

Feasibility of the SIMSUPER Simulation Model in the Renovation of Building Projects

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ABSTRACT

Building renovation projects are unique in its nature and quite different from new building construction projects. Uncertainties and unforeseen conditions play a much bigger role in building renovation projects making construction planning traditional methods not suitable for these purposes. Soft-logic allows for the modification of predefined network models when a new set of conditions is encountered. An existing computer simulation program called SIMSUPER provides such approach. SIMSUPER (SIMulation SUPERvisor) is a network-based, discrete-event simulation model that has the capability of incorporating conditions of uncertainty and to dynamically respond to changed conditions. The model is capable of combining different networks to respond to changed external factors already embedded in the model networks. The logic followed by SIMSUPER has the flexibility of selecting between networks depending on the conditions inputted. SIMSUPER was primarily developed to conduct research in productivity analysis for adaptable tunneling construction, where excavation and support methods are adapted to changing ground conditions.

The main objective of this research is to determine the ability of SIMSUPER to analyze the dynamics of the building renovation process under its particular conditions of uncertainty and to provide the user with the flexibility of adapting the model as these conditions change, optimizing project's productivity. The renovation of Daniels Hall, a four-story dormitory facility at Worcester Polytechnic Institute (WPI), Worcester, Massachusetts, is used as the case study of this research. Two computer runs, the contractor's plan, and observed data were tested using the WPI's running version of SIMSUPER. Differences between the computer simulation and observed actions were found. A hand simulation that incorporates resource allocation, preempting rules and conflict management capabilities was conducted to investigate the observed actions in more detail. The hand simulation was able to replicate the observed actions. The concept contained in the program proved to be efficient. The soft-logic rules that drive the simulation of the process replicated the observed plans.

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TABLE OF CONTENTS

ABSTRACT	ii
ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	iv
LIST OF FIGURES	ix
LIST OF TABLES	xiii
1 INTRODUCTION	1
1.1 General Background	1
1.2 Soft-Logic and SIMSUPER	2
1.3 Research Objective	4
1.4 Report Structure	5
2 BUILDING RENOVATION PROJECTS	7
2.1 Introduction	7
2.2 Planning of Renovation Projects	8
2.3 Buildings' Conditions and Deficiencies	13
2.3.1 Building Exteriors	14
2.3.2 HVAC and Plumbing Systems	16
2.3.3 Electrical Systems	17
2.3.4 Exterior and Interior Finishes	19
2.4 Conclusions	20
3 MODELING TECHNIQUES FOR CONSTRUCTION	

PLANNING	23
3.1 Introduction	23
3.2 PERT/CPM	24
3.2.1 PERT/CPM Background	24
3.2.2 General Characteristics of PERT/CPM Model	25
3.2.3 The Process Network or Precedence Diagram	26
3.3 Queueing Models	34
3.3.1 General Characteristics of Basic Queueing Models	36
3.4 Computer Simulation	37
3.5 Conclusions	39
4 EXISTING COMPUTER SIMULATION MODELS	40
4.1 Introduction	40
4.2 Discrete-Event Simulation Models	41
4.2.1 SIMAN	44
4.2.2 GPSS	45
4.2.3 SLAM II	45
4.3 The CYCLONE Model	46
4.4 CYCLONE-Based Simulation Models	50
4.4.1 INSIGHT	50
4.4.2 RESQUE	51
4.4.3 COOPS	55
4.4.4 STROBOSCOPE	57
4.4.5 Hierarchical Simulation Modeling (HSM)	60

4.5	Additional Tools Complementing Simulation Models	62
4.5.1	Geotechnical Support Graphic User Interface	64
4.5.2	PICASSO	66
4.6	Existing Models and Renovation Projects	69
4.7	Conclusions	71
5	SIMSUPER: A SOFT-LOGIC SIMULATION APPROACH FOR ANALYSIS OF PRODUCTIVITY	73
5.1	Introduction	73
5.2	SIMSUPER and the DAT	76
5.2.1	Geologic Module	77
5.2.2	Construction Module	80
5.2.3	Resource Module	86
5.2.4	Additional Components	91
5.3	The Multi-Tunnel System	92
5.4	Heading and Bench Operations	96
5.5	Soft-Logic Rules	97
5.6	Conclusions	100
6	SIMSUPER IN BUILDING RENOVATION	102
6.1	Introduction	102
6.2	SIMSUPER Modules in Building Renovation	103
6.2.1	Using the Geologic Module for Renovation Projects	104
6.2.2	Using the Construction Module for Renovation Projects	108
6.2.2.1	Combination of Different Construction Methods	108
6.2.2.2	Construction Equations and Variables	110

6.2.2.3	Preempting Rules	111
6.2.2.4	Spatial Tracking	112
6.2.2.5	Heading and Bench Operations	114
6.2.2.6	Multi-Tunnel System	116
6.2.3	The Resource Model	120
6.3	Conclusions	127
7	THE CASE STUDY	129
7.1	Introduction	129
7.2	Case Study Scope of Work	130
7.2.1	Asbestos Abatement	133
7.2.2	Temporary Services	135
7.2.3	Sitework	135
7.2.4	Concrete	136
7.2.5	Masonry	137
7.2.6	Finishes	137
7.2.7	Fire Protection and Plumbing Systems	138
7.2.8	Heating and Ventilating Systems	139
7.2.9	Electrical Systems	140
7.3	SIMSUPER Input and Output Files	140
7.3.1	Input Files	141
7.3.2	Output Files	144
7.4	Sample Runs	146
7.4.1	The Contractor's Plan	146

7.4.2	The Observed Process	153
7.5	Simulation Runs Results and Discussion	156
7.5.1	The Contractor's Plan Simulation Results	156
7.5.2	The Observed Process Simulation Results	159
7.5.3	Manual Simulation	163
7.6	Conclusions	173
8	CONCLUSIONS AND FUTURE WORK	174
8.1	Summary	174
8.2	Conclusions	176
8.3	Future Work	179
	REFERENCES	181
	APPENDIX A - USING SIMSUPER	184
	APPENDIX B - INPUT FILES	201
	APPENDIX C - OUTPUT FILES	230

LIST OF FIGURES

Figure 2.1	Plan view of a typical dormitory facility	12
Figure 2.2	Renovation operations	14
Figure 2.3	Removal of masonry blocks and roof caps for roof membrane replacement	16
Figure 2.4	Plumbing pipes ready to be replaced	17
Figure 2.5	New data-communication lines	19
Figure 2.6	Decontamination unit	21
Figure 2.7	High efficiency particulate arresting (HEPA) filters	21
Figure 3.1	Project planning	23
Figure 3.2	Typical network for the gross removal of asbestos	28
Figure 3.3	Gantt chart	31
Figure 3.4	The CPM network diagram	31
Figure 3.5	The CPM network with slack time	33
Figure 3.6	Simple queueing model	35
Figure 4.1	Components of a discrete-event simulation model	43
Figure 4.2	CYCLONE diagram representing a laborer filling a sandbox	49
Figure 4.3	Resources calling	52
Figure 4.4	Resource handling	53
Figure 4.5	Resource routing	53
Figure 4.6	The geotechnical support graphic user interface	65
Figure 4.7	Knowledge base components	66
Figure 4.8	PICASSO implementing strategy	68
Figure 4.9	The soft-logic approach	70

