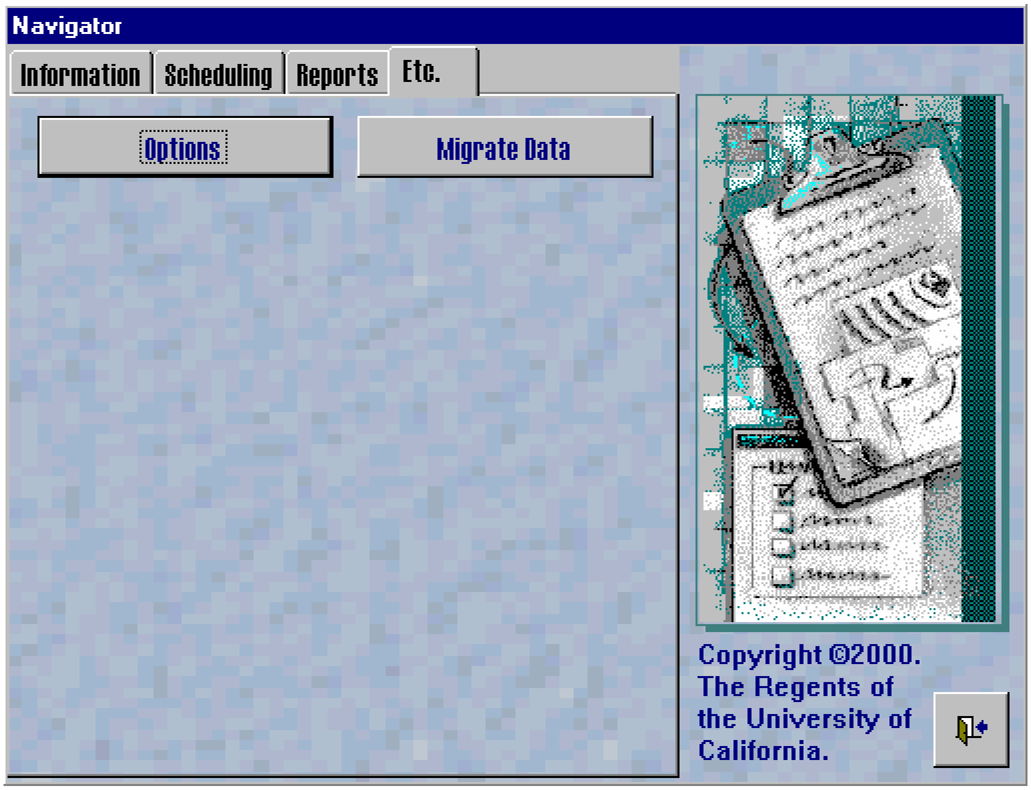


Figure 49. Navigator Screen Page 4

In its present implementation, WorkPlan does not treat materials as a separate resource to be allocated, though material availability can be modeled as a constraint. This omission is intentional. A research project conducted concurrently with the research on WorkPlan has resulted in the development of a tool, named CADSaPPlan (Computer Aided Design, Sourcing, and Procurement Planning) (Sadonio 1998, Sadonio et al. 1998), to manage data pertaining to the materials supply chain. CADSaPPlan provides access to procurement information during design so that the design solutions can be developed that optimize construction costs, duration, and quality, and reduce their uncertainty.

4.4 DEPLAN

DePlan is developed for managing a production unit working in a service-sector setting, usually a designer with a team of design and engineering specialists.

4.4.1 Design of DePlan

DePlan (Hammond et al. 2000, Choo et al 2001) assists planners in planning, scheduling, and controlling the design process according to the LPS. The term "planning" refers to determining the required activities to meet the design goal, the relationships between activities, and an optimal sequencing for these activities. The term "scheduling" refers to assessing the status of activity readiness to be performed, assigning resources, and determining the start time, duration, and completion time for each of the activities. The term "controlling" refers to assessing the status of activities after completion of work, and calculating resource use in terms of time and cost. Unlike the traditional meaning of control, control as specified here also encompasses the make-ready process (Ballard and Howell 1994a, 1994b), i.e., figuring out what needs to be done and attend to those needs to make activities ready to be performed.

DePlan combines an extended version of WorkPlan with ADePT (Analytical Design Planning Technique) (Austin et al. 1999a, 1999b, 1999c, 2000) (Figure 50). WorkPlan as described in the previous section was extended to enable the data exchange with ADePT. ADePT (top portion of Figure 50) improves design activity sequencing by allowing design managers to focus on the flow of information between design tasks rather than deliverable. DePlan thus combines the benefits from planning work using ADePT with scheduling and controlling work using the extended WorkPlan production management tool (bottom portion of Figure 50). The extended WorkPlan plus ADePT combination suits an integrated approach to managing the design process.

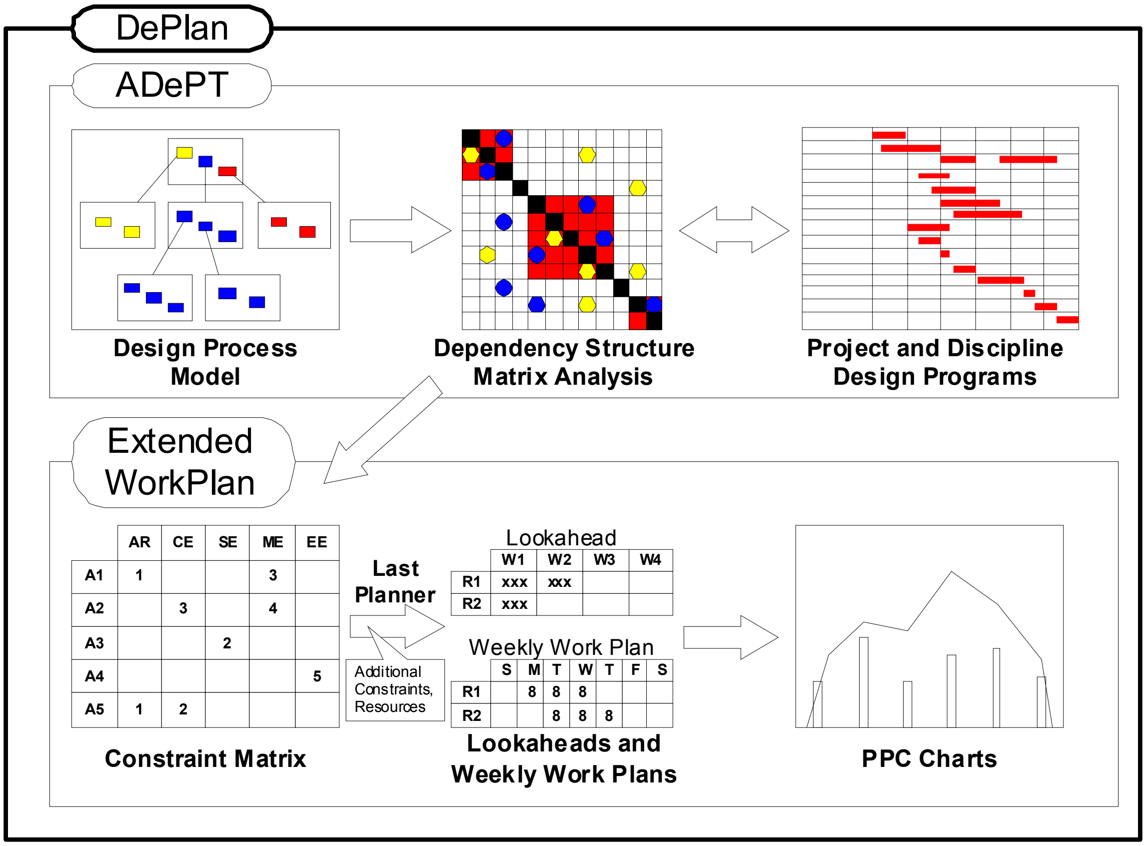


Figure 50. DePlan

Using DePlan is relatively straightforward: define the design process from a generic model and produce an integrated project plan by Dependency (Design) Structure Matrix (DSM) analysis[5]; then schedule and control the design production process using a

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5 Steward (1981) proposed that a complex problem could be divided into contributing sub-problems by using a matrix to represent interrelationships between tasks. The Dependency (Design) Structure Matrix (DSM) analysis is used in ADePT to identify

lookahead plan and weekly work plans by assigning design activities to design teams, as the required information and resources become available. Design is thus planned and managed based on the generation of information with realistic and achievable activities. The effects of change can be managed by further DSM analysis and process reliability monitored by measuring PPC.

The input design model for ADePT (and thus for DePlan) was developed based on UK industry practices; a similar model would have to be created based on US industry. Data generated from the extended WorkPlan tool will facilitate the creation of this model because it will reflect US practices by means of a description of activities and the relationships between them. Nevertheless, developing a sufficiently generic design model for use on a multitude of projects, does require a substantial amount of additional work and this is beyond the scope of the present PhD research.

4.4.2 Implementation of DePlan

ADePT and extended WorkPlan were each developed by and are being improved by students and faculty at educational institutions that are geographically distant. Therefore, an ASCII file format rather than a dynamic link was chosen as the interface mechanism between the two programs.

Extended WorkPlan allows the Last Planner to generate project data from the start but is also capable of importing the ADePT output matrix (Figure 51), i.e., the list of

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iterations within the design process and their relationships with tasks in the rest of the matrix.

activities, the responsible disciplines for each activity, and the informational dependencies.

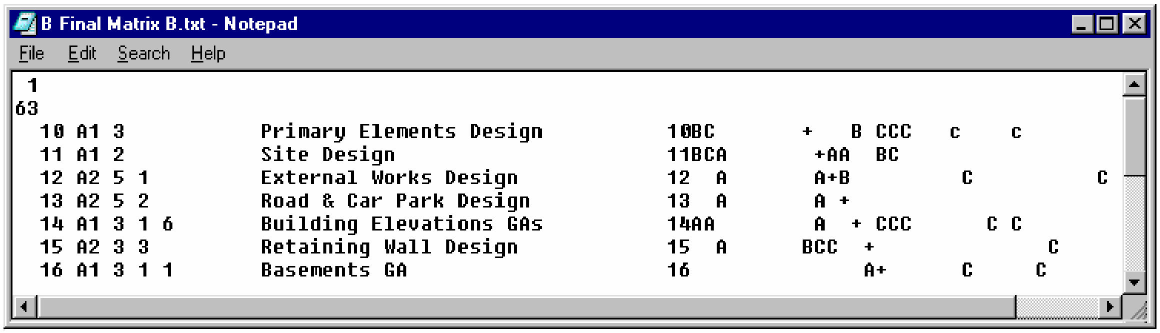
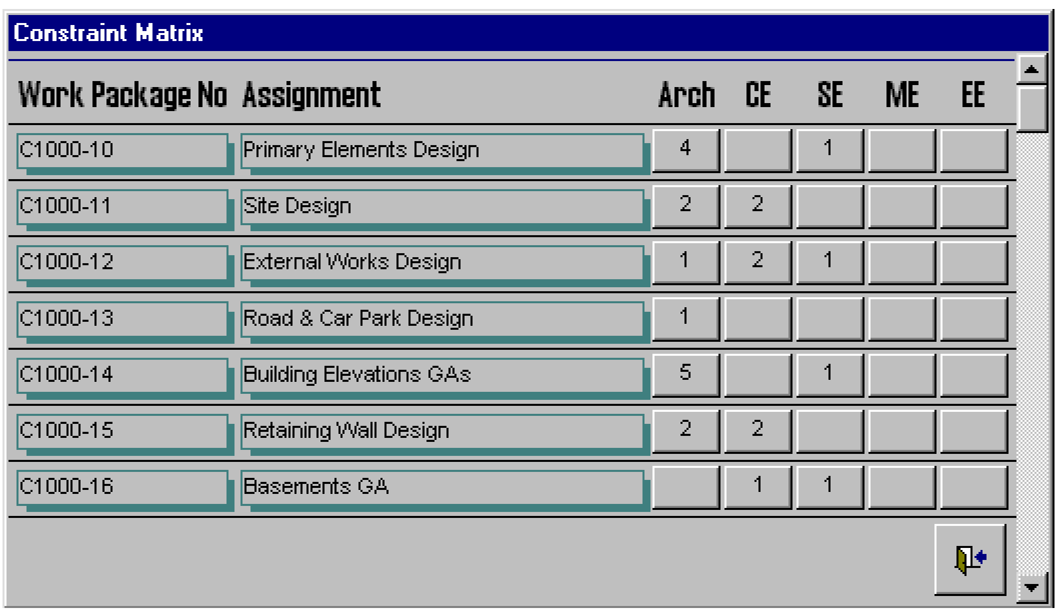


Figure 51. Sample Output Matrix Generated from ADePT

The imported information is then automatically restructured to generate the constraint matrix (Figure 52).



Work Package No	Assignment	Arch	CE	SE	ME	EE
C1000-10	Primary Elements Design	4		1		
C1000-11	Site Design	2	2			
C1000-12	External Works Design	1	2	1		
C1000-13	Road & Car Park Design	1				
C1000-14	Building Elevations GAs	5		1		
C1000-15	Retaining Wall Design	2	2			
C1000-16	Basements GA		1	1		

Figure 52. Constraint Matrix based on Figure 51

Each design activity corresponds to a work package in extended WorkPlan. The constraint matrix shows the number of design activities that belong to each responsible discipline. Completion of these activities will satisfy the informational constraints that need to be met in order for each activity to be carried out successfully. By categorizing constraints by discipline, the Last Planner can determine which discipline is most critical to the release of design activities. By clicking on any numbered cell in the matrix, details of the corresponding number of constraints can be seen. For example, the detailed description for "1" in the civil engineering discipline (CE) for work package C1000-16 can be seen by clicking that number. Figure 53 shows two sections of constraints.