Figure 5.1	DAT modules	77
Figure 5.2	Segments with different combinations of parameter states and associated probabilities	78
Figure 5.3	Ground class tunnel profile	80
Figure 5.4	Construction simulation module structure	81
Figure 5.5	Simulation system flowchart	85
Figure 5.6	The SUPERVISOR for multi-tunnel systems and resource modeling	88
Figure 5.7	Resource-activity relation	89
Figure 5.8	Partial face excavation	96
Figure 5.9	Multiple drifts	97
Figure 5.10	A network diagram for tunneling excavation	98
Figure 5.11	Simulated events	100
Figure 6.1	Rooms with different combinations of parameter states and associated probabilities and building profile	107
Figure 6.2	Network diagrams for two different building areas	109
Figure 6.3	Relationship among building areas, building classes, renovation methods and resources	114
Figure 6.4	Sample of a network diagram for the renovation of a dormitory bathroom	115
Figure 6.5	Resource flow between the mechanical rooms during the Preparatory phase of the asbestos abatement process	117
Figure 6.6	SIMSUPER modeling of renovation operations at different Locations	119
Figure 6.7	SIMSUPER computer simulation with resource modeling	121
Figure 6.8	Resources model flowchart	123
Figure 6.9	Resources flow	125

Figure 7.1	Daniels Hall	129
Figure 7.2	Plan view of a typical dormitory floor of Daniels Hall	132
Figure 7.3	Daniels Hall renovation project contracting agreement	133
Figure 7.4	Pre-cast concrete parapets and bricks to be removed and replaced	137
Figure 7.5	Sample of WPI's SIMSUPER version main input file	142
Figure 7.6	Contractor's plan for the renovation of Daniels Hall bathrooms	147
Figure 7.7	Contractor's plan for the renovation of Daniels Hall interiors	148
Figure 7.8	Contractor's plan for the renovation of Daniels Hall exteriors	149
Figure 7.9	Sample of the contractor's bathrooms plan as a network diagram	150
Figure 7.10	East bathroom second floor network diagram	155
Figure 7.11	Contractor's plan simulation output	157
Figure 7.12	Observed plan simulation output	160
Figure 7.13	Demolition phase activity network for east and west second floor Bathrooms	165
Figure 7.14	Manual simulation	168
Figure 7.15	A comparison among the planned, observed process and simulated plan for the east and west baths 2 nd floor	172
Figure A.1	A sample of the "monitor.dat" input file	186
Figure A.2	Structure of the network and activity input file	190
Figure A.3	The "l and m group"	190
Figure A.4	The "n group" structure	191
Figure A.5	The "t group" structure	192
Figure A.6	The "s group" structure	193
Figure A.7	The ground file structure	195

Figure A.8	The construction file structure	196
Figure A.9	The equations file structure	197
Figure A.10	The multi-tunnel system file structure	198

LIST OF TABLES

Table 4.1	The CYCLONE diagram modeling symbols	47
Table 4.2	Identical resources	54
Table 4.3	Non-identical resources	55
Table 4.4	Modeling symbols for STROBOSCOPE	59
Table 4.5	Operation sequencing links in HSM	61
Table 4.6	Process modeling elements in HSM	62
Table 5.1	Basic tunnel types	95
Table 5.2	Soft-logic rules	99
Table 7.1	Sample of a simulation statistics round-wise report	144
Table 7.2	Sample of a simulation statistics output file	145
Table 7.3	Activity data for east and west second floor bathrooms	166

1 INTRODUCTION

1.1 GENERAL BACKGROUND

Building renovation projects are unique in its nature and quite different from new building construction projects. The characteristics and conditions encountered in renovation projects make the project planning with precision a very difficult task. Uncertainties and unforeseen conditions play a much bigger role in building renovation projects making traditional planning methods not suitable.

Major characteristics that are commonly found in building renovation projects and that affect productivity analyses for this type of projects include:

- 1) *Sequencing of project activities.* In building renovation projects, is very difficult to predetermine in detail the sequence of activities for the work to be performed. Technical dependencies that exist among project activities must be modified by the characteristics of the building and by the accuracy of the building information that is available during the planning stages.
- 2) *Unforeseen conditions.* As a consequence of the lack of information, several assumptions have to be made due to unexpected conditions. The plan developed by the contractor may suffer numerous changes. In order to account for potential changes, contingencies for renovation projects are very high.
- 3) *Scheduling issues.* Estimating the duration of each task is also very complicated. Defining what constitutes an activity is challenging, because many tasks have a short duration if the predicted conditions occur. However, a very short task may

take much longer due to unforeseen events.

- 4) *Space confinement.* Space congestion presents another difficulty for the project planner. Many tasks need to be performed in very congested spaces. For example, the abatement of hazardous materials used as glue, insulation, fire protection, etc. In many cases these are found within partitions in very enclosed spaces in which is very difficult and time consuming to perform such tasks.
- 5) *Operations reach.* Operations reach refers to the simultaneous execution of various activities at different locations. In building renovation projects, resource distribution and flow are very complex. This is a consequence of the unforeseen condition factor and the activity time duration.

Due to these conditions, contractor's experience and understanding of the work are critical to make accurate estimates of cost and time of execution. Depending only on contractor's knowledge exposes the plan to miss small details that can provoke drastic changes in the operations logic. For this reason, some contractors may rely on network models, like the Critical Path Method (CPM). CPM models are based on a hard logic that prevents their adaptability to dynamic changes in the conditions of work. The question becomes how to model building renovation projects. A soft-logic approach may provide is the best answer.

1.2 SOFT-LOGIC AND SIMSUPER

During the course of construction projects, project planners must review, reschedule and replan due to changes in the expected conditions. This rescheduling process may turn to

be a very complex one and very time consuming (Tamimi and Diekmann, 1988). Providing computer solutions that could adapt to changes in the original conditions is a very key to reduce the number of iterations that a project planner would have to go through to adapt his/her plans.

Soft-logic allows for the modification of predefined network models when a new set of conditions is encountered. An existing computer simulation program called SIMSUPER provides such approach. SIMSUPER (SIMulation SUPERvisor) is a network-based, discrete-event simulation model that has the capability of incorporating conditions of uncertainty and to dynamically respond to changed conditions. The model is capable of combining different networks to respond to changed external factors already embedded in the model networks. The logic followed by SIMSUPER has the flexibility of selecting between networks depending on the conditions inputted.

SIMSUPER was developed to conduct research in productivity analysis for adaptable tunneling construction, where excavation and support methods are adapted to changing ground conditions (Salazar, 1983). The program has been used for productivity analysis of shaft excavation in the Exploratory Shaft Facility at the Yucca Mountain candidate repository site in Nevada. Its use extends to validating productivity rates in the excavation of Mount Lebanon tunnel in Pittsburgh, Pennsylvania; the excavation of the section in Washington Metro, DC; and the Deer Island Tunnel in Boston, Massachusetts. Other analyses have also been conducted in Europe.

In tunneling construction the main source of uncertainty is the variability of ground conditions as the tunnel is excavated. SIMSUPER simulates the geological profile

and internally selects the appropriate excavation and initial support methods based on predefined decision rules. The program determines the impact of these changes on the advance rate and on the corresponding utilization of labor crews and equipment. The output of the simulation determines a probabilistic description of the overall advance rate. This information allows the user to select the most appropriate methods for rapid construction and better utilization of resources. It also aids the user in preparing estimates of labor and equipment costs as well as of time dependent job and home-office overhead charges. Finally, it enables the contractor to establish reliable contingency figures on his/her bids.

By contrast, building construction the sources of uncertainty are different. The most significant uncertainty variables are productivity levels (learning curve), weather conditions, crew absenteeism, space congestion, regulatory requirements, design changes and rework, economic activity level, labor unrest, and other specific variables. In building renovation, these changes occur more frequently.

1.3 RESEARCH OBJECTIVE

The main objective of this research is to determine the ability of SIMSUPER to analyze the dynamics of the building renovation process under its particular conditions of uncertainty and to provide the user with the flexibility of adapting the model as these conditions change, optimizing project's productivity.

In this regard, an extensive literature review about existing computer simulation models was required. From this review, the researcher selected SIMSUPER as the

computer simulation tool for the modeling of building renovation projects. A second literature review included all available documentation about the computer program including publications, Ph.D. and M.S. thesis dissertations, and the programmer's manual. After this review, the researcher trained himself to use the current SIMSUPER version running WPI's UNIX network.

A case study of the renovation of an on-campus dormitory facility provided the required data for the modeling of a real building renovation projects using the features developed for the modeling of tunneling operations in SIMSUPER. These data was built into the simulator and several testing were conducted to prove the feasibility of adapting the program for its use in non-tunneling projects. This report presents the finding of such analysis.

1.4 REPORT STRUCTURE

This report includes an extensive research on SIMSUPER applications as well as on other simulation approaches used in construction operations such as CYCLONE and other CYCLONE-based models like INSIGHT, COOPS, DISCO, and STROBOSCOPE. It also includes the review of a case study provided by the Physical Plant Department at Worcester Polytechnic Institute (WPI). Based on data gather from this study, an assessment on the adaptability of SIMSUPER for the modeling of building renovation projects will be preliminary established.

The second chapter of this report presents a general background of the characteristics that are found in building renovation projects. This includes buildings'

conditions and deficiencies (e.g., exterior and interiors, HVAC and plumbing systems, electrical systems, and finishes), owner and tenants requirements, and planning issues.

Chapter 3 presents an overview of several modeling techniques that are currently used in the academia and industry for construction productivity analyses. These include PERT/CPM models, queuing models, and computer simulation models. Among computer simulation models a discussion of CYCLONE and CYCLONE-based models is presented in Chapter 4.

Chapters 5 and 6 present a more thorough review of SIMSUPER as a soft-logic approach. The modules that compose this program are discussed. Several techniques that are implemented by SIMSUPER are also presented: multi-tunneling systems, heading and bench operations, and soft-logic rules. Chapter 6 discusses in more depth preempting rules and spatial tracking as well as resource modeling and how can they be applied to renovation projects.

Chapter 7 presents the case study from where all data was gathered to build the simulation runs. It presents the scope of the work, construction of input files and output files interpretation for two different plans: the contractor's plan and the observed process. Finally, a formal discussion of the simulation results for the case study. Conclusions and future work are presented in Chapter 8.

2 BUILDING RENOVATION PROJECTS

2.1 INTRODUCTION

Building renovation projects are unique in its nature and quite different from new building construction projects. The characteristics and conditions encountered in renovation projects make the project planning with precision a very difficult task. Uncertainties and unforeseen conditions play a much bigger role in building renovation projects making construction planning traditional methods not suitable for these purposes. During the planning stages of renovation projects, general contractors have to consider several aspects that are not thought off in new building construction projects. These issues force contractors to be more conservative or less aggressive in renovation projects' bids than they usually are for new building construction projects.

In the case of building renovation, the most significant planning variables are considered to be productivity levels, weather conditions, crew absenteeism, space congestion, regulatory requirements, design changes and rework, economic activity level, labor unrest, and unforeseen conditions, among others (Ahuja and Nandakumar, 1985). This last variable, unforeseen conditions, is a major factor for changes in the original plans.

This chapter presents a general overview of the issues that general contractors must take into consideration for scheduling, cost estimating, and resource allocation purposes for building renovation projects.

2.2 PLANNING OF RENOVATION PROJECTS

Scheduling a building renovation project requires paying attention to all the constraints that may be encountered in an occupied building. These constraints have to be thoroughly considered for the prediction of the duration of project activities. The project planner must have to consider the availability of the areas to be renovated. It is common practice to perform the renovation work as the tenant leases expires. The planner needs this information in order to schedule materials arrival time and prepare storage areas. Depending on the tenants' requirements, the work to be performed on a particular area can be scheduled during normal hours or after hours. If the work cannot be done during normal hours, overtime will have to be factored in. As a result, additional activities will have to be scheduled in order to keep the building open as the renovation work is performed. Several activities will be delayed due to the limitations of working around tenants. Basically, the construction process becomes constrained by the owner and tenants requirements.

The owner, tenants, and contractor are all interested in performing the work as fast as possible. However, tenants impose certain limitations in the contractor to minimize the level of disruption. Depending on the construction activities to be implemented, the contractor might have to schedule the work after office hours. Some other activities, those with a low level of disruption, can be scheduled for daytime hours. Scheduling of renovation activities must attempt to minimize the level of disruption of the construction activities on the normal building operation.

Building construction codes have been established in order to provide safety to

the tenants of the building as to the laborers performing the renovation work. These requirements can be divided into three basic areas: means of egress, fire safety, and architectural barriers. Each of these areas have certain priorities (Novak, 1988):

- 1) *Means of egress.* Each tenant must have two safe means of egress from the building. The purpose of this requirement is to provide additional exits in the case that tenants have to escape and one of the exits get blocked.
- 2) *Fire safety issues.* The principal fire safety issues are smoke detection, segregation, and fire suppression. Some codes require the installation of sprinklers, smoke detectors, emergency lighting, and exit signage.
- 3) *Architectural barriers.* Certain building codes have requirements for minimum and maximum height for light switches, elevator controls, telephones, handrails, and drinking fountains. In addition, requirements for audible signals apply for elevator controls. Doors, thresholds, and designs for lobby entrances and stairways; handicapped bathrooms stalls and lavatories are also covered by building codes.

Some other architectural requirements like the number and size of handicapped parking spaces, are related to the building exteriors. In addition, there are requirements that cover the construction of curb cuts, sidewalks, and handicapped ramps. Others emphasize in dust prevention and control. These requirements need to be met during renovation activities.

Once the planner has determined the hours free for construction work, he/she will use his/her own judgement and experience to design the sequence of performance. For

this, he/she will consider the level of difficulty of executing the work, the time needed, the actual conditions versus the ones presented in the building plans, among others. These factors will determine what construction methods will be feasible to finish the job in time and within the budget.

Site restrictions are a very important factor that has to be considered during the planning stages of any construction project. In particular, during renovation projects demolishing activities requires space for dumpsters. This factor can also be critical for the storage of materials in site. In an occupied building the flexibility of using cranes and other lifting equipment when unloading from trucks is very limited. For exterior work, temporary sidewalks and overhead protections have to be provided.

Movement and storage of materials is another constraining factor in renovation projects. Construction materials have to be moved in within a closed structure. On the other hand, removing material from the structure might require the use of cranes or chutes. Due to space limitations, construction materials might have to be stored off site.

In order to reduce the level of disruption between the construction activities and the tenant's services, temporary construction may be required. This applies not only to the architectural system, but also temporary electrical and mechanical systems must be provided during the removal of old systems and during the installation of new systems.

During renovation, unexpected conditions may arrive, causing construction delays. Construction activities will have to be rescheduled, and resources reallocated on site. Contingencies for unforeseen conditions have to be factored in.

Finally, clean up of the building site is a very important activity to consider. Due

to the fact that renovation is performed within an occupied building, more clean up is required if comparing with new construction clean ups.

Accurate cost estimates of any construction project depends on the experience and good judgement of the estimator. Also, they will depend on the amount of historical data at the disposition of the estimator. In renovation projects, the estimator will be able to make an accurate estimate if, having all the characteristics mentioned, he/she understands that the level of control over a renovation project is reduced compared to new construction projects. Because the control is pretty much on the tenants' hands, the ability to make accurate estimates is limited. As a result of this situation, renovation projects' estimates are characterized by high contingencies. These contingencies will add an extra cost within a range of 5 to 30% over the total estimated cost (Novak, 1988).

There are other issues that are commonly encountered in building renovation projects, which are of enormous relevance during the planning aspects of the work. For example, consider a typical dormitory building facility (refer to Figure 2.1).

This plan view shows the four major building areas in which renovation operations are taking place: bathrooms, bedrooms, hallways, and exterior facade. In this particular case, the demolition of the project, within the bathrooms requires all electric and plumbing fixtures to be removed. Also, toilet partitions, mirrors, doors, drop ceilings, and partitions have to be demolished. This demolition work takes place before and after all asbestos-containing materials (ACM) are removed, from plumbing pipes. These tasks are going to be executed by several specialized crews: demolition, HVAC, plumbing, electrical, and asbestos crews. Some of these operations are performed simultaneously.