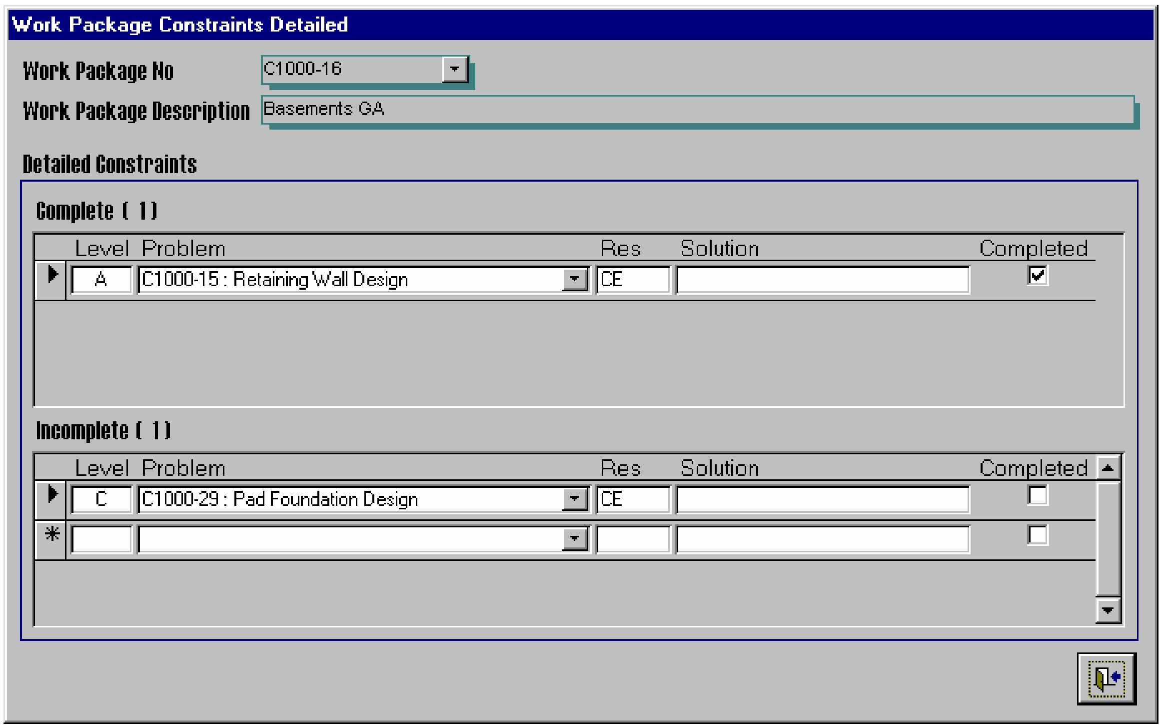


Figure 53. Detailed Design Constraints for C1000-16

The top section refers to the constraints that have been met and the bottom section refers to the constraints that have not yet been met. The number "1" corresponds to the number of filled-out rows in the bottom section of the screen, where each row represents a constraint that remains to be met. The top section, which represents the constraints that have been met, enables the Last Planner to keep track of what constraints have been satisfied. Thus, the Last Planner is able to track what needs to be done but also what was done. This is valuable if the Last Planner needs to recheck the constraints due to unforeseen changes that may occur to design activities.

In addition to constraints imported from ADePT, the planner can also add additional constraints when they are identified during project execution. These constraints are divided into five categories: (1) contract, (2) engineering, (3) samples, (4) resources, and (5) design constraints (Figure 54). Contract refers to constraints regarding contractual finalization, commercial constraints, permits, subcontracting, etc. Engineering refers to constraints from other engineering functions such as construction management and planning supervisors. Samples refer to instances where design is constrained by an agreement to provide samples or mock-ups. Resources refer to constraints regarding planning and management of resources, including designers and supporting services**.** Design Constraints are information provided by ADePT. Design Constraints for all disciplines are shown on “Work Package Constraints” screen (Figure 54). Figure 53 shows Design Constraints that belong to a single discipline where as Figure 54 shows Design Constraints that belong to all disciplines as well as other types of constraints.

When constraints for a design activity are satisfied or are expected to be satisfied at the time the activity is to start, this activity can be released for scheduling. In the scheduling phase, explicit resources such as designers and supporting services (accounting, administration, drafting department, etc.) are assigned to generate weekly work plans (Figure 55). For tracking purposes, constraints that are expected to be satisfied are automatically printed in the “make ready” section. Weekly work plans are special purpose planning that is carried out with the highest level of detail prior to carrying out the work. Ballard and Howell (1994a) refer to weekly work planning as “commitment planning” because, at this stage, the specific resource assignments need to be made so that work can actually be performed and promises are made between Last Planners regarding handoffs. The scheduling window for weekly work plans is one week.

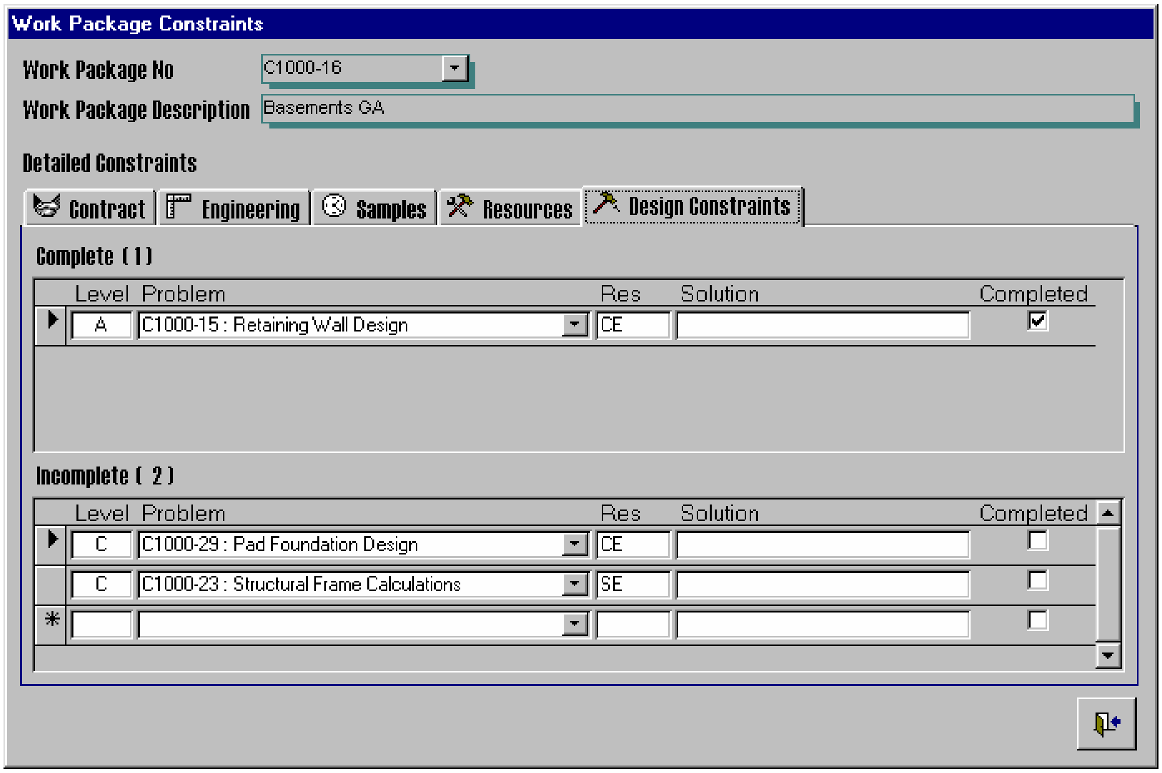


Figure 54. Detailed Constraints for C1000-16

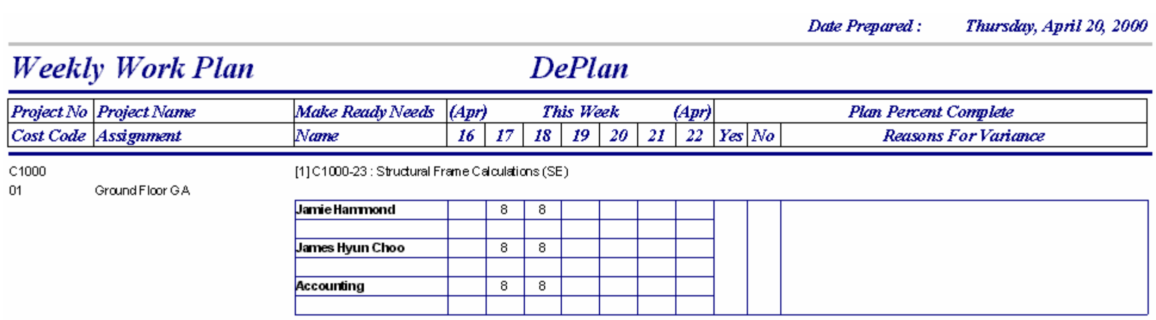


Figure 55. Weekly Work Plan Generated from Extended WorkPlan

Design activities in the weeks beyond one week are scheduled using the lookahead window (not shown). Since precisely determining which individual designers and corresponding supporting services will be assigned to each design activity one week in advance can be unreliable, the planner can denote with a simple “yes/no” whether each design activity will need to be carried out each week, irrespective of the specific assignment of resources.

The lookahead acts as an interface between the overall project schedule and the weekly work plan (production schedule). The production activities (design activities) need to be executed according to the overall project schedule since there are milestone dates (meetings, inspections, due dates, etc.) that determine the latest finish dates for certain activities. Therefore, it is important to note that the main objective of the lookahead is to determine which activities need to be carried out in which week, and to make those activities ready according to the project schedule, so that they will meet the LPS’s criteria for assignment during weekly work planning. Figure 56 is an example of a lookahead generated from extended WorkPlan.

Lookahead

		Apr.													May
WP No	Assignment	23	24	25	26	27	28	29	30	1	2	3	4	5	6
C1000-10	Primary Elements Design														
C1000-11	Site Design														
C1000-12	External Works Design		Yes	Yes	Yes	Yes	Yes								
C1000-13	Road & Car Park Design		Yes	Yes	Yes					Yes	Yes	Yes			
C1000-14	Building Elevations GAs									Yes	Yes	Yes	Yes		
C1000-15	Retaining Wall Design														
C1000-16	Basements GA														

Figure 56. Lookahead Generated from Extended WorkPlan

After each week, the Last Planners need to fill out the actual number of hours they worked on each design activity and check whether or not their assignment was completed as planned. If not, they must provide reasons for variance in order to allow for calculation of PPC and root cause analysis.

4.5 VALIDATION OF WORKPLAN AND DEPLAN

WorkPlan and DePlan were validated and assessed in terms of usability through a process of beta-testing. Beta-testers included three member companies of the Lean Construction Institute (LCI) (Pacific Contracting, Oscar J. Boldt Construction, and Gowan Inc.) and two academic institutions (Loughborough University in the U.K. and Universidad Catolica de Chile). The beta-testers took anywhere from one day to two months to become familiar with the software, use it, and then provide their assessment. The lessons learned are described below. Several findings in this validation process helped to improve WorkPlan and DePlan, but others had to be accommodated in yet another program, namely WorkMovePlan. Where this is the case, WorkMovePlan is mentioned in the following text and then described in detail in Section 6.2.

The beta-testers were familiar with the LPS, especially the part related to weekly work planning, which enabled them to make suggestions. Some of them had developed in-house spreadsheet applications to support the Last Planner process given their own specific needs. These applications did not necessarily meet all their needs but they provided a temporary solution. However, the main advantages of these spreadsheet tools were simplicity of interface and ease of use[6]. The beta-testers had wish lists expressing

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[6] For Oscar J. Boldt Construction, the use of different software also emphasized the difference between production control and scheduling. They are now turning to the integration of scheduling and production control.

additional, desired features for the software. Their feedback and recommendations on WorkPlan and DePlan ranged from suggestions regarding the addition and deletion of fields in forms and reports (sometimes to make the forms and reports resemble their own), to changing how the tools should be used or what additional capabilities they should have (implementing their own wish lists). Having understood the LPS and having been involved in creating their own tools allowed them to focus on making suggestions on how to improve the tools, rather than first needing to be convinced that is was worthwhile to adopt the Last Planner process. However, their previous knowledge of the LPS also prevented them from assessing how well this methodology was in fact embedded and enforced in WorkPlan and DePlan as the beta-tester could use the program without the process guidance embedded in the tool.

4.5.1 Feedback on Implementation

One obstacle to the adoption of WorkPlan and DePlan is the industry's reluctance and often unwillingness to change especially when it comes to buying in to the latest computer tools. "Don't fix it if it ain't broke" is an expression one often comes across when talking to people in the industry. In order for new tools to be adopted, the industry has to realize that the current planning methodology has faults, that it is broken and needs to be fixed, or replaced by a new method. New methods often require new tools.

During the development of WorkPlan, Glenn Ballard (the developer of the Last Planner concept) and Todd Zabelle of Pacific Contracting (President of a specialty contracting firm and an early implementer of the LPS) provided valuable input to the authors regarding the planning process itself as well as the functional requirements for the development of the software. As the LPS itself was (and still is) evolving during the development of WorkPlan, the software took on many different forms as well.

4.5.1.1 Work Package vs. Assignment

A key decision was made during the first implementation phase of WorkPlan regarding whether or not to adopt a "work package" as the scheduling unit. The primary reason for adopting a work package rather than a more detailed, smaller unit of work, was to prevent general contractors from micro-managing specialty contractors. The specialty contractor's concern was "if we give them too detailed a schedule, we end up creating smaller milestones for ourselves and lose the flexibility to do the job as we would like to." Although the term work package has not survived the conceptual evolution of the LPS, it is still an intricate part of WorkPlan and DePlan

A closer observation of the primary reason for adopting a work package reveals its usefulness. The weekly work planning effort to manage production units was complicated by the need to report weekly work plans to general contractors. In order to prevent micro-management, creating big enough units of work to hide detailed processes seemed reasonable. However, if a work package is too big, it does not satisfy the sizing criterion (Ballard 1997) of the LPS and it also makes managing production units less effective.

This finding led to formulating an important requirement specifically for distributed planning and coordination: the unit of work for work planning does not necessarily have to match the unit of work for reporting. However, if the units are not the same, the relationship between them must be maintained explicitly. Consequently, WorkMovePlan (which tackles distributed planning and coordination) incorporates a hierarchical work package structure.

One project manager who applied the LPS to his project identified the need for explicit links:

> "We have convinced our subcontractors to tell us what they can do rather than give us an unrealistic schedule. However, one subcontractor is right now delaying our completion date. So we informed him that he was delaying the completion date and would be charged a penalty accordingly. However, he came back and told us that he could not be held responsible because he just did what he was told, i.e., "tell us what you *can* do [according to the Last Planner concept: what is on your weekly work plan and what is your workable backlog?]."
>
> In the first week on the project, this subcontractor did not know the LPS and he submitted a schedule as usual showing what he *should* be doing, namely complete four walls in a week. He ended up completing only half of what he had said he was going to complete that week. So we sat down with him to develop the following week's weekly work plan, with an aim to increase his planning reliability (PPC). He committed to completing two walls. However, it was unclear what effect this change would have on the total project duration until last week, when we updated the master schedule. It would be great if somehow the weekly work plans were linked to the master schedule."

In discussing this case with other planners, the most common and immediate response was "The duration should have been set in the contract." This contracting mentality does not create an environment where information can be shared freely. All too often, information regarding failure to meet a schedule then is withheld until the last moment, when it is too late to respond or inform others of the delays. In some cases, the schedule in the contract is purely for contracting purposes and it is never enforced. One project engineer on a building project presented this case:

> "Completion of the building is going to be delayed by one subcontractor. They submitted a schedule to finish their portion of work within a month because that was the duration set forth by the owner's master schedule. But there is no way they can finish that work in a month. They know it and we know it. So the schedule used for contracting sits in the cabinet and we use another schedule developed by our superintendent."

Contracting is not an effective means to coordinate the work of specialty contractors. A hierarchical distributed planning system that effectively links project planning with production planning helps to effectively coordinate specialty contractors.