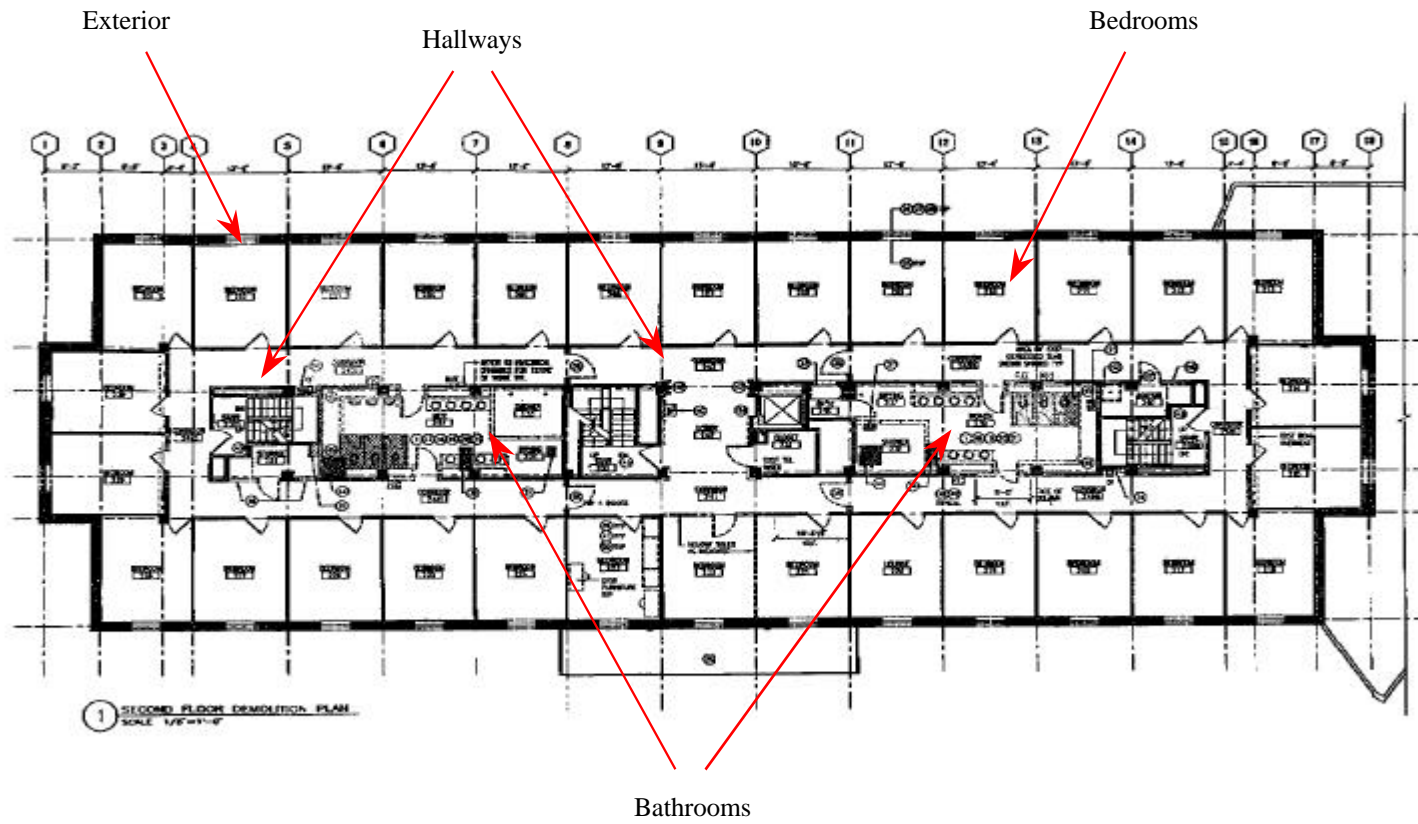


Figure 2.1. Plan view of a typical dormitory facility

This situation raises issue of space confinement and operations reach. Multiple tasks are performed in a small and congested area (see Figure 2.2a).

In addition to the issue of space confinement and operations reach, the presence of asbestos in unexpected areas forces the contractor to make changes in the project plan. In many cases, the contractor has difficulties identifying all building locations in which asbestos may be found. As in the case of the bathroom shown in Figure 2.2(a), asbestos was found within the bath partitions, as an insulator of plumbing pipes. As a result, there is no predetermined sequence of activities.

Figure 2.2(b) shows the operations being performed in the bedrooms. As the operation shown, it is common to find that certain operations are very short in length. This aspect makes harder to accurately predict and monitor the flow of resources within the facility. The purpose of Figure 2.2(c) is to show that, while all the mentioned operations are taking place in the facility's bathrooms, bedrooms, and hallways, there are other tasks being executed in the exterior of the building. In other words, it is very likely to have operations running simultaneously in different building areas.

In summary, these issues of changes in sequence, unforeseen conditions, tasks' duration, space confinement, and operations reach, makes the planning process of building renovation projects a very challenging one.

2.3 BUILDINGS' CONDITIONS AND DEFICIENCIES

A thorough investigation of the actual building conditions must be performed in order to predict duration and cost of the renovation work. In renovation projects, actual building



Figure 2.2. Renovation operations

conditions become the contractor's constraints. In some cases, these actual conditions will determine which contractors are capable to perform the work. Some of the deficiencies commonly encountered in old buildings are discussed in the next sections.

2.3.1 BUILDING EXTERIORS

Aging of a building exposes it to weathering processes that could structurally damage the facade system of the building. As time passes, the waterproofing of exterior walls and

exterior roofs suffers the attack of the weathering. Cracks in walls and roofs allow the water to penetrate the building interior, especially in masonry and concrete buildings. In masonry buildings, the caulking will get cracked due to the changes on the weather conditions during long periods of time. Cracks can also be caused by ice infiltration into joints in concrete walls. Steel buildings are not exempt of this attack either. Steel facades must be inspected for corrosion. Water leaking through walls could become a serious problem, causing structural damage to the curtain wall and its supports.

Some of these problems can also be encountered in exterior roofs. Weathering related problems, weakening of membranes, and water leaking, are the most common roof systems' problems. To prevent water leaking, in walls and roofs, sealing of facades must be improved. An investigation of the roof flashing must be performed in order to determine the degree of disintegration. In addition, terminations of the membrane should be observed to determine the sealant condition, or to check for blistering and cracking. Other waterproofing methods like paving blocks increase the moisture within the roof materials. This moisture acting against the roof membrane may cause puddling.

Lack of insulation is another problem that could be found in old buildings. Most of the systems used before have inefficient coatings. This factor affects tenants comfort. The resistance values of old buildings facades have been changed. Old systems' resistance values fall below new values. In addition, solar systems are another development in new buildings that is not present in old buildings (refer to Figure 2.3).



Figure 2.3. Removal of masonry blocks and roof caps for roof membrane replacement

2.3.2 HVAC AND PLUMBING SYSTEMS

HVAC systems of old buildings are not as efficient as those in new buildings. Older systems are less flexible. New insulation systems does not require high volumes of airflow, factor that makes old systems over designed. Replacing air conditioning motors and pumps with smaller units can solve this situation. Airflow control, temperature control, air speed control, running and shut down times are another set of efficiency problems particular of old systems. However, if the HVAC system is in good condition, most owners decide to keep it than to replace it. Since the replacement cost of this type of system is very high.

The most significant problem in plumbing system is related to the pipe material. If the material used does not comply with the local building codes, all pipes have to be replaced (see Figure 2.4). Another important issue is related to hot water distribution.

Most old buildings were equipped with just one boiler. This makes hot water distribution inefficient, specifically when it has to be pumped to upper floors. New buildings provide separate heaters on every story. Other than these, restrooms and water drinking fountains must be capable of serving handicaps because of new building code requirements.

2.3.3 ELECTRICAL SYSTEMS

There are four common shortcomings of older high voltage electrical systems (Novak, 1988):

- 1) *Insufficient vertical riser space.* Old buildings do not provide enough core space to distribute additional power capacity to upper stories.



Figure 2.4. *Plumbing pipes ready to be replaced*

- 2) *Undersized transformers.* Old transformers do not provide the actual demand and contain PCB, which is a hazardous material that has to be removed and disposed.
- 3) *Inefficient lighting fixtures.* New lighting technology can reduce the space lighting energy demands. This helps to offset the increased energy requirements of actual office spaces.
- 4) *Lack of separate meters.* Past systems do not provide the separate meters for each tenant.

Communication systems are also more demanding in these days. Many of the telephone system features in actual buildings are not found in older communication systems. For this reason, old buildings do not provide sufficient room above drops ceilings or below raised floors. This constraint brings the issue of installing more wiring ducts. PVC for conduit is not an option because its presence is prohibited by the building code requirements.

Communication systems bring some uncertainty and potential danger to the renovation process, and trying to determine which lines are active could be very time consuming. Commonly, electrical system's plans do not represent what is on site. It is recommended to take out all the existing lines and replacing them with all new wires (see Figure 2.5).

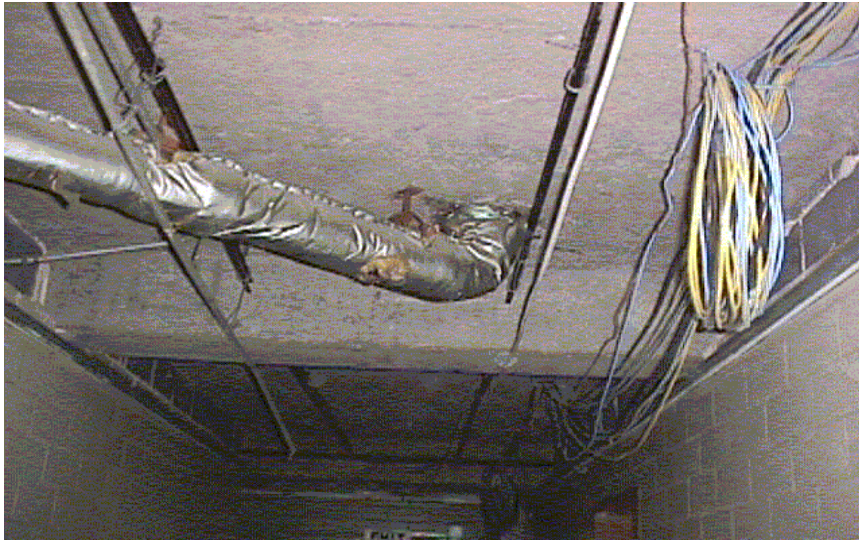


Figure 2.5. New data-communication lines

2.3.4 EXTERIOR AND INTERIOR FINISHES

Building exterior and interior appearance deteriorates with time due to continuous usage and aging of the facilities. Building interiors like partitions, elevator cabs, carpets, restrooms, furniture, corridors, ceilings, and doors receive most of the damage. Water penetration will damage interior partitions and ceiling tiles color. In the interior of the building, proper signage for emergency exits and maps of every floor are required. Carpets get severe damage due to the continuous traffic of tenants. Elevator systems need to be updated to satisfy the tenants traffic demands. Handicapped service capabilities like handicapped bathrooms, and handicaps drinking fountains must be provided.

A major problem encountered in old building interiors is the presence of asbestos. Asbestos has been used in office buildings for the fireproofing of structural steel members and as thermal insulation for hot water pipes or air conditioning ducts. New

building requirements prohibit the presence of asbestos. Before any renovation work is performed, all asbestos needs to be disposed. This is one of the most critical issues within the renovation process.

Contractors have to be very careful on how to handle and dispose this material. Tenants can not be exposed to it, they must have to be moved out, along with furniture, within the area under asbestos disposal, and the space has to be isolated. All ventilation to this space must be blocked. Also, the space must be sealed with various layers of plastic and duct tape. Decontamination chambers must be provided for laborers to enter and exit the area, in order to eliminate the possibility of contaminating other building areas. Blowers must provide pressurization with High Efficiency Particulate Arresting (HEPA) filters (refer to Figures 2.6 and 2.7).

Building exteriors demand periodical improvements. Exterior walls and facade, landscapes, sidewalks, parking areas, and building entrances have to comply with local building codes new requirements. Building entrances must provide ramps for handicaps access. Facades sheetrock is damaged by recurrent water leaks. Also, air infiltration may be noticed when people stand near exterior wall openings. Air infiltration can also produce noise problems, especially on high rise buildings.

2.4 CONCLUSIONS

The main characteristics of building renovation projects have been presented in this chapter. The main issues discussed are:



Figure 2.6. Decontamination unit



Figure 2.7. High efficiency particulate arresting (HEPA) filters

- 1) Existing conditions of old buildings HVAC, plumbing, electrical and communication systems, as well as exterior and interior finishes, and facade systems;
- 2) Owner and tenants driven contractor constraints; and
- 3) Other issues like changes in planned sequence, unforeseen conditions, space congestion, and operations reach.

The issues and constraints hereby presented have to be thoroughly considered for the prediction of the duration and cost of the project activities. The next chapter discusses the tools that are available to general contractors for the planning of construction projects and how these tools could be implemented for the planning of building renovation projects. Their advantages and limitations are also well reviewed.

3 MODELING TECHNIQUES FOR CONSTRUCTION PLANNING

3.1 INTRODUCTION

The planning of building renovation projects is a very difficult task for general contractors (see Figure 3.1). As it was discussed in Chapter 2, the contractor lacks control over the project schedule compared to new building construction projects. For this reason, contingencies in renovation projects tend to be very high (5 to 30%).

The contractor's experience and judgement become critical in the determination of contingencies. Due to time constraints, contractors are forced to come up with an educated guess. To accurately assess these contingencies, contractors could make use of available planning tools like the Critical Path Method (CPM), queueing models, and computer simulation.

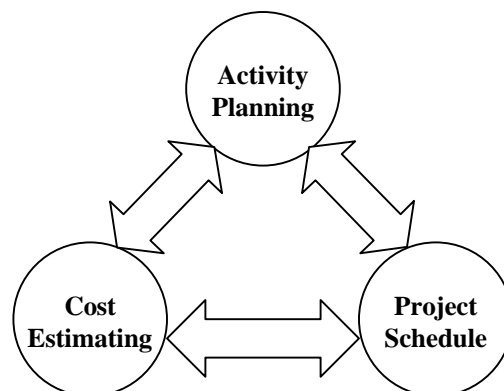


Figure 3.1. Project planning

This chapter presents general characteristics, advantages and disadvantages of using these tools in the planning of building renovation projects. The first section of this chapter presents the Program Evaluation and Review Technique (PERT) and the Critical Path Method (CPM) which are currently used in the construction industry for activity planning. The following section presents the queueing model. Queueing models have proven their effectiveness for resource allocation and identification of areas of potential bottlenecks. Finally, a discussion of computer simulation and its use for productivity analyses of construction processes is presented.

3.2 PERT / CPM

3.2.1 PERT/CPM BACKGROUND

The Program Evaluation and Review Technique (PERT) and the Critical Path Method (CPM) are two network-based procedures that were originally developed with the purpose of managing project schedules for manufacturing and construction projects, respectively. PERT and CPM have their origin from 1956 to 1958 (Kerzner, 1995).

PERT was developed to assess control issues regarding the Polaris Missile Program contracts of the U.S. Navy Special Projects Office with Lockheed Aircraft, Co. The major concern was to determine the completion date for all contracts by means of a three-point estimate approach. This model did not consider cost as a variable. A later version of this technique, named as PERTCO (PERT with costs), introduced cost into its analysis.