4.5.1.2 Modifications regarding Interfaces and Reports

One project manager provided important feedback related to the distribution of information. He requested that once constraint analysis and weekly work planning is done, WorkPlan and DePlan automatically categorize the information according to the responsible participants and then generate reports to send in electronic format or to print and hand out as hardcopies. He wanted to have an efficient way to distribute the constraints to each responsible group or participant right after the coordination meeting. Specifically, he requested that the planner be able to generate reports from the constraint list, categorized by work package and responsibility. These functionalities are available in WorkMovePlan.

Many other suggestions related to additional fields were made, such as adding a responsible participant to each work package and so on. Some suggested functions have not been implemented as either they exceeded the scope of our research or we determined them to be low in terms of implementation priority.

4.5.2 Requirements for Last Planner Tools

Based on experience in implementing and modifying WorkPlan and DePlan, several requirements for the Last Planner computer tools became clear. These requirements are:

- Effective and Uncomplicated Last Planner Procedure

  It goes without saying that the Last Planner computer tool needs to be based on comprehensive understanding and effective translation of the LPS. This methodology is based on a very different view of construction planning than the view taken by traditional construction project managers. It may take some time for some project participants, whether they work for the owner, engineering design firm, general contractor, specialty contractors, or vendors/suppliers, to change their traditional practice.

- Familiar User Interface and Data Structure

  A familiar user interface and data structure will promote acceptance and avoid confusion when planners migrate from paper-based tools or other computer tools to the Last Planner tools. As pointed out earlier, some project managers specifically asked that GUIs would look like Excel. Figure 31 and Figure 36 are the results of these requests. Other project managers requested that reports look exactly like the reports they had been using. Some but not all of these requests have been realized, depending on whether or not they met general needs. In terms of data structure, maintaining a level of detail for all information close to the level planners currently are used to seeing is very important, unless there is a strong reason to do otherwise.

- Other Requirements

  The requirements listed above are either very important or they are requirements specific to the Last Planner tools. However, other generic requirements came to bear in the validation process. For instance, computer tools should:

  - be reliable, e.g., the software should not crash or compute erroneous results
  - allow for collection of information once and at the source, then allow for re-use anywhere it is required
  - be able to archive and recall past information

4.6 CONCLUSION

WorkPlan, DePlan, and WorkMovePlan, have gone through several stages of modification from their inception until their current implementation, based on feedback from beta-testers. Between each stage, the requirements for the Last Planner tools have become clearer. Deepened understanding of requirements and barriers to implementation will help in developing yet better specifications to enhance these tools.

5 DISTRIBUTED PLANNING AND COORDINATION

The coordination of project participants has become one of the most important, if not the most important role of a prime contractor in delivering a successful project. The involvement of specialty contractors in projects has increased due to increases in size and technological complexity of projects and a decrease in the amount of work that is self-performed by general contractors. Additionally, shortening project durations are forcing more activities to be executed simultaneously. Thus, coordination of all project participants is now more complex than ever before.

Cohenca-Zall et al. (1994) researched the involvement of project managers, general superintendents, project engineers, home office personnel, and 'externals' (clients, designers, subcontractors) in planning areas such as information gathering, development of alternatives, and choice-making stages regarding engineering and method, organization and contract, schedule, cost and cash flow, major equipment, layout and logistics, work methods, manpower allocation, and materials allocation. They categorized the level of involvement into six categories: (1) not at all, (2) very low, (3) low, (4) medium, (5) high, and (6) very high. Their work shows that there is always more than one party highly involved in any one of the planning areas at any stage. It also points out that, more often than not, the participants making the decision are not those responsible for gathering information or developing alternatives.

The "project coordinator", a role that is often played by the prime contractor (traditionally, a general contractor), has to coordinate the efforts of all project participants. Solving this coordination problem is daunting, as it requires collection of information from all participants that might not "speak the same language", seeing the relationship between these different bits of information, determining the best possible execution plan that does not necessarily come at the expense of any one participant, and then distributing that information to all participants. This coordination problem can be seen as a "wicked problem" (Rittel and Webber 1973, Conklin and Weil 1998). Wicked problems are defined as having the following characteristics.

1. The problem cannot be fully understood until it has been formulated and perhaps even after a solution has been determined.
2. The stakeholders (those who have a stake in it's the problem's solution) have radically differing world views.

First step in solving the coordination problem, in most cases, is to create a a tentative solution whether it is based on a master schedule or on a mental picture in the project coordinator's head. However, these schedules seldom are carried out as planned. The final solution is reached through trial-and-error. Each trial is tested according to the delivery milestones, actual situation of the site, availability of resources, constructability, regulations and permits, and execution preferences of the owner, prime contractor, and specialty contractors. Once a conflict is detected, the problem is better defined as to eliminate the conflict. The solution then can be adjusted until a satisfying solution is reached. The merits and demerits of the decisions made at each coordination meeting cannot be fully understood until the project is completed, as the impact of each decision on the rest of the project is hard to quantify at the time the decision is made. The problem is even more complicated as the project participants share a different view of the problem, for example a project-view as opposed to a job shop-view as was explained in Section 4.1. Thus the coordination problem must be solved opportunistically, where continuous improvement or radical changes to the solution are pursued as more information becomes available. However, a single party cannot fully furnish all information that is required to generate a solution. The responsibility of coordination does not rest on a single party such as the general contractor or any specialty contractor but it rests on all participants involved in a project. The solution must be generated by incorporating information from all the participants involved in a project. This approach promotes a distributed, bottom-up approach to planning that complements the current centralized top-down approach. This approach also radically differs from practices supported by existing computing tools though it may more closely fill the needs of actual practice.

In such an environment, real-time information sharing is critical. The communication channels between the specialty contractors are no longer "up and down the chain" because these hugely increase the information turnaround time. Instead, the communication channels will take on the form of a web, where all specialty contractors can communicate directly with each other (Figure 57) and the information turnaround time is short.

The specialty contractors will share necessary information, suggest alternatives, and then decide among themselves. The project coordinator has to step in only when it is necessary to make sure these decisions do not violate the overall objectives of the project and when the specialty contractors cannot reach an agreement by themselves. Project incentives and performance measurements can also be aligned to promote collaboration.

5.1 COORDINATED PLANNING

A company's operational plan takes on the form of a job-shop schedule regardless of its role within a project. Project schedules are part of that operational plan. Whether any one project can be scheduled without regard to other projects depends on whether or not each project participant is fully dedicated to that project. According to the author's experience, general contractors usually dedicate a team to work on a project during the whole duration of that project although some upper managers might work on multiple projects concurrently. In contrast, specialty contractors are rarely dedicated to a single project.

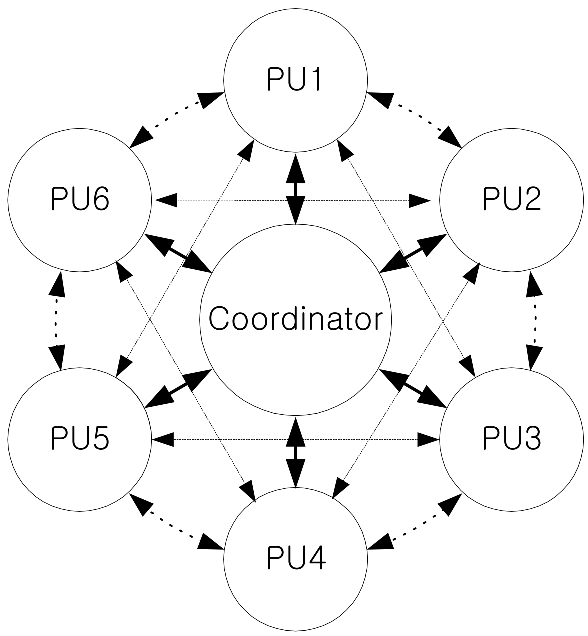


Figure 57. Communication Channel Scheme under Distributed Planning and Coordination

In section 3.1, the author has highlighted the lack of interrelationships between project planning and production planning as described in the literature and also in current practice. He chose as an alternative the Last Planner System as a means to increase plan reliability. A comparison of these two systems using the PDCA cycle revealed that their underlying philosophies are very different. Thus, the planner has to decide whether to adopt one system or the other, but cannot adopt both. Specifically, in order to fully reap the benefit of the LPS, the project participants at all levels, i.e., everyone involved in creating, executing, and maintaining master schedules, lookahead plans, and weekly work plans, must adopt the system.

Nevertheless, in this dissertation, the author has chosen (1) to focus on the creation of the middle level- and the lower level plans, i.e., the lookahead plans and the weekly work plans, (2) to develop computer tools for the application, and (3) to study the acceptance of the proposed planning method by the participants responsible for production. The author has taken the generation process of high level plans, i.e., master schedules, as a given with one disclaimer: the master schedule must not have too much detail. Too much detail would constrain the production planners' ability to structure the work or further break the work down and to consider different construction methods.

However, the author has maintained the link between the high level plan(s) and the middle level plans by introducing "work package" as an interface between project planning and production planning. This made the implementation of the proposed planning method easier as the link across the planning hierarchy is loosely maintained at the same time, meeting the requirements for the LPS.

The coordination approach followed in this research is different from the coordination approach followed in currently available tools in that it allows planners to schedule their own work for multiple projects within a job-shop environment. As each project participant is trying to maximize the use of their resources by levelling them across multiple projects within the boundaries of project milestone dates (called 'due dates' in job shops), each project participant should be able to plan work for these projects as if they were multiple orders in a job-shop.

The computer tool then should be able to selectively gather information that belongs to each project and present it in such a way as to assist with collaborative scheduling. However, gathering and presenting information is complicated by the fact that not all project participants create schedules at the same time or at the same level of detail, with the same lookahead duration, or with the same reliability. Figure 58 shows the relationship between multiple schedules where project participants have a different lookahead duration. In such a case, the coordinated schedule may show six weeks worth of schedules (one week of weekly work plan and five weeks of lookahead). However, only up to three weeks of coordinated schedule can be reliable (provided that the lookaheads themselves are reliable) because specialty contractor 1 (SC1) has a lookahead window of two weeks. After the completion of week 1, SC1 will start creating a lookahead schedule for the fourth week. This information may create conflict with information already input by other specialty contractors. Therefore, the reliability of the coordinated schedule after the third week decreases due to lack of information. In order to minimize unnecessary re-planning or miscommunication, it is desirable to have pre-agreed lookahead windows of the same length at various times during project execution for all project participants whose work must be coordinated.

As seen from the example, the quality of the coordinated schedule heavily depends on the quality of the input schedules, which can be described in terms of (1) correctness, (2) adequacy, (3) stability, and (4) timeliness. Correctness assures that the schedule contains accurate information. Adequacy assures that the schedule is developed at a sufficient level of detail. Stability assures that the information does not change (or seldom changes) once it has been entered, especially at the level of weekly work planning. Timeliness assures that the schedule is shared with other project participants with enough lead-time to allow other project participants to detect conflicts and develop solutions for them.

The proposed planning and coordination methodology employs a work package structure and a planning method in order to minimize the potential deterioration of schedule quality due to variability in timing, detail, lookahead, and reliability.

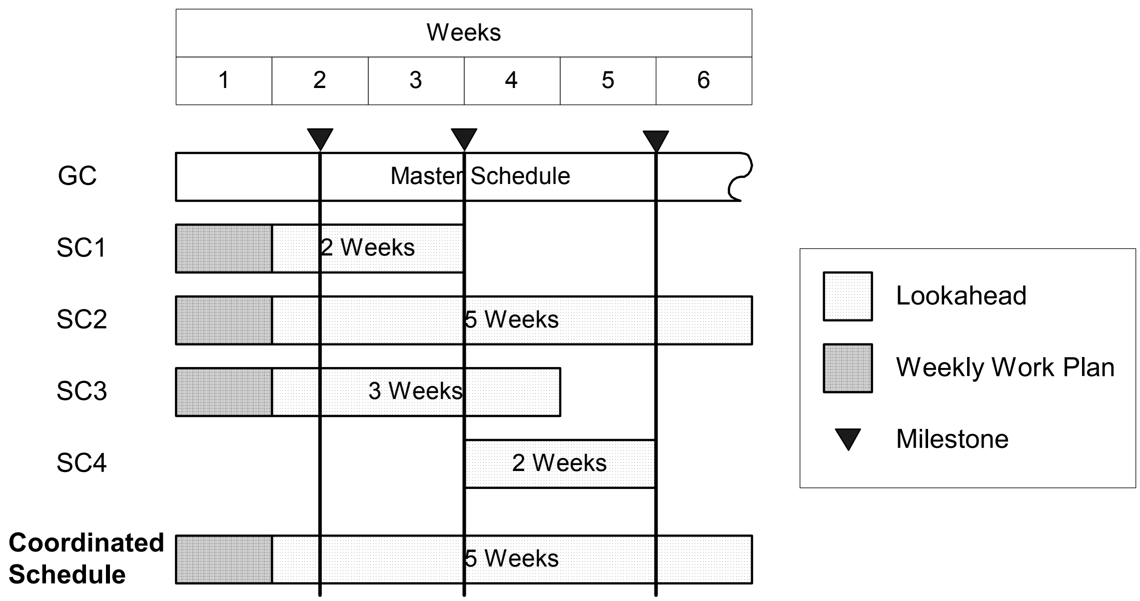


Figure 58. Relationship between Schedules with Different Lookaheads

5.2 Work Package Structure to Support Multi-Level Planning

In designing a work package structure to support multi-level planning, a key decision to make during the first implementation phase was whether or not to adopt “work package” as the scheduling unit, as was done in WorkPlan and DePlan.

In WorkPlan and DePlan, assignments were made at the work package level, according to an early conception of the LPS. In the current conception of the LPS, resource assignments are made at the assignment level. As said in 4.2, a work package is defined as a definite amount of work to be done using specific design information, material, labor, and equipment, and with prerequisite work completed (Choo et al. 1998a, 1998b, 1999). Assignments are "a directive or order given to a worker or workers directly producing or contributing to the production of design or construction" (Lean Construction Institute 1999). It is therefore necessary to maintain links between two distinctively-sized units of works, namely work packages and assignments. These links, shown in Figure 59, maintain the relationship between the project schedule and the production schedule. Work packages refer to work that is assigned (or contracted for) by a general contractor to a specialty contractor. The specialty contractor can then break these work packages down into one or more assignments using the Activity Definition Model (ADM) (Lean Construction Institute 2000). However, this breakdown may be made visible or invisible to the general contractor depending on the specialty contractor's willingness to share that information. When the breakdown is made invisible, it is presented to the general contractor as aggregated data.

Ballard uses phase schedules (2000b) and/or lookahead schedules (1997) to link the project schedule to weekly work plans. However, maintaining an explicit link between these three (four) requires effort. Different parties use different tools to develop these schedules. Typically, project managers develop project schedules using CPM-based scheduling tools; superintendents develop lookaheads using either scheduling tools or spreadsheets; and specialty-contractor foremen develop weekly work plans using spreadsheets or mere crib sheets. Any of these may be done on a computer. Currently no single data repository or tool exists to support such different levels of scheduling by different parties. As mentioned in Section 4.5.1.1, a project manager who applied the LPS to his project identified the need for explicit links:

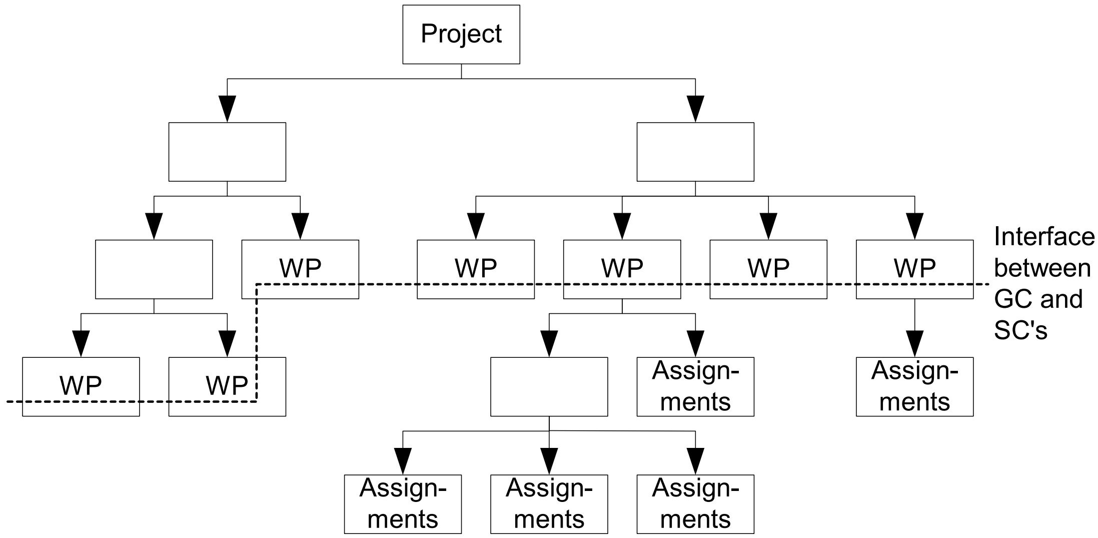


Figure 59. Relationship between Work Packages and Assignments

In order to effectively carry out distributed planning and coordination, the definition and data requirements for work packages and assignments need to be clear.

It is often taken for granted in construction that the fastest way to get the job done is to get any work done whenever possible, but this assumption disregards the effort and time that goes into mobilizing and demobilizing for any assignment. In order to avoid repeated mobilization and demobilization, an assignment should not be started unless it can be finished without interruptions and it has no negative downstream impacts; i.e., it's done in accordance with the sequence criterion. This criterion helps delimit an assignment's amount of work. Grouping of similar work allows for a continuous flow of resources by moving the crew from one area to the next. Unnecessary interruptions can thus be avoided. This enables the learning process, which in turn increases productivity (cf. the 'learning curve').

In order for work packages to be useful in production management, that is, support those who are performing construction work in the field, work packages at the master schedule level need to be broken down and detailed so that the required resources and construction methods can be specified. These work packages need to be detailed into assignments, before resources can explicitly be assigned and be made ready for construction before they are released to site as proposed in the Last Planner concept.

A work package at the master schedule level is divided into one or more work packages at the phase schedule or lookahead level. A work package at the lookahead level is also divided into one or more work packages at the weekly work plan level. Therefore, a work package at a high level schedule (parent WP) is composed of multiple work packages at a lower level schedule (child WP). A child WP must contain information about which parent WP it belongs to. For instance, a parent WP can be ‘place concrete’ and the child WPs of it can be ‘place formwork’, ‘place rebar’ and ‘pour concrete’. If a work package in the lookahead or weekly work plan cannot be assigned to any parent WP, the work is said to be ‘out of scope’ and therefore requires a change order or at least an appropriate notification before work can begin. Table 3 shows the data structure of a work package at the lookahead level. The sample work package in Table 3 is a part of work package 97-309-C-1000 at the master schedule level.

Figure 60 exemplifies relationships between work packages in a GC’s lookahead and those in two specialty contractors’ lookaheads. Three work packages that are divided by work area, i.e., room and floor, are shown in the general contractor’s lookahead. Lookaheads of two specialty contractors, i.e., the HVAC and the electrical specialty contractor, demonstrate the process of creating a coordinated schedule. This example shows only two specialty contractors but in a real situation quite a few specialty contractors may have to coordinate their schedules.

Table 3. Work Package Data Structure

Field	Format	Sample Data
Work Package No	TEXT	"L-97-309-C-1000"
Project No	TEXT	"97-309-C"
Work Package Code	LONG	1000
Assignment	TEXT	"Roof-Area 2: Rough-In Roof Drains"
Parent Work Package No	TEXT	"97-309-C-1000"
Duration	SINGLE	5
Start Date	DATE	4/1/1999
Completion Date	DATE	4/5/1999
Budgeted Cost	CURRENCY	$2,900
Cost-To-Date	CURRENCY	$200
Released	BOOLEAN	Yes
Completed	BOOLEAN	No
Remaining Unit Cost Labor	CURRENCY	20
Remaining Amount Labor	SINGLE	30
Remaining Unit Cost Equipment	CURRENCY	100
Remaining Amount Equipment	SINGLE	20

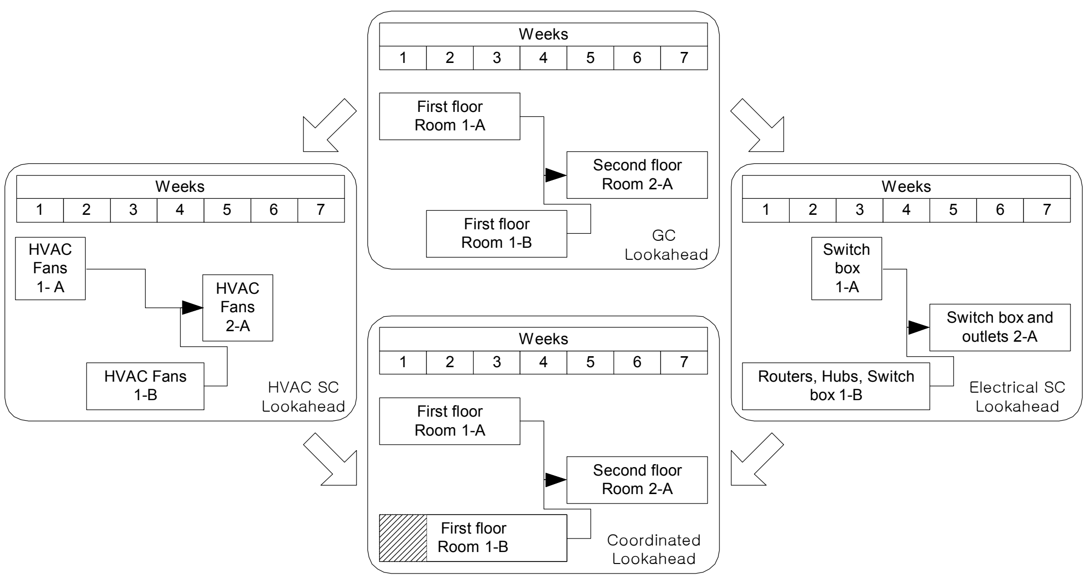


Figure 60. Relationship between General Contractor's Lookahead and Two Specialty Contractors' Lookaheads

Each specialty contractor developed a detailed schedule to a level appropriate for carrying out the work. These schedules were then checked for potential conflict. The coordinated schedule shows that the schedule for the 1st floor, room 1-B will have to start a day earlier than originally scheduled in order for the electrical specialty contractor to get their work done in time to meet the general contractor's lookahead schedule. In addition, the HVAC and the electrical specialty contractor will be working in the same room and therefore need to coordinate space use to avoid conflicts. By keeping track of parent WPs, schedule changes at the lower level schedule can be automatically incorporated into a higher-level schedule.

5.3 SPACE SCHEDULING

The representation for planning of labor and equipment data is straightforward and well established. It is described in terms of "WHO (or WHAT) is scheduled to be used WHEN for HOW long". The description for space scheduling can be similar to that for labor and equipment: "WHERE is WHAT scheduled to be used WHEN for HOW long". But there is a large difference between WHO (or WHAT) and WHERE. WHO (or WHAT) can be described with a name, a one-dimensional scalar variable. However, several components are needed to describe WHERE. WHERE consists of the center (or any referential point) of the location (X, Y, Z) and the dimension of space (X, Y, Z), thus making spatial data not as easy to convey to other data. Therefore a 2-D or a 3-D drawing usually shows this data.

Currently no commercially available project management tools include functions for space scheduling. However, space allocation and coordination are primary tasks in the coordination effort required in construction management. Thus, a distributed planning and coordination tool must include space scheduling capabilities as well.

Riley and Sanvido (1995) categorized space uses required to support construction activities (Table 4). This categorization shows that construction activities consume much more supporting space in addition to the actual work area. It also shows that each space use has a different 'occupancy life.' For example, a storage area is occupied as soon as material, tools, or equipment are brought in regardless of when the activity starts. A storage area can remain occupied even after the work is finished, until the area is cleared out. A work area usually is occupied during the duration of the activity. Failing to specify or share this information can result in havoc on the site. Therefore, a coordination schedule must be given flexibility to depict all space requirements and different occupancy life.

Table 4. Space Requirement

Storage area	Activity requirement	Movement	Generated
Layout area	Unloading area	Material path	Hazard area
Staging area	Prefabrication area	Personnel path	Protected area
Tool and equipment area	Work area	Debris path	

The space scheduling capability as implemented in this research provides a planner with the flexibility to specify any space use with different occupancy life. However, each space use is linked to a specific assignment so that all other project participants can see which activity and participant it is supporting.

5.4 CONFLICT DETECTION

Echeverry et al. (1991) formalized four types of constraints that may determine activity sequencing in a construction project. These are (1) physical relationship among building components, (2) trade interaction, (3) path interference, and (4) code regulation. They also noted three time dependence constraints. These are (1) space competition, (2) resource limitations, and (3) unsafe environment effects. Time dependence constraints are those that can be checked for violation only after the activity start and finish time is specified. In other words, time dependence constraints can be checked only after the coordinated schedule has been developed.

The coordinated schedule can be used to detect potential conflicts before they occur on site. A first potential conflict pertains to prerequisite work. One specialty contractor may schedule work when prerequisite work has not yet been finished. The prerequisite relationship must be carefully studied in order to ensure that it will not result in a conflict on site. One way to avoid this conflict is to schedule the specialty contractor responsible for the prerequisite work before scheduling the succeeding specialty contractor. These specialty contractors will have to work together to develop a solution. The responsibility for coordination does not rest on a single party such as the general contractor or any one specialty contractor, but rests on several participants involved in a project. The project coordination system can represent and distribute information about resource schedules but solutions must come from the participants of the project.

A second potential conflict pertains to personnel and equipment. Since the work force normally is unique for each specialty contractor, there is practically no chance for a person to be assigned to work packages belonging to different specialty contractors. But there is a chance of conflict involving general contractor-provided personnel or equipment as they often are shared resources, e.g., inspectors, cranes, and elevators..

A third but not the least potential conflict pertains to space. Even though one of the first duties of a superintendent on a new project is to prepare a job layout (Peurifoy 1956) and field supervisors do spend a large portion of their time managing the site layout, construction managers have been treating space scheduling as secondary to schedules of material, equipment, laborers and prerequisite work. This can partially be attributed to unavailability of a standard for representing space scheduling and tools to support it. A challenge to be addressed in this research was thus to provide an effective scheduling tool with a clear representation for space scheduling.

By explicitly assigning space as shown in Figure 61, it can be seen that the HVAC and the electrical specialty contractors will occupy room 1-B at the same time. Since both trades apparently require the whole room to execute their work, even though they may not need all this space at once, they must coordinate by sequencing their work, e.g., HVAC may work on the left side of the room first while the electrical contractor works on the right side first. If the two layouts were superimposed to produce a higher-level site layout, it becomes obvious what work will be going on in room 1-A and 1-B on the first floor during the third week.

Each party involved in a project can use PPC to measure whether planned work got done by the end of a week. Accordingly, each party can achieve a perfect PPC while still having flexibility within a week to juggle the plans as long as it can finish its work at the end of a week. But some shared resources, such as a crane, a work area, or a staging area, and the output of work may need to be handed off during the week. A perfect PPC does not guarantee that a party has not disrupted another party's schedule. By looking at the coordinated plan, each party can determine whether scheduled work can be properly performed without disrupting another party's schedule. Numerous other conflicts could arise.

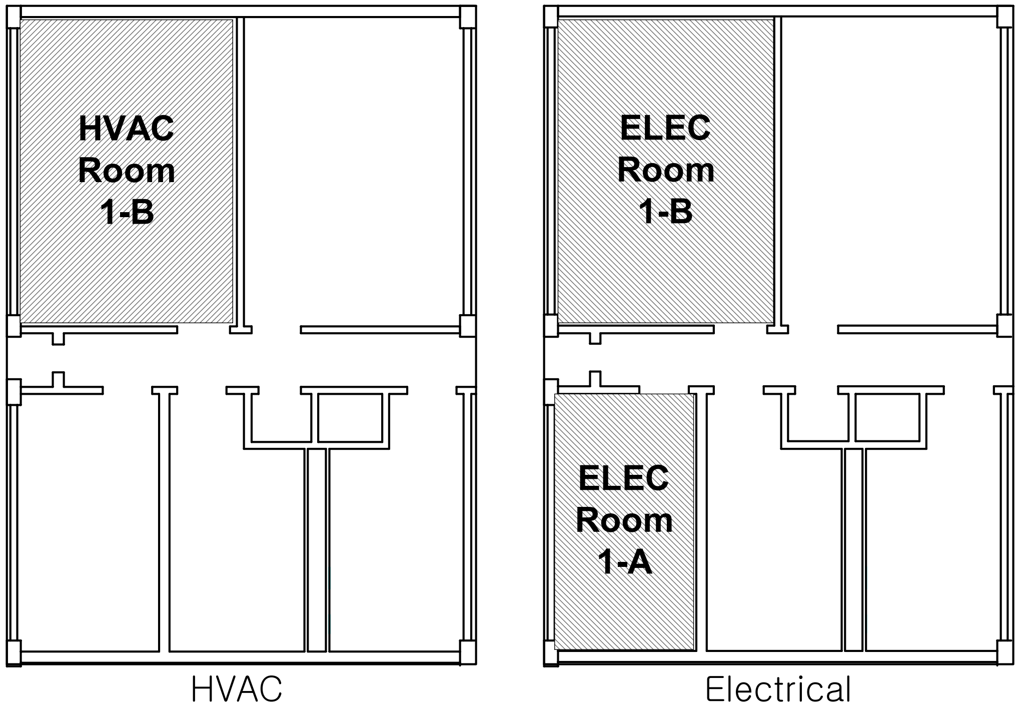


Figure 61. Site Layouts for Third Week for Schedule in Figure 60.
Left: site layout for HVAC contractor; Right: site layout for the Electrical contractor

5.5 CONCLUSION

Many obstacles that prevent the new planning methodology to become a new standard still exist in the industry. One large obstacle is the dominance of the "centralized control" view. During an interview with a project manager and a superintendent of one of the largest contracting firms in California, it was clear that the notion of centralized control prevails in our industry. The superintendent said, "You always want to have more information than your subs, so that you have leverage over them." This mentality is both naive and short-sighted. The lack of transparency of information creates adversarial relationships and risk. He also said, "We have a very detailed master schedule [with activity durations no more than 4 to 5 days], so we can keep tight control over the subcontractors." When the project manager was asked to estimate PPC, he answered

35%. If that is indeed so, clearly, the superintendent's "tight control" is not very tight. However, tight control is rarely criticized as being the source of the problem, whereas the lack of specialty contractors' abilities to execute as planned often is. Therefore, "tighter control" is exercised.