On the other hand, Du Pont Company, a chemical manufacturer, developed an

approach that not only included scheduling but also cost estimates. The company started using this approach for the construction of chemical plants within the U.S. This technique was originally called Project Planning and Scheduling (PPS), nowadays known as the Critical Path Method. This approach is widely used in the construction industry.

3.2.2 GENERAL CHARACTERISTICS OF PERT/CPM MODEL

PERT and CPM provide the basis for the analysis of the sequence and dependency among the activities to be performed during a specific project. These management tools provide the information needed for scheduling and based on required completion dates, contractors determine the number of resources (manpower) and equipment required to meet those dates. For instance, resources are not explicitly recognized in the network diagram. They allow identifying *critical* activities that should be carefully monitor for project success. Based on the project schedule, project costs can also be estimated. Even though there are many uncertainties in construction, these techniques provide estimates and allow contractors to review the process anticipating certain conditions that may occur during actual construction.

Different project scenarios could be evaluated to determine their impact on project performance or completion. The logic of the process can be changed to determine the impact on project completion time and cost. For example, two different construction methods for building construction (i.e., up/down versus traditional method) could be evaluated using the PERT/CPM approach to determine which alternative should be implemented based on time and cost constraints. Another option for analysis purposes

could be the use of a range of values or probabilistic distributions for the duration of the activities, like in PERT (e.g., most pessimistic, most likely and most optimistic activity completion times). These sensitivity analyses provide deviations in project schedule and project costs that will be the key for decision making. This characteristic assesses the effect of change orders, overtime or deductions and its impact in project cost and completion.

As will be discussed in the next section, PERT and CPM are network-based models that ease the decision making process for a project of any size. As mentioned before, the graphical nature of PERT/CPM allows the user identifying *critical* activities. The word *critical* suggests that special attention should be given to these activities in order to keep the project on schedule. Any delay in these critical activities will definitely delay the project completion (refer to section 3.2.3 for more details).

3.2.3 THE PROCESS NETWORK OR PRECEDENCE DIAGRAM

In order to accurately analyze and review construction operations, schematic networks or precedence diagrams are constructed. These networks present all the operations that have to be executed for the completion of work tasks.

For example, assume that during a renovation project, asbestos have to be removed from water pipes. The gross removal process is composed of three general phases: preparatory phase, asbestos removal and removal of all barriers. Each one of these phases could be broken down into various activities:

- 1) The preparatory phase include the installation of special polyethylene sheeting

that covers all surfaces that could absorb airborne particles. This sheeting is also used as a barrier to prevent the airborne particles to be dispersed to adjacent rooms.

- 2) Another activity that is part of this phase includes the installation of a High Efficiency Particulate Air Filter (HEPA) that will filter all airborne particles larger than 0.3 microns.
- 3) The last activity of this first phase includes the installation of the Decontamination Unit (DECOM). These are a series of connected rooms with polyethylene doorways for the purpose of preventing contamination of areas adjacent to the work area. Depending on the number of resources that are assigned to a project, these three activities could be performed simultaneously.
- 4) Once the preparatory phase is completed, the next step is the removal of the asbestos, which is commonly used as an insulator, from all pipes' surfaces. This activity includes the disposal of the asbestos material.
- 5) Once all asbestos have been disposed, a hygiene consultant (IH) tests the air quality to ensure that there are no airborne particles that could represent a hazard to the health of any person.
- 6) The last phase includes the removal of all barriers. This includes the removal of all sheeting, of the decontamination unit and the air filter.

All these activities can be presented in a process network as the one shown in Figure 3.2. The notation used to develop the network presented in this figure is known as the *precedence notation*. Here, each activity is depicted as a circle or a rectangular box.

An *activity* is a single task that contributes to the total process of construction. It is one single step that has certain duration. The sequence lines that go from one activity to another indicate the dependencies between activities. In addition to this notation, there is a second notation, the *arrow notation*, in which each activity is shown as an arrow.

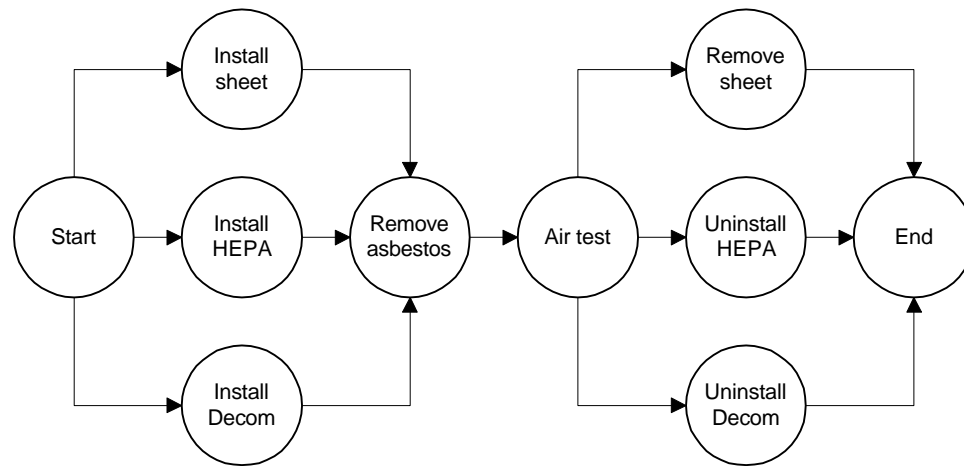


Figure 3.2. Typical network for the gross removal of asbestos

This diagram serves the purpose of demonstrating all dependencies among project activities and the process' logic. By looking at this network, without really understanding the process, the reader could conclude that once the sheeting has been installed, as well as the decontamination unit and the air filters, then the asbestos can be removed. Once the IH consultant has approved the air quality, then all barriers are removed and the DECOM and HEPA are uninstalled.

The correctness of the PERT/CPM network depends on the experience and judgement with which it is generated. The network to be constructed must accurately replicate the process by which a project is going to be performed. At the initial planning

stages of the project, the general contractor develops a general or conceptual plan. This plan is then passed to the subcontractors to fill in the process and details of their work. In other words, the level of detail with which this network is developed and transformed depends on the level of expertise in the different segments of the project of the person constructing it. The conceptual steps that help to construct a CPM network are discussed in the following section.

In order to construct the network or precedence diagram, the process to be modeled has to be broken down into a set of activities. The number of activities in which a particular process is broken down depends on the level of detail required to perform certain analysis or the use that will be given to the model's output. If the network is too general, relevant steps of the process could be overlooked, not providing enough information to describe the process accurately. On the other hand, if the level of detail is extreme, it will be more difficult to identify clearly which steps of the work are more significant.

As mentioned before, the level of detail is a function of the user's needs as well as the project phase for which the plan is being developed. For example, during the conceptual stage of a project, the plan is very general since it is only needed to present the client a general scope of the work. However, if the information is required during the construction phase, it must be in as much detail as to enable the contractor to supervise daily activities.

Consulting with experts on the different trades of the project (i.e., plumbing, electricity, masonry, etc.) can be useful to develop a valid network. Integrating

knowledge from all project divisions will definitely result in a useful plan. This interaction will provide management with logical aspects of the process, which are the keys to understanding the technical dependencies among all activities. As these dependencies are defined, the sequence of the process is also determined. Reviewing the technical dependencies and constraints that will influence the start, execution, and end of an activity, help to recognize areas of conflict and potential delays. These conflicts may arise because certain activities have a higher priority of execution than others do or because certain activities are limited by the availability of resources. Also, based on the logic of the process, certain activities may require the completion of other activities before their start. A mistake in recognizing this logic implies that the network is not valid.

Once the user has identified the logic of the process as well as dependencies among all activities, then the project plan can be presented in the form of a network diagram. Gantt charts may be helpful to develop the CPM network (see Figure 3.3). The Gantt chart presented in Figure 3.3 can be easily converted into a CPM network diagram as shown in Figure 3.4.