A project engineer working on a construction project, which implemented the LPS, expressed his frustration when trying to shift the subcontractors' thinking away from centralized control to distributed control. He said that some subcontractors came back and said, "Don't ask us what we can do, but just tell us what to do." Where these views of construction management are predominant, acceptance of the Last Planner tools will not be easy. However, he also commented that "Now they understand [the Last Planner] and they have accepted it."

Transitioning from centralized control to distributed control is not easy for all participants, especially those primarily responsible for production, i.e., general contractors and specialty contactors. However, with the increasing specialization of specialty contractors and complexity of projects, and with the rapid advancements in information technology and communication infrastructure, the change seems to be underway.

Other obstacles are contracting strategies and performance indicators used on projects. Current contracting strategy is to divide a project in to small commercial packages (usually referred to as 'work packages') and contract out one or more of these packages to a specialist. The owner (or prime contractor) then measures performance for each work package. These performance measurements are usually linked to incentives, i.e., a bonus or penalty for each specialist. The prevailing mental model for such contracting strategies is the “win-lose” model, not a “win-win” model. In such cases, the guideline for making a decision is “what is in it for me?” rather than “what is in it for the project/client?” The “win-lose” model does not promote a cooperative environment. More research is needed on contracting methods and performance indicators that are aligned with the LPS.

6 WORKMOVEPLAN

WorkMovePlan (Choo and Tommelein 1999) is an extension of WorkPlan developed to support distributed planning and coordination. In WorkPlan and DePlan, coordination information is managed by treating it as a constraint. However, even if all specialty contractors (or other production units) developed quality weekly work plans, the interaction between them would be coordinated better if managed explicitly to guarantee a smooth execution of work. WorkMovePlan combines the LPS, implemented in WorkPlan, with distributed scheduling and coordination, space scheduling, and web posting features.

6.1 DESIGN

WorkMovePlan assists specialty contractors in the co-creation of coordinated weekly work plans from each specialty contractor's quality weekly work plan. The implementation of WorkMovePlan inherits all functionality of WorkPlan and extends its capability to support distributed planning and coordination as well as space scheduling. The distributed planning and coordination capabilities allow production units to increase the reliability of their plans by sharing work package-, space scheduling-, and constraint information. The space scheduling capabilities allow each planner to explicitly allocate space, including workspaces, laydown areas, storage areas, and access paths.

6.1.1 System and Data Architecture of WorkMovePlan

WorkMovePlan's distributed planning and coordination feature is based on near real time data sharing. Near real time data sharing is based on technology called synchronization, meaning "the process of updating two replicas in which all updated records and objects are exchanged. The exchange of data between two replicas can be one-way or two-way…" (Microsoft Corporation 1999).

Each WorkMovePlan database contains two parts, i.e., one part that contains private information and another part that contains public information. The private information is information regarding the owner of the database, specifically regarding its resources, associate costs, and detailed schedules. WorkMovePlan automatically generates public information by filtering out information that does not have to be shared (Figure 62).

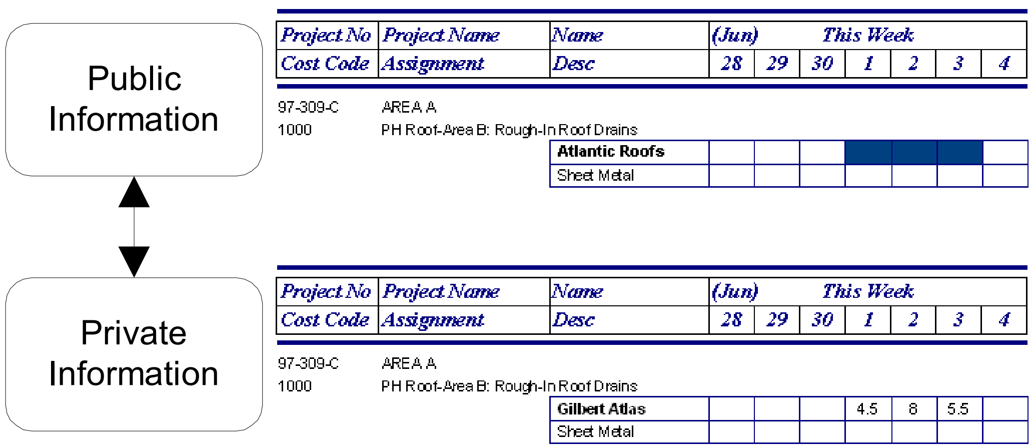


Figure 62. Relationship between Private Information vs. Public Information

For example, the private information in Figure 62 shows the name of a craftsman (Gilbert Atlas) and the exact hours (4.5, 8, and 5.5) of the work he is scheduled to do. However, the automatically generated public information shows only the name of the company he belongs to (Atlantic Roofs) and the days (Wednesday, Thursday, and Friday) he is going to be on site. The public information reflects a commitment to other project participants at a level less detailed than the private information, so that the production person retains some flexibility to carry out the work. The commitment to other project participants will be met as long as the work starts within any time of the scheduled duration and as long as the output is delivered in such way as to not prevent others from starting their work.

The public information is a replicated part of the database (Figure 63). It gets replicated to all instances of WorkMovePlan that are distributed and belong to the various project participants, so that schedule information regarding all project participants is automatically updated. The main reason for designing the database in such way rather than using a centralized on-line database was because not all specialty contractors have an 'always-on' Internet connection. By keeping a copy of the near real time information, i.e., the information that was available the last time the database was synchronized, the owner of each WorkMovePlan instance can still view the schedule information of others off-line.

6.1.2 Space Scheduling

Researchers have advanced space scheduling methods and developed various tools to support these methods as described in Section 3.6.1. Some have focused on generating space schedules using artificial intelligence programming techniques; they have mimicked human planners or reused knowledge captured on past projects to plan for a new project. Other methods have been more algorithmic in nature. Yet most of these systems (except for a few, e.g., Tommelein et al. 1991, Tommelein et al. 1993) employed a centralized approach where a single user was responsible for the space scheduling including site logistics. This is very different from how space schedules are actually created. In practice, each project participant mostly those responsible for production, best understand their space requirement for actual production work, to store materials and resources, and to access the production work areas and storage.

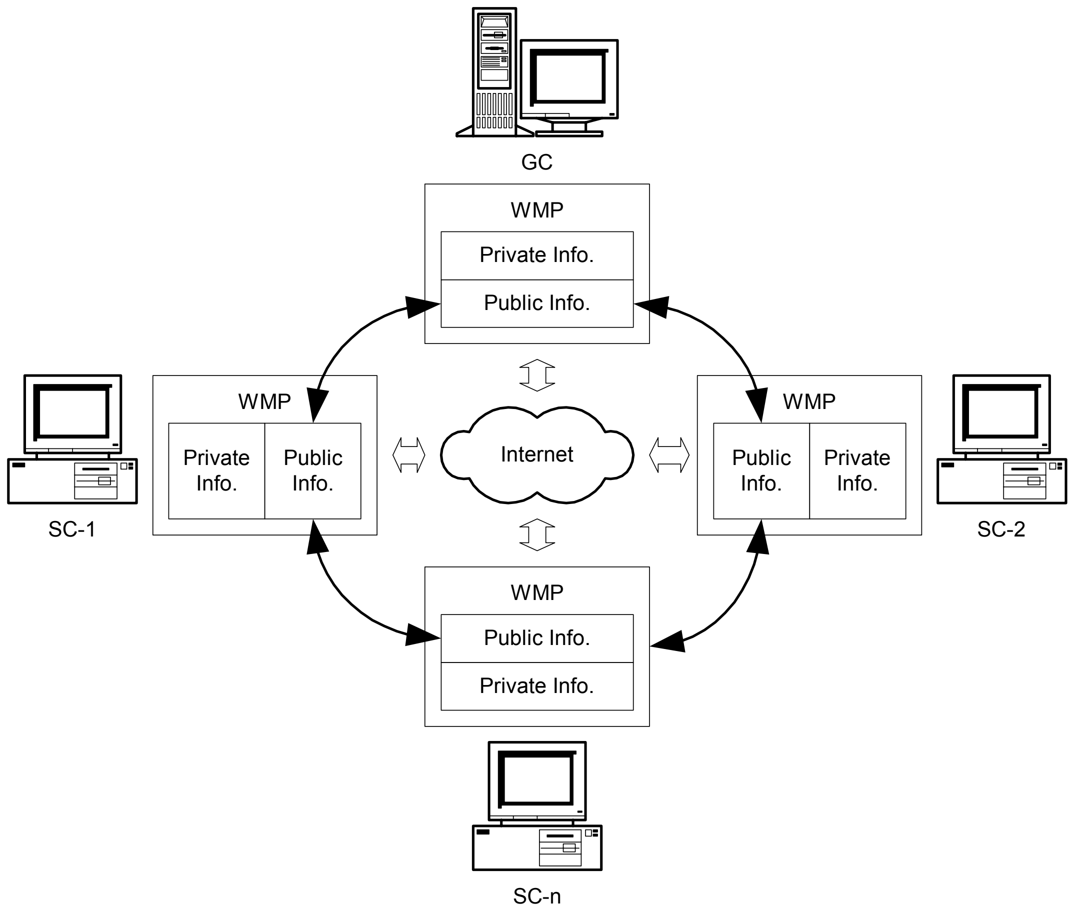


Figure 63. WorkMovePlan(WMP) Synchronization Scheme

Distributed space scheduling more closely models actual practice and allows for an efficient way to ensure accurate information exchanges. It is an alternative to a less efficient way, which is to have a person meet all project participants one by one or in groups to assign space use, detect space use conflicts, discuss options, develop solutions, and then go back to all affected participants to update them on the new solution. In this situation, though, project participants cannot in-and-by-themselves study their options ahead of the meeting time and generate alternative solutions that would create less conflict or no conflict at all. The role of the coordinator in this situation might be to set a boundary on spaces project participants can use freely to develop their space schedule.

Once all project participants have determined their space use within those boundaries, these space schedules can be integrated to produce a total solution. If a project participant's space use extends beyond the boundaries, the boundaries and space use of the affected participants will have to be revisited.

WorkMovePlan extends WorkPlan's planning procedure for labor and equipment to include space scheduling (explained in 5.3). A planner can specify site space needs on a day-to-day basis for labor, equipment, and materials in terms of work-, laydown-, staging area, or access path as needed throughout the execution of a work package.

WorkMovePlan requires the user to explicitly input information on resources that need to be considered during space scheduling (Figure 64). Default categories refer to material, equipment, and labor but others can be included, if needed. Shape refers to the physical shape of the space required. X, Y, and Z refer to the dimensions of the space.

Elzarka and Bell (1995) integrated materials management with a scheduling system to allow for the procurement schedule to be driven by construction. Such a system would further benefit from integration with explicit information about the production work performed on site so that procurement schedule can be developed and adjusted to meet changing site needs.

Lean construction allows for "pulling" materials to the site by making information about the production work explicit (e.g., Tommelein 1997a, 1997b). With this information, procurement decisions can be made such as when and how much material need to be pulled to which location. In addition, materials could be specified in terms of the space they will require on site. If the start date of an activity can be anticipated with more time than the lead-time needed to procure and deliver a material, then delivery dates can be scheduled so that the material will arrive just-in-time or with only a minimal lead-time.

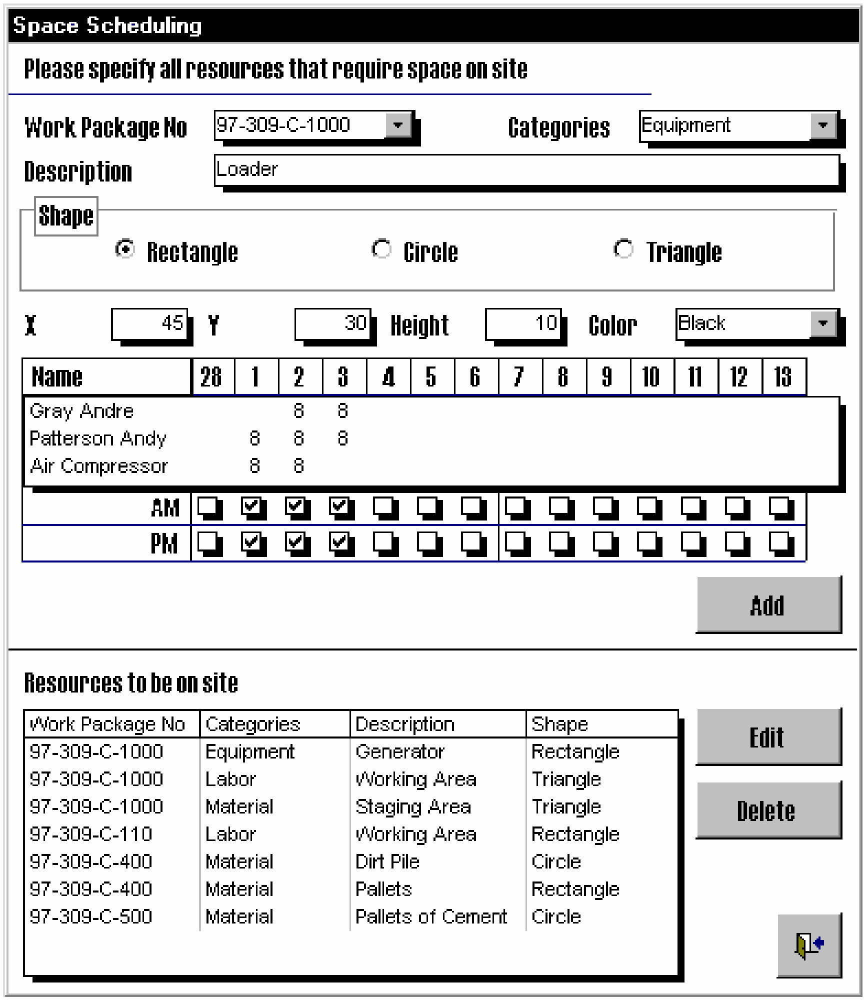


Figure 64. Space Scheduling Screen

Doing so is far more advantageous (as discussed in Section 3.3.2.2) than following a "push" approach where the material is purchased and delivered to the site not knowing precisely when the activity actually will start. The planner then must allow for the material to be delivered some additional time in advance of the anticipated activity start so that the activity will not be delayed due to material shortage. This thinking can also be applied to equipment. Therefore weekly work planning must include a material and equipment schedule in addition to a laborer schedule so that space can be assigned to them.

The list in the middle of the space scheduling screen (Figure 64) shows the schedule for labor and equipment assigned to the selected work package. Although the default schedule for space use is from the first day of labor or equipment assignment to the last day, it can be adjusted to represent actual day-by-day needs.

The "Resources to be on site" list refers to all resources that have been input through the space scheduling screen. These resources will share site space for the week under consideration. Once all resources to be assigned are specified, their positions can be selected using a GUI, namely Visio (Microsoft Corporation 2002). Figure 65 shows a sample screen of the finished space schedule.

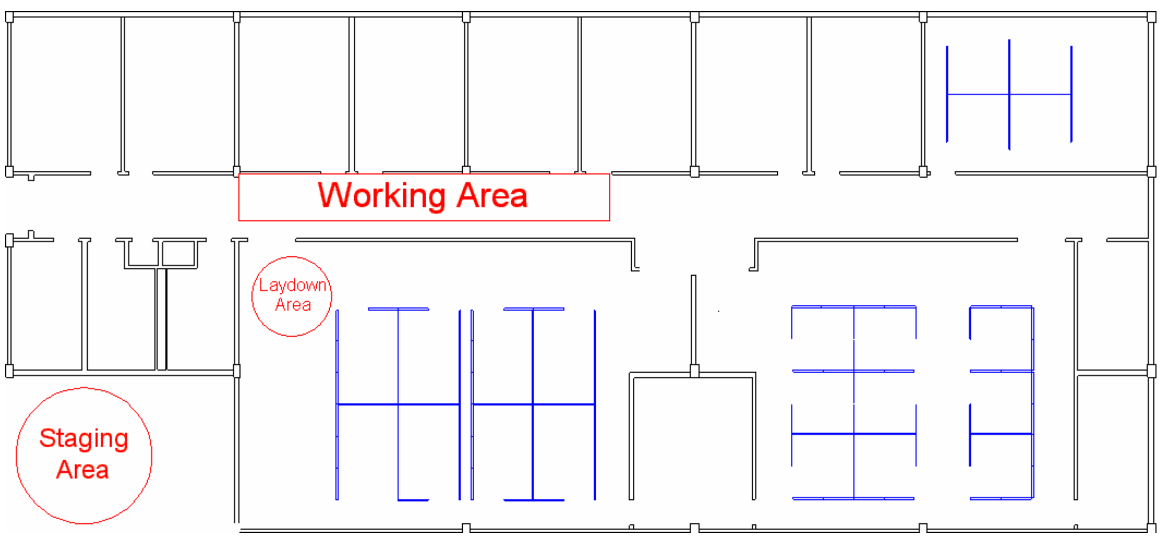


Figure 65. Completed Space Scheduling Screen

6.2 IMPLEMENTATION

The work package structure to support multi-level planning and explicit link to master schedule (both discussed in Section 5.2) is implemented in WorkMovePlan. Figure 66 shows that a master schedule can be imported to populate the list of work packages. These work packages can be then further broken down using a hierarchical fashion as seen in Figure 67. Only the lowest level in the hierarchy can be released and assigned resources.

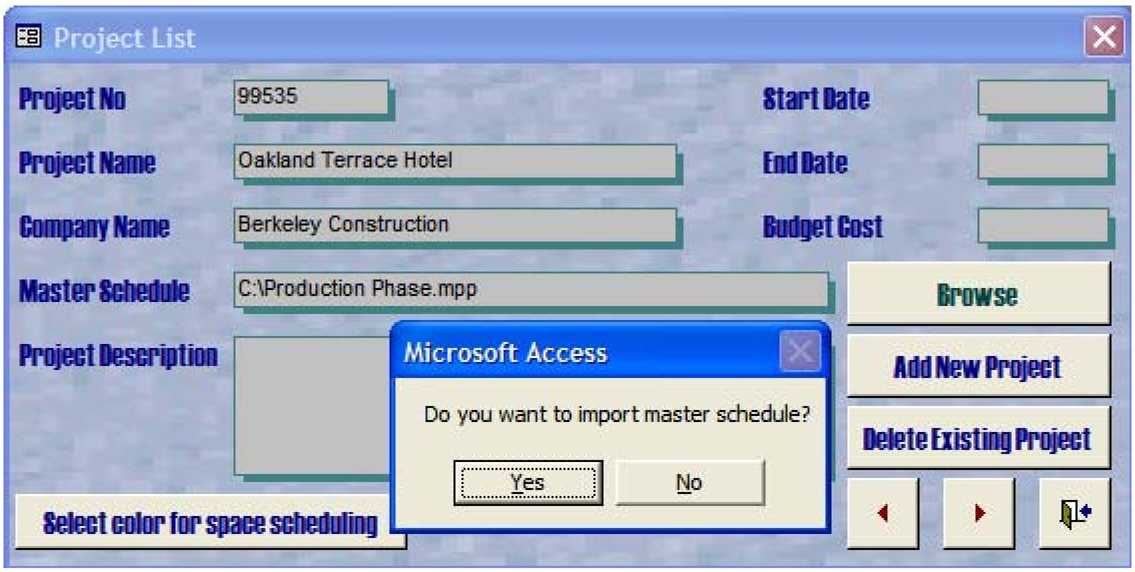


Figure 66. Project Information

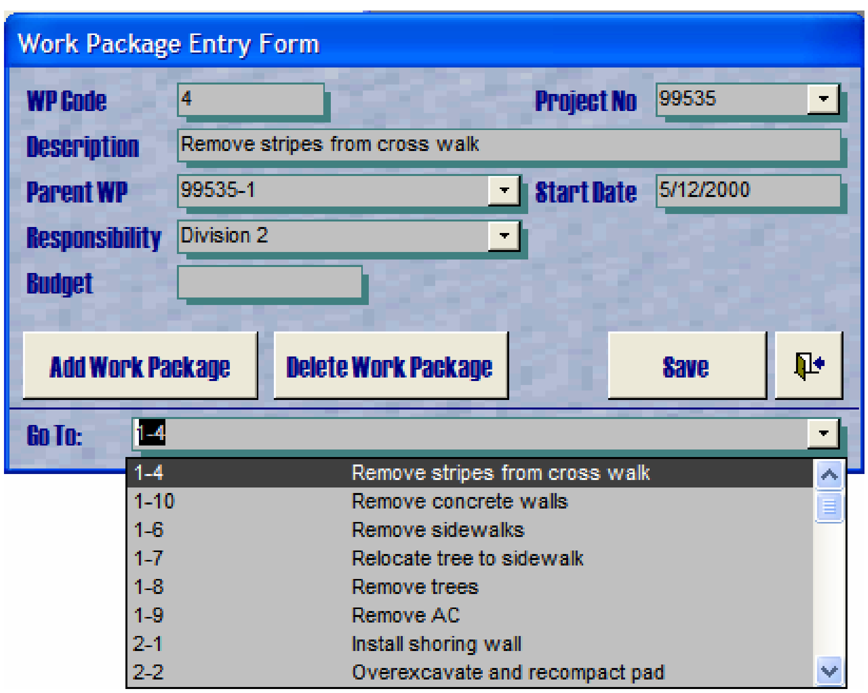


Figure 67. Work Package Information

In addition to the explicit assignment of resources for weekly work planning, WorkMovePlan requires the user to explicitly input information on resources that need to be considered during space scheduling, such as the category of the space use (material, equipment, labor, etc.), the shape of space required, and the dimensions (X, Y, and Z) of the space. Although the dimensions are specified in 2½-D (width, length, and height), WorkMovePlan's space scheduling will take place in a 2-D environment. 2-D drawings are more widely available and space assignment can be done much more easily in 2-D than in 3-D. 2-D layouts convey space scheduling information in a straightforward fashion. Nevertheless, the height dimension entered in WorkMovePlan can later be combined with the layout schematic to generate a 3-D virtual reality mock-up using the Virtual Reality Modeling Language (VRML 1995) for instance (Figure 68). An example application of WorkMovePlan is described by Choo and Tommelein (1999).

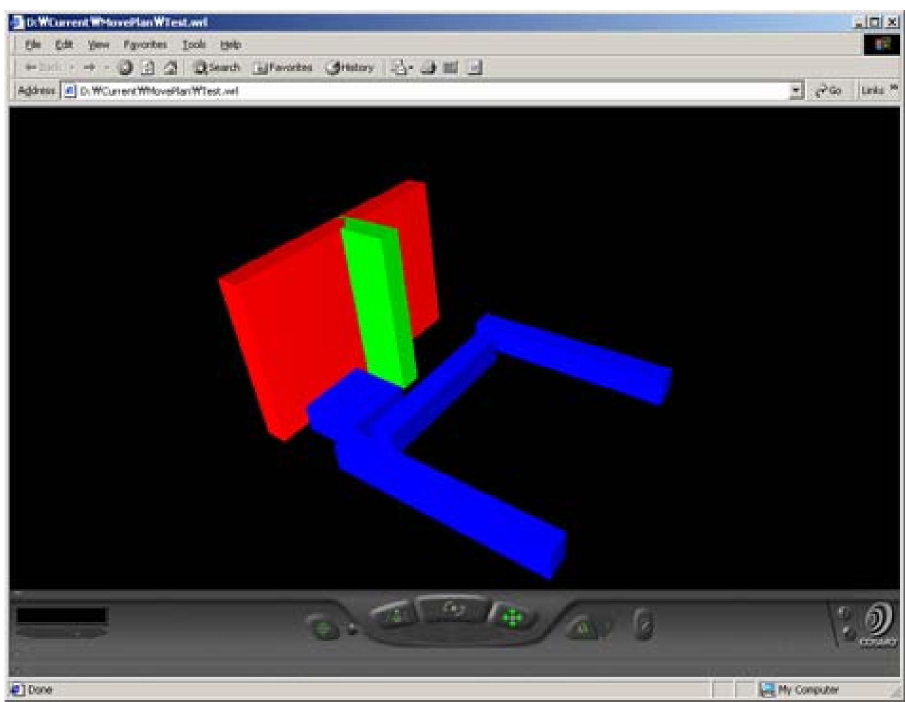


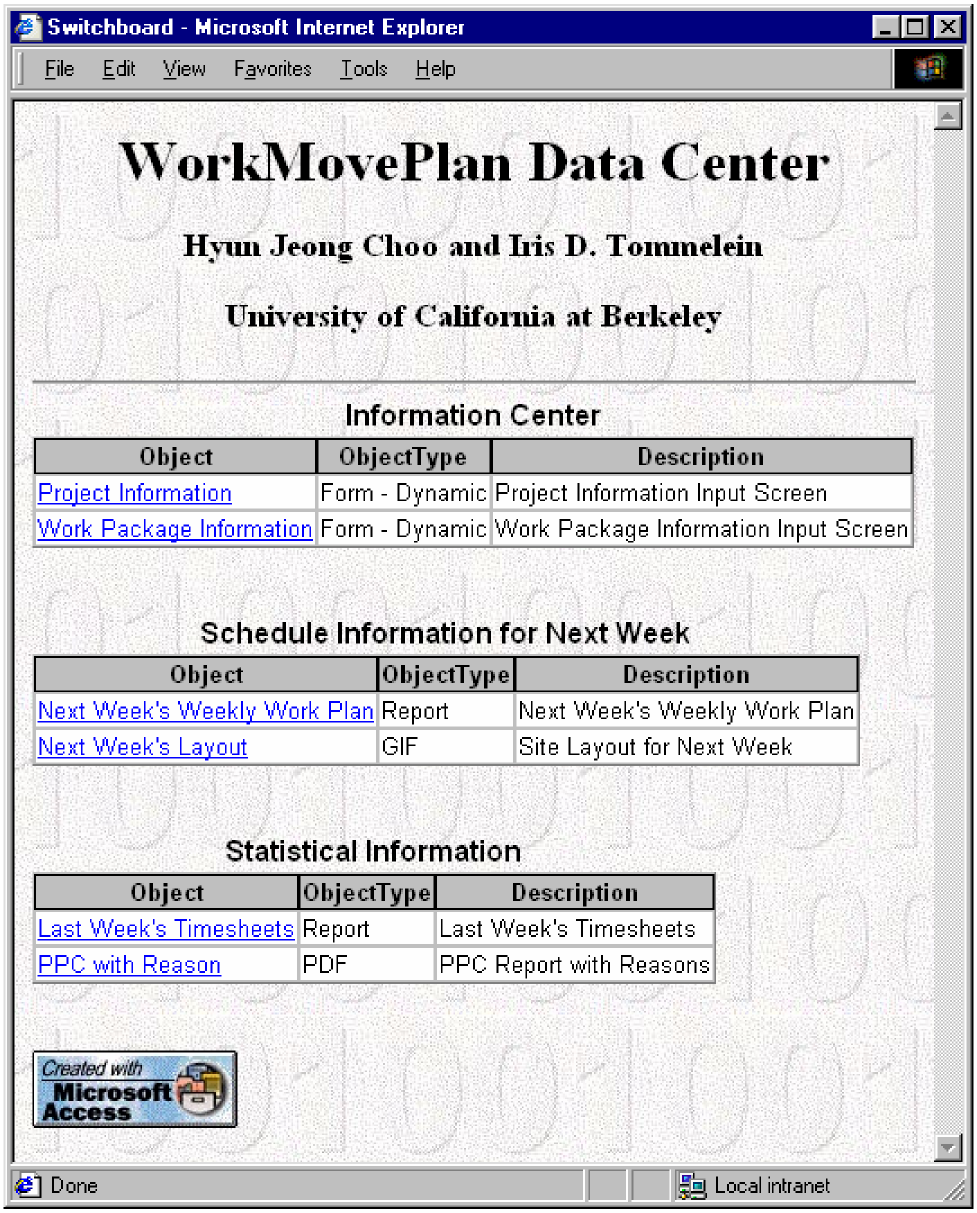
Figure 68. Sample Site Layout using VRML

The process of creating a space schedule will allow the planner to consider constraints that may be overlooked when space is not assigned explicitly. The finished space schedule then can be used to communicate expected space use to the general contractor and among other specialty contractors.

Public information in WorkMovePlan is automatically shared among the WorkMovePlan users. WorkMovePlan also allows project participants to access the latest weekly work plan information through the Web. Figure 69 is the homepage for accessing WorkMovePlan.