The network presented in Figure 3.4 is a management planning and control tool. Based on the information presented on this network, the user can determine how much time is needed to finish the work. Based on this time, the user can also estimate the total project labor cost. In this notation, arrows are used to link one activity or various activities with others and to represent all dependencies among them. The circles are events; for example, the circle that contains the activity "*Install sheet*" represents the start

of that activity. The arrow is the activity itself, which in this case has duration of 130 minutes¹.

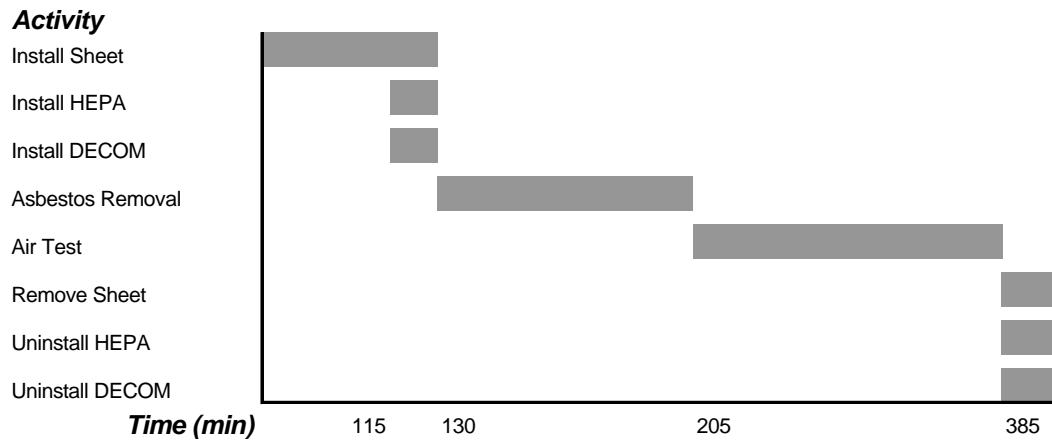


Figure 3.3. Gantt chart

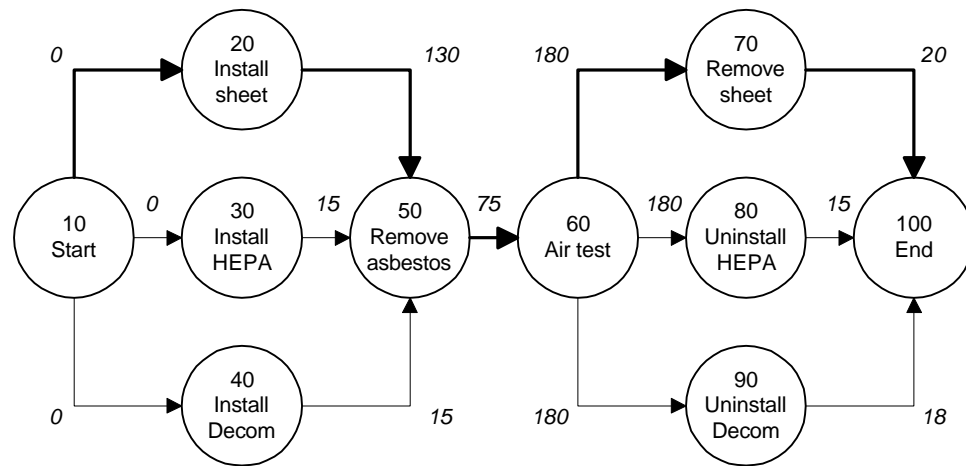


Figure 3.4. The CPM network diagram

As can be observed from the figure, all activities are preceded either by an activity called *Start* or by other activities. In this case, the "Start" activity is followed by

¹ The "Start" and "End" activities are considered dummy activities.

three activities (*Install Sheet*, *Install HEPA*, and *Install DECOM*). Each activity must be followed by at least one activity, until an activity called ***End*** is reached. In addition, time advances from left to right. Using this notation, all activities must start once its preceding activities have been completed or at the earliest possible occurrence of the starting event of the activity. In other words, there are no overlaps between project activities start and finish.

Each activity is given an ***Activity Identification Number***. This number is presented above the activity's description as shown in Figure 3.4. Some users prefer to use identification numbers in multiples of ten in order to leave gaps to accommodate project revisions. For instance, some new activities might be inserted into the network between existing activities.

With the information presented in the network diagram of Figure 3.4, it is possible to determine the critical path, which is represented by the bold sequence lines. This path is established by the longest time span through the total plan of events. Since there is only one path that is the longest, the other paths must be either equal or shorter in length than the critical path. For this reason, there must exist events and activities that can be completed before the time when they are actually needed. This time differential between scheduled completion date and the required date to meet critical path is defined as the ***slack time***. All activities within the critical path have a slack time equal to zero. Any change in the duration of these activities will result in a slippage of the project completion date. In this particular example, the critical path is composed of events 10-20-50-60-70-100. All these events are the most critical for the success of the project. For this

reason, special attention must be given to these activities.

All events and activities that are not part of the critical path have a slack time different than zero. In Figure 3.4, events 30, 40, 80 and 90 are not in the critical path. From the start of the project to the removal of asbestos a period of 130 minutes is required, however if the path 10-30-50 is taken, it will only required 15 minutes as well as path 10-40-50. This means that events 30 and 40 could start from time zero to 115 minutes. Taking into consideration these slack times, the user could more effectively allocate resources for a better balance, reducing idle time periods. Once the slack time is calculated for each event on the CPM network, the earliest (E) and latest (L) starting dates of all events can also be calculated (refer to Figure 3.5).

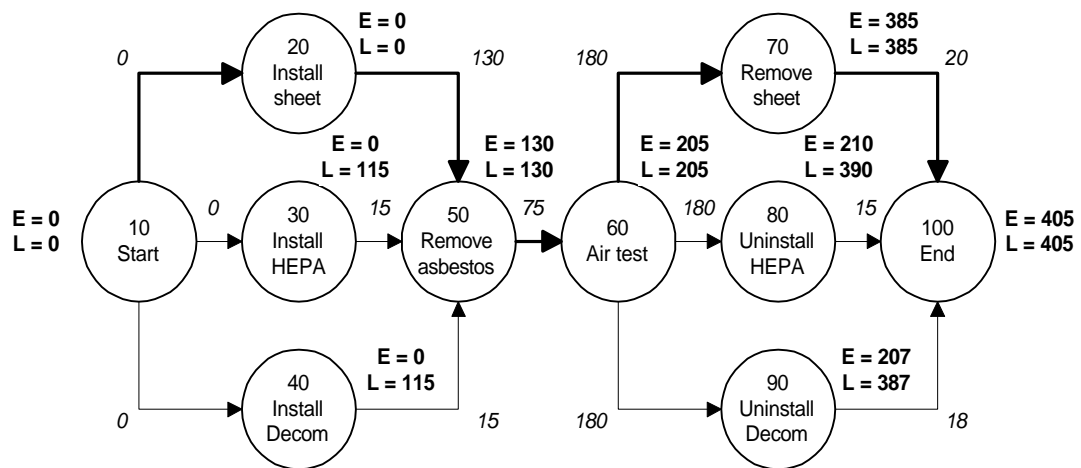


Figure 3.5. The CPM network with slack time

As can be observed from Figure 3.5, the events and activities on the critical path have the same earliest and latest date. By contrast, the earliest time for event 30 (0 min.) and the latest time, which is obtained by subtracting the time required to complete the

activity from events 30 to 50 (15 min) from the latest starting date of event 50, are not equal ($130 - 15 = 115$ min).

Using this graphical model, it is possible to identify the earliest date on which a particular activity is going to start or end. Some variations of this approach that are currently used are the implementation of ranges for the duration of activities in PERT (i.e., optimistic, most likely and pessimistic duration). These approaches allow calculating the "risk" in completing a project (Kerzner, 1995).