WorkMovePlan users can not only view the information but also input and edit the information such as project information and work package information through WorkMovePlan's Data Center, provided that they are given the authorization to do so. Schedule information such as "Next Week's Weekly Work Plan" (Figure 70) and "Next Week's Site Layout" and statistical information such as "Last Week's Timesheet" (Figure 71) and "PPC with Reasons" can be also accessed.

Posting the latest schedule information allows those concerned to schedule their work so that they can avoid (or at least be aware of) conflict on site. People in the home office will be apprised of the current status of on-going work by viewing the statistical information posted by people on site, e.g., the PPC data and reasons posted by people on site. Thus the home office will be able to better assist those on site by focusing their attention to satisfy constraints that have prevented successful execution of schedules. This allows the site office to "pull" information from the home office. It also allows owners or vendors/suppliers to better support site operations by using the latest information.

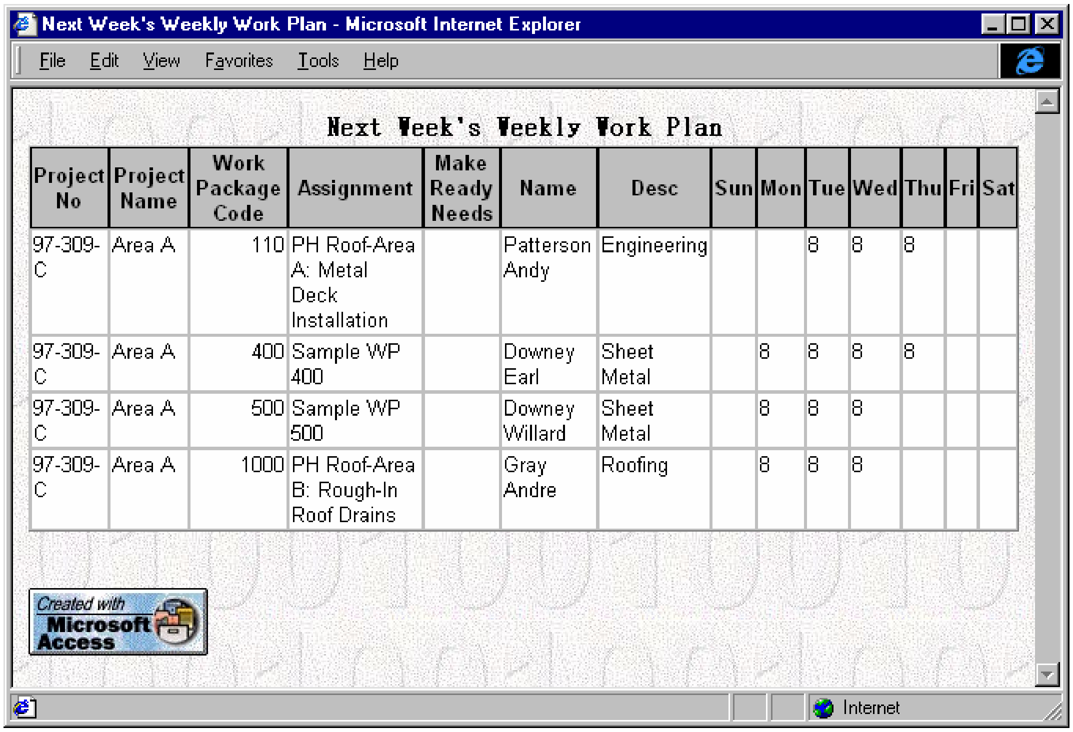


Object	ObjectType	Description
Project Information	Form - Dynamic	Project Information Input Screen
Work Package Information	Form - Dynamic	Work Package Information Input Screen

Object	ObjectType	Description
Next Week's Weekly Work Plan	Report	Next Week's Weekly Work Plan
Next Week's Layout	GIF	Site Layout for Next Week

Object	ObjectType	Description
Last Week's Timesheets	Report	Last Week's Timesheets
PPC with Reason	PDF	PPC Report with Reasons

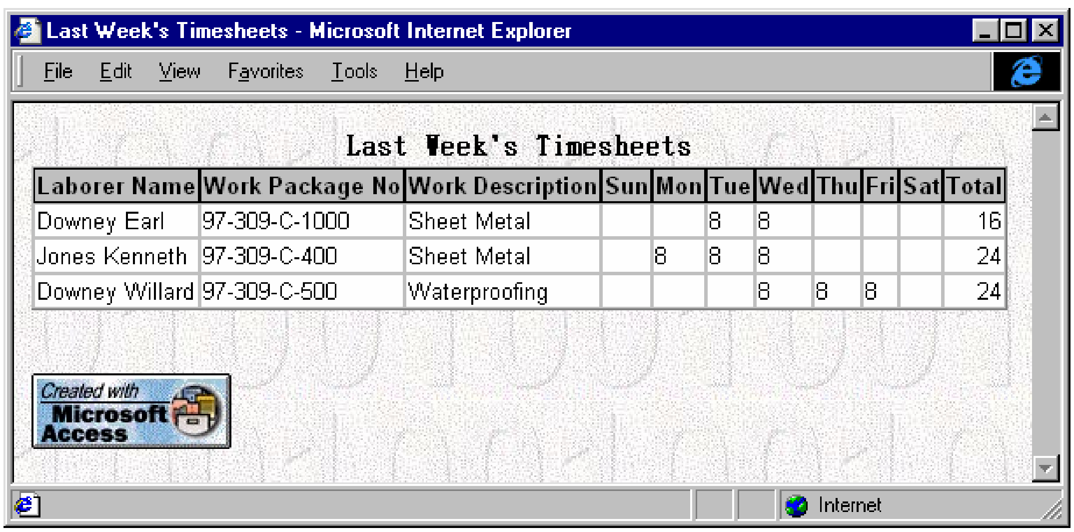
Figure 69. WorkMovePlan Data Center



Next Week's Weekly Work Plan

Project No	Project Name	Work Package Code	Assignment	Make Ready Needs	Name	Desc	Sun	Mon	Tue	Wed	Thu	Fri	Sat
97-309-C	Area A	110	PH Roof-Area A: Metal Deck Installation		Patterson Andy	Engineering			8	8	8		
97-309-C	Area A	400	Sample WP 400		Downey Earl	Sheet Metal		8	8	8	8		
97-309-C	Area A	500	Sample WP 500		Downey Willard	Sheet Metal		8	8	8			
97-309-C	Area A	1000	PH Roof-Area B: Rough-In Roof Drains		Gray Andre	Roofing		8	8	8			

Figure 70. Next Week's Weekly Work Plan



Last Week's Timesheets

Laborer Name	Work Package No	Work Description	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Total
Downey Earl	97-309-C-1000	Sheet Metal			8	8				16
Jones Kenneth	97-309-C-400	Sheet Metal		8	8	8				24
Downey Willard	97-309-C-500	Waterproofing				8	8	8		24

Figure 71. Last Week's Timesheet

6.3 VALIDATION

As was done for WorkPlan and DePlan, LCI member companies (mostly Barnes Construction, Inc, and Gowan Inc.) have tested WorkMovePlan. Below are feedbacks and requested capabilities specifically for WorkMovePlan.

- Coordination Meeting Support

  Implementation of the Last Planner process relies heavily on the ability to collect information especially during the development of constraints, analysis of work package status, and formulation of reasons for failure. Information collection can occur either in a face-to-face meeting or in a distributed fashion. Regardless of how information is collected, coordination meetings will be helpful for project participants to get to know each other and establish a basis for communication, to identify and resolve conflicts, and to clear up vague items. In these meetings, the most up-to-date information needs to be available to the meeting participants in a format that they can easily recognize and interpret. The tools should be easy-to-use and easy-to-understand so that it could be used in the meeting if necessary.

- Effective Information Distribution

  Once all updates have been collected and processed, the latest information needs to be distributed either electronically or in hard-copy format. WorkMovePlan automatically synchronizes with other instances WorkMovePlan to ensure that every project participant has the latest information. WorkMovePlan also allows a planner to view the latest information on the web. This information is either pulled or pushed depending on the frequency of updates and their data formats. WorkMovePlan already provides many preformatted reports, ready to be sent out or printed. What additional information needs to be distributed and in which form needs further study.

During the validation of WorkPlan and Deplan, it was identified that an efficient way to distribute the constraints to each responsible party or person right after the coordination meeting was needed (as discussed in 4.5.1.2). The "Constraint Report by Work Packages" (Figure 72) allows the planner to see all outstanding constraints for a single work package. The "Constraint Report by Responsibility" (Figure 73) prints out a separate page with outstanding constraints for each responsible party.

Work Package No	Responsibility	Type	Constraint	Solution	Start/Due Date	Completed
99535-4-5	**McGrady**		**Install rebar along Broadway**		**6/29/00**	
	BBB					
		Contract	Resolve contract amount		6/14/00	☐
		Design	Resolve weight of rebar on PT deck		6/14/00	☐
		Design	Submit shop drawings to KFFP		6/14/00	☐
	Cortis Elevator					
		Prerequisite	99535-4-9 : Drill elevator shaft		6/16/00	☐
	Divisions					
		Prerequisite	99535-4-3 : Excavate footings		6/15/00	☐
	KFFP					
		Design	Approve shop drawings		6/21/00	☐
	McGrady					
		Design	Submit shop drawings to BBB		6/13/00	☐
		Material	Fabrication of rebar		6/27/00	☐
		Material	Delivery of rebar		6/28/00	☐

Figure 72. Constraints Report by Work Packages

Constraints Report

Responsibility	Work Package No	Type	Constraint	Solution	Start/Due Date	Completed
BBB						
99535-1-5	Install temp. fence					
		Prerequisite	99535-1-4 : Remove stripes from cross walk		5/12/00	☐
		Prerequisite	99535-1-3 : Install closed sidewalk signs		5/12/00	☐
99535-4-5	Install rebar along Broadway					
		Contract	Resolve contract amount		6/14/00	☐
		Design	Resolve weight of rebar on PT deck		6/14/00	☐
		Design	Submit shop drawings to KFFP		6/14/00	☐

Figure 73. Constraints Report by Responsibility (for responsible party BBB)

- Interface with Legacy Systems

WorkPlan, DePlan, and WorkMovePlan are specifically designed to support the lookahead and weekly work planning process. The responsibility for master scheduling is left to CPM-based scheduling tools. However, in order to fully maintain data integrity between the project schedule and the production schedules, WorkPlan, DePlan, or WorkMovePlan, and CPM-based master scheduling tools need to work together. WorkMovePlan allows CPM-based master schedule to be imported from Microsoft Project (Microsoft Corporation 2000c), as discussed in Section 6.2 to promote data integrity between the project schedule and the production schedule. Capability to export to the CPM-based master scheduling tool from WorkMovePlan has not been automated yet. However, author is currently involved in a development of such a tool in a large and complex project.

Additionally, many companies have their own accounting system and are not keen on changing it in any way. Therefore, the Last Planner tools must be able to interact with these systems as well. Other interfaces might include interfaces to a personnel database, an equipment maintenance database, document control tools, etc.

The latest version of WorkMovePlan already has most of these requested features. Nevertheless, some feedbacks were not acted on because they were not directly aimed at providing a reliable and easy to use tool that would promote higher plan reliability.

7 CONCLUSIONS

7.1 RESEARCH SUMMARY

The research presented in this dissertation focused on (1) capturing and understanding of the formal and informal project planning practices as well as production planning practices currently used by project participants during construction, including the method proposed by the Project Management Institute as described in the PMBOK, (2) studying the Last Planner System (LPS) as an alternative planning method, and (3) developing the Distributed Planning and Coordination (DP&C) method to support the adoption and implementation of Lean Construction planning principles and several corresponding tools for use in design and construction.

Distributed planning and coordination presents a view on planning that is very different from the models formally adopted by most practitioners in the construction industry today. The major differences stem from dissimilarity in (1) acknowledgment of and approaches towards managing uncertainty, (2) underlying control paradigms, (3) scheduling environments, and (4) explicitness of planning. First, the current planning model either ignores uncertainty, or reactively manages it through, e.g., time buffers and contingencies, whereas the DP&C method consists of proactively managing uncertainty with a goal to minimize the impact of uncertainty on the project. Second, the current planning model enforces a strong top-down approach, whereas the DP&C method shifts the planning paradigm to a structured bottom-up approach with informed top-down guidance. Third, in the current planning model, each project schedule is created separately, whereas the DP&C method assists planners in creating their project schedules within their job-shop scheduling environment. Fourth, in the current planning model explicit work breakdown and assignment of specific resources at the production level are rarely captured and communicated, whereas the DP&C method guides the planner to break down tasks into manageable sizes and specify the actual resources (laborers, equipment, and space) that are needed to carry out each task. These differences called for the development of a new tool. Thus, WorkMovePlan, was created to guide planners through the Distributed Planning and Coordination method.

Three computer programs based on the LPS were developed during this research, namely WorkPlan, DePlan, and WorkMovePlan. WorkPlan is for specialty contractors to develop weekly work plans. DePlan combines WorkPlan with ADePT (See Section 4.4.1) to represent design process models, perform dependency structure matrix analysis, and develop design programs for projects overall and for individual disciplines. WorkPlan was then extended into WorkMovePlan, to include capabilities for distributed planning and coordination as well as space scheduling. The relationship between these tools is shown in Figure 74.

WorkMovePlan's design and architecture are based on those of WorkPlan and DePlan, which guide the production units in construction and design, respectively, in creating reliable weekly work plans. The knowledge gained from process embedment, database design, interface design, and feedback during creation and modification of WorkPlan and DePlan proved to be valuable in creating WorkMovePlan. There is no doubt that WorkMovePlan needs further improvement and modification. However, these conceptual design and programming efforts has proven that there are no technological barriers in implementing the DP&C method.

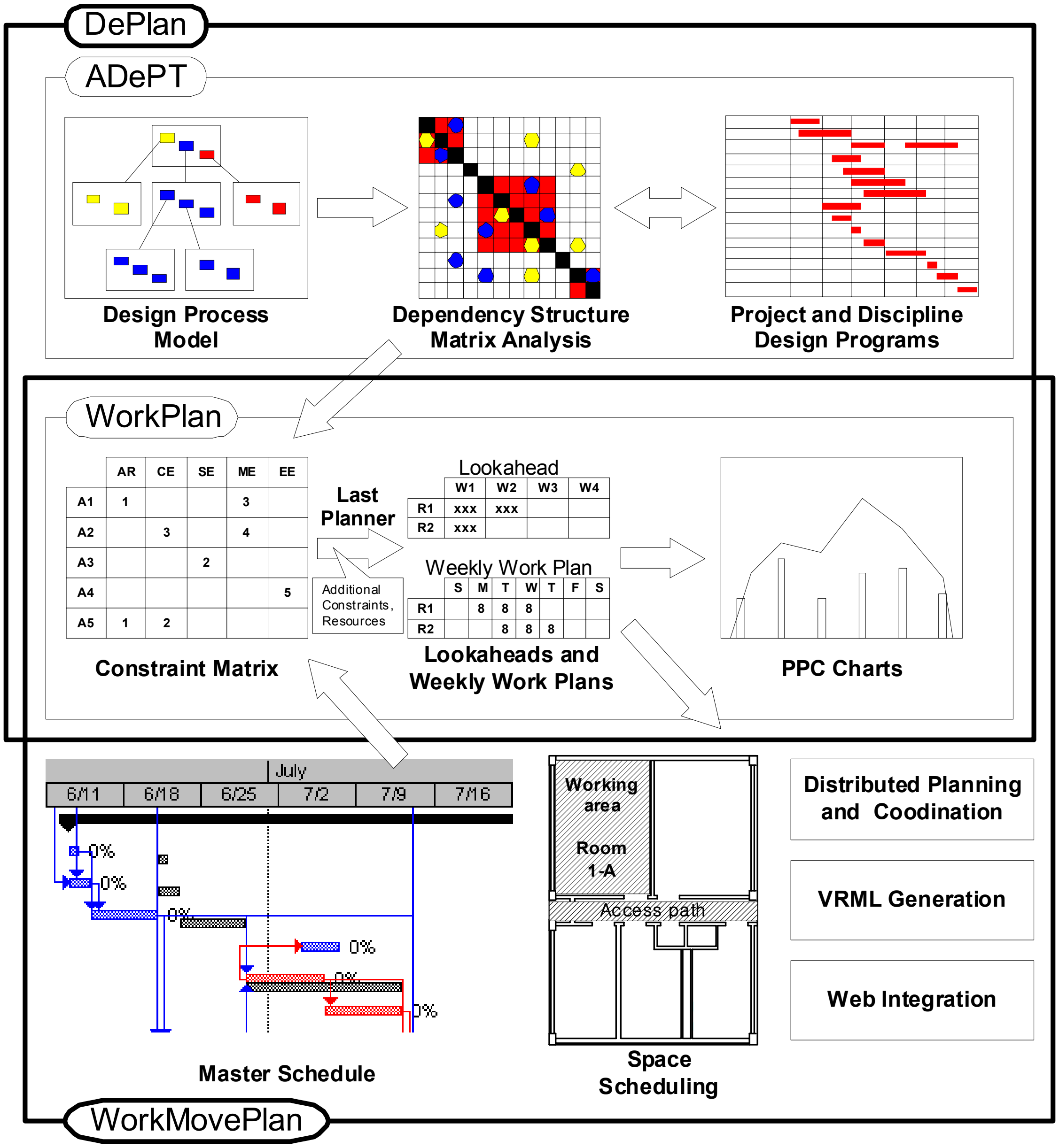


Figure 74. Last Planner Software including WorkPlan, DePlan, and WorkMovePlan

Beta-testers and other people interviewed for the validation process of WorkMovePlan showed varying levels of interest and resistance to adopting the DP&C method as was to be expected. They showed relatively less resistance to change in planning focus and explicitness, than to change in approach to uncertainty and control paradigm. It is expected that the DP&C method or the like will become more widely used in the industry as inefficiencies of tight centralized control are becoming untenable and Lean Construction gains momentum in changing how projects are delivered.

7.2 Contributions to Knowledge

The thesis set forth in this dissertation, i.e., that an interactive planning and coordination method will help to decentralize and improve planning performance by providing communication channels for reliably coordinating schedules at the appropriate level of detail, and the corresponding research, have resulted in several contributions to knowledge.

7.2.1 Understanding of Current Project Planning Practices and Production Planning Practices and Their Interrelationship

This dissertation has presented an overall picture of formal and informal planning, scheduling, and coordinating practices currently used in the construction industry; it also described the interrelationships between those practices. An overall picture was compiled from findings based on (1) review of the literature on various planning methods and planning tools, (2) interviews with project managers, project engineers, superintendents, and foremen from construction companies of varying sizes, and (3) feedback received during implementation and testing of WorkPlan, DePlan, and WorkMovePlan.

On one hand, project planning techniques based on network models (such as CPM) were widely accepted. However, interviewees more often than not complained about their ineffectiveness in managing the production according to the schedule. These findings were consistent with findings of numerous other researchers. On the other hand, superintendents and foremen were using some form of production planning tool to execute their projects. These tools were neither systemized nor formalized. A clearer understanding of the current practices has pointed out a direction for improvement and a need for tools to support the transition towards integrated project- and production planning.

7.2.2 Paradigm Shift from Centralized to Distributed Planning

The Distributed Planning and Coordination (DP&C) method presents a model that is very different from the widely accepted practice of centralized planning, where a single or several planner(s) from a general contractor's organization (or an external planning specialist such as a construction management firm) creates a detailed project schedule with limited input from the specialty contractors. These inputs are usually reactive feedback on planning decisions already made by the project scheduler(s). The DP&C method is based on a distributed control view, where the decision-making responsibility is pushed down to the production units with minimal if any constraints added by the project scheduler(s).

The detailed production plans created in such a distributed environment does not necessarily guarantee the "optimal" solution in terms of duration or cost. It, however, guarantees the accuracy of information regarding activity description, activity duration, activity sequencing, and resource assignment. It also facilitates the buy-in of the production teams that will execute the plans as it is created by them. Thus, it could be argued that the "optimality" of the production plans created in a DP&C environment is measured in terms of how accurately and reliably the plan describes the execution of plan.

The advancement of the Internet as well as other wireless communication technology has brought an end to many formal routes of communication. They have opened up many unorthodox routes for communication between participants. There is practically no way to prevent anyone or any organization from communicating with one another. These communication channels will enable planners to have more accurate and timely information. However, these communication channels may violate or eliminate need for some of the existing channels. These violations may have legal implications. The author has many instances where a more efficient route of communication had to be altered for the sake of meeting legal requirements. Nevertheless, some industry leaders are making effort to minimize such instances.

The trend towards decentralization of decision-making is consistent with movements in other industries. Distributed planning and coordination will create a need for more effective yet more unorthodox routes of communication.

7.2.3 Shifting Single-Focus Planning Focus to Dual-Focus Planning

Specialty contractors' involvement on a project tends to be intermittent and relatively short compared to the total project schedule. Additionally, the required capacity required from them varies from project to project. In order to effectively use their production capacity, specialty contractors work on multiple projects simultaneously or move to and from jobsites as needed. Thus, their planning efforts resemble those used in job-shop scheduling where each job is a designated portion of the project, i.e., their scope of work. A change or a conflict in one project can effect the start date, end date, or resource availability for another project. A shift is thus needed from single-focus planning, which means that specialty contractors' schedules for each project is created independent of each specialty contractor's resource loads and dependencies across multiple projects, to dual-focus planning, which means that specialty contractors' schedules need to be created within a framework that allows their resource loads and dependencies across multiple projects to be explicitly described and managed. WorkMovePlan supports dual-focus planning where specialty contractors can plan their project schedule under a job-shop environment while maintaining links to project information.

7.2.4 Managing Uncertainty and Reliability

The author learned from attending many design and construction coordination meetings and studying planning system performance on several projects that much disturbance can be avoided with proactive management of uncertainty through reliable planning and communication among project participants.

Two by-products of preliminary research, namely the StroboCPM and the 'Parade of Trades' software the author developed, graphically demonstrate the effect of uncertainty and dependency in construction projects. StroboCPM allows users to graphically view the effect of uncertainty on the project duration. The Parade of Trades allows users to graphically view the importance of reliable planning. The author has used the Parade of Trades discussed in 3.6) in many presentations for educational purposes. This software is being freely distributed in order to promote need for better management of uncertainty (http://www.ce.berkeley.edu/~tommelein/parade.htm). The author has also participated in many workshops held by Strategic Project Solutions, Inc. and Lean Construction Institute where the Dice Game (discussed in 3.6) is used to demonstrate the effect of uncertainty and dependency. After the result of the game is reviewed, most of the workshop participants report that the construction industry currently lacks the understanding of effect of uncertainty and dependency. They also suggest that a revolution in thinking is needed in order to move toward recognizing and then proactively managing uncertainty and dependency.

7.2.5 Computer Tool for Production Planning in Construction Based on the Last Planner

Three computer tools have resulted from this research, namely WorkPlan, DePlan, and WorkMovePlan.These are among the first computer-based production planning tools created specifically for use in construction. These tools offer a very different approach to planning than commercially available tools.

The use of these Last Planner tools is closely tied to the adoption of the LPS. Currently, practitioners first adopt the LPS, and then look for supporting computer tools. It remains to be seen whether the use of tools, such as those presented here, can lead to the wide acceptance of lean construction principles with the LPS in its broadest sense, encompassing front-end planning and lookahead planning as well.

7.2.6 Distributed Space Scheduling to Support Production Management

WorkMovePlan adopts the DP&C method to space scheduling. The program facilitates distributed space scheduling by allowing users to create their own space schedules and communicating these schedules to all project participants. Project participants can, thus, have the latest space schedules available and plan their space use accordingly. This research represents one among the first suggestions that space scheduling for construction be done in a distributed fashion. Although much more robust and user-friendly tools are desired, WorkMovePlan has created a platform for further research in this area.

7.3 Future Research Issues and Questions

The author is currently working for a company that is implementing an ASP version of a distributed planning and coordination system, similar to the DP&C system presented in this dissertation, as part of a solution for a very large and complex project. The author's main role is to lead the design process and to program the system, as well as to implement the methodology and the tools to support the design and construction phase of this project. Many research questions remain and new issues have come to bear as this project is advancing.

7.3.1 Distributed Planning and Coordination Method

The author is in the process of further improving the DP&C method. Some questions that need more research are the following:

1. "What is the best work structuring strategy DP&C?"

The latest understanding of the requirements suggests using "work package" as the interface between the general contractor and assignments to support detailing of the production work done by specialty contractors. However, this does not guarantee that the schedules will have adequate detail or an adequate level of abstraction for others to understand what is really going on, as many project participants speak a "different language." Since the schedule serves as a communication tool in the distributed planning scheme, it must be explicit enough for other participants to be comprehensive while at the same time showing enough detail to support coordination effort and conflict detection. Ballard (2000b) proposes phase scheduling as the mechanism for defining handoffs between specialists and between scheduling and control. A further study is required to determine what the right levels of detail are adequate for coordination at the phase scheduling level and production level. The answer to this question also heavily depends on the answers to the next questions.

2. "What is the best organizational structure DP&C?"

The discussion and examples in this research used a specialty-based organization structure, where a WorkMovePlan user corresponds to a specialty contractor. However, the author's current endeavour suggests that a cross-functional group of project participants that represent an area, a product, or a system may be a better organizational structure for DP&C in a large, complex project. This organizational structure allows project participants who need to coordinate their actions more frequently to co-create a solution before it is communicated to others who have fewer coordination needs.

3. "Will participants be willing to detail their schedule and reveal it to others?"

Revealing a detailed schedule to others may commit that party to performing exactly what is in the schedule. Participants fear, if they are unable to deliver, that this will get them into claims and disputes as is all too true when CPM schedules are being misused. Clearly, performance data needs to be used for improving planning performance, rather than for all-too-closely monitoring production units. Also, if the planning system is reliable so that what is scheduled can be delivered, there is less of a chance for a claim or dispute. If claims or disputes do occur, the party that has maintained explicit data on the issue at hand is more likely to be successful to get their point across.

4. "What is the impact of DP&C on the overall system?"

Planning is only one managerial task in administering a construction project. The impact of distributed planning and coordination on other aspects of construction project delivery such as contracts, accounting, or project controls, remains to be studied.

5. "What is the best way to implement the DP&C?"

As discussed in Section 5.5, the main barriers to implementation of DP&C are not technology but many current mental models and contracting strategies. Therefore, project participants need to be continuously taught and trained so that DP&C can be properly implemented. Their contractual relationship with other participants as well as their individual needs must be addressed as well.

7.3.2 Shifting Single-Focus Planning Focus to Dual-Focus Planning

The dual-focus planning system closely resembles the planning process production units actually use in practice today. WorkMovePlan systemizes the process, and may be a first in that regard. In WorkMovePlan, the planners are required to explicitly represent their planning decision. How to best represent data to accommodate both the project centric as well as the production unit centric view at the same time needs further research. Also, the tool needs to be further developed to accommodate "what-if" analyses to better assist planners in developing alternatives and making choices.

7.3.3 Computer Tool for Production Planning in Construction Based on the Last Planner

WorkPlan, DePlan, and WorkMovePlan acan be further improved and expanded. Changes need to occur in architecture, operating platform, and user interface. The scope of the tools needs to expand to include master scheduling including work structuring and supply chain management. The author's experience during this research as well as on-going commercial efforts will allow him to better understand the requirements for these tools.

Various companies and researchers are toying with computer implementations of the LPS. The author hopes that the computer tools developed in this research will encourage others to do the same, so that lean construction will be practiced on a broader scale.

7.3.4 Distributed Space Scheduling to Support Production

The distributed space scheduling system developed as part of WorkMovePlan uses 2½D dimensions to specify space uses. However, for more accurate analysis of alternative space uses and access, the tool needs to be linked with a 3-D product model. As footprints and heights for material and equipment change according to their orientation and stacking method, value may be derived from using 3-D objects.

Also, a scheme to accommodate hierarchical space scheduling has to be developed. As done for planning and scheduling of tasks, space scheduling needs to be developed in a hierarchical fashion (e.g., Tommelein (1989), Thabet (1992)). The general contractor can designate certain areas for each specialty contractor. Then each specialty contractor can develop a more detailed space schedule as space requirements become clearer. In the current implementation of WorkMovePlan, space uses can be overlapped to represent different detail levels of space assignment. However, there is no direct link to accommodate automatic abstraction and grouping of the space use.

7.3.5 Impact of DP&C on Other Project Control Systems

Most large and complex projects use many different computer-based systems including budget and cost monitoring tools, contract management tools, document management tools, drafting tools, 3-D modeling tools, and other planning tools. How DP&C affects the use of these other systems has yet to be made clear. For example, Kim and Ballard (2000) have pointed out that using earned value analysis to measure project progress is contrary to the spirit of the LPS, and the author is currently involved in designing the architecture to use 3-D modeling to enforce the LPS. However, more research is desired regarding these and other project control systems.

7.4 CONCLUSION

The research presented in this dissertation captures the theory and the practice of current project- and production planning and presents the Last Planner System (LPS) as an alternative planning method. The research also presents Distributed Planning and Coordination (DP&C) method as a production management strategy that promotes the adoption and the implementation of the Lean Construction planning principles. Accordingly, the research has resulted in the conceptualization, development, and validation of several tools, namely WorkPlan, DePlan, and WorkMovePlan, for production planning in design and construction. It has also resulted in tools, such as StroboCPM and Parade of Trades, for use in training.

The DP&C method as well as the tools have revealed that the largest obstacle to adoption of distributed planning and coordination is not the technology but the underlying mental model of practitioners that is based on traditional contractual arrangements, organizational structures, and common practices of the construction industry. As the construction industry learns to adopt the distributed control paradigm rather than the centralized control paradigm and develops better understanding and management process of uncertainties, continuous improvement in the quality of project delivery can be expected.

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