3.3 QUEUEING MODELS

Construction processes can also be modeled as queueing or waiting line problems. In construction projects, units are served or delayed due to resource states, which are defined as idle or busy.

When units arrive to the site, these units are processed directly if the processor is idle. When units wait pending processor is busy, waiting lines are developed for a time period. This time period depends on the processor rate and the arrival rate of the units to be served or processed. This queue or waiting line is either empty or occupied by a specific number of units that are delayed until the processor is ready to serve. Once the processor is idle, the number of units in the waiting line is reduced by the number of units that are immediately served by the processor. At the instant that those units are served, the processor becomes busy.

A classical example of a queueing approach in construction processes is the arrival of concrete mixer trucks at a concrete mixing plant. In this case, the units in the

waiting line or mixer trucks are served by the processor (i.e., concrete mixing plant loading system) as they cycle in and out of the system. Figure 3.6 shows a graphical representation of this simple queueing system. As can be observed, this system consists of a processor activity (loading system) and the waiting line (mixer trucks queue). All trucks arrive to the concrete plant, are loaded, and leave the plant. Once the mixer truck exits the plant, it proceeds to take the mix into the construction site, where it releases the mix and returns back to the plant to continue the cycle. This cycle finishes until the required number of cubic yards of concrete are released on site.

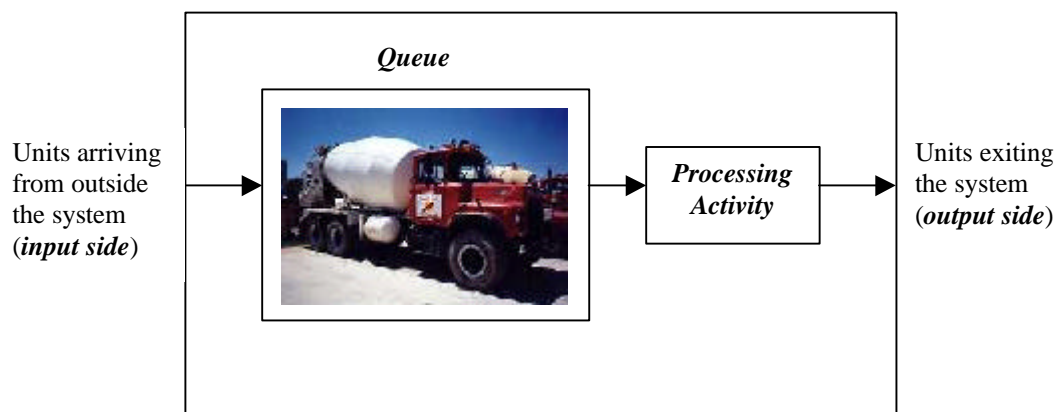


Figure 3.6. Simple queueing model

The part of the cycle that engages all operations since the truck leaves the plant and returns back to it is called *back cycle*. This cycle is characterized in terms of the arrival rate of the mixer trucks at its input side. These activities are not of interest to the model presented in the figure.

Is very common to see, for queueing systems in construction, that the processor will be moving from point to point to serve the units. By contrast, in most manufacturing

processes, for which queueing models were first developed, the processor is always stationary and the units are the ones arriving to and exiting from the system. For instance, during formwork operations, laborers (servers) will be supplying wood panels to carpenters to place them in the wall (client). The arrival time of the carpenters to be served is the rate at which they receive the panel and install it. The processor time is the time that it takes to the laborers to run one cycle.

3.3.1 GENERAL CHARACTERISTICS OF BASIC QUEUEING MODELS

There are four major characteristics of queueing models. They are as follows:

- 1) The first characteristic of queueing models is the arrival rates of units to the input side. These rates can be represented by random or deterministic time intervals. The mathematical solutions of this problem could assume exponentially distributed interarrival times and processing times. This assumption gives a mathematical expectation of an interarrival time value, from which a discrete probability is established (Halpin and Woodhead, 1976). This probability distribution is called Poisson distribution.
- 2) The number of laborers and carpenters or population size is another factor that characterizes the input process of the queueing system. Populations are defined as finite or infinite. In the finite population, units are arriving the system from a finite pool (resource center). These units are reentering the system until certain number of cycles is reached and the operations end. This type of model is known as the *finite queueing model*. By contrast, in the infinite population, units are entering the system

from an infinite resource center. In this model, units do not reenter the system. This type of model is known as the *infinite queueing model*.

- 2) A third characteristic is the processor's serving rate. It is commonly assumed that this rate is exponential. Although, deterministic rates can also be considered.
- 3) Finally, the sequence in which arriving units are served by the processor is another important factor. For construction processes, the first-in-first-out (FIFO) systems are the most commonly used.

In the modeling of construction processes, the client is considered to be stationary while the server moves to serve its clients.

3.4 COMPUTER SIMULATION

Computer simulation is used as an alternative technique to make prediction of system performance and to understand its behavior (Law and Kelton, 1991). In order to simulate these operations, the process or *system* has to be studied in thorough detail in order to know how does it works. From this study, certain assumptions are made and are translated into a set of mathematical or logical relationships. These relationships constitute what is called a *model*.

Based on the complexity of the model, algebraic, calculus or probabilistic methods can be used in order to obtain an analytic solution. Although, due to the complexity of real-world processes, like many in the construction industry, computer simulation represents an automated mean capable of numerically evaluating and estimating the model's characteristics under given conditions. By computer means, these

conditions can be changed as desired to perform sensitivity analyses.

Law and Kelton present a list of various problems for which simulation models has been proved to be a powerful tool:

- 1) Design and analysis of manufacturing systems
- 2) Evaluation of hardware and software requirements for computer systems
- 3) Evaluation of new military weapons systems and tactics
- 4) Evaluation of ordering policies for inventories
- 5) Design of communication systems
- 6) Design, construction and operation of transportation facilities (i.e., highways, airports, subways, tunnels, and ports)
- 7) Evaluation of designs for service organizations (i.e., hospitals, restaurants, and post offices)
- 8) Analysis of financial or economic systems

Law and Kelton also presented that during the years of 1978 to 1989, simulation was ranked fifth among fifteen research subject areas in terms of its added value after graduation for Master of Science graduates. Among Ph.D. graduates it was ranked second. Both ranks correspond to operations research and management sciences. Even though these statistics correspond to past decades, due to improvements in computing technologies the value of simulation models continue to grow. Chapter 4 will discussed the use of simulation models in construction operations.

There are certain limitations or disadvantages that have been identified. These are:

- 1) Large-scale systems are very complex; as a result, programming tends to be a very

- difficult task and very time consuming. Various software has been developed. These include features that ease the coding of simulation models (i.e., graphic user interfaces).
- 2) In many cases, more time is dedicated to the coding of the program than to the concept that is going to be modeled. For this reason, the exercise becomes more a programming task than an analysis exercise. The computer program will only serve as a tool that to perform the simulations. For instance, the system to be modeled should be well understood in order to obtain meaningful answers.

3.5 CONCLUSIONS

As it has been mentioned before, these three approaches, PERT/CPM, queueing models and computer simulation have proven their usefulness for the analysis of complex systems. However, there has been established certain limitations. For that reason, recent models have tried to combine all these concepts into a single model. This aspect will be discussed in more details in the next chapters.

Chapter 4 of this report presents existing computer simulation models that are very powerful in analyzing construction operations (e.g., CYCLONE, RESQUE, STROBOSCOPE, HSM and SIMSUPER). These models replicate the construction process.

4 EXISTING COMPUTER SIMULATION MODELS

4.1 INTRODUCTION

Computer simulation has been used for construction productivity analyses since 1973, with Daniel W. Halpin at the University of Illinois and Cyclic Operations Network (CYCLONE) and by Robert Lorgcher and David Ashley at Massachusetts Institute of Technology with GPSS. CYCLONE and GPSS adopted the concepts of previously developed discrete-event simulation models that were in use at the time for manufacturing and operations research purposes (refer to section 4.2 for more details).

Many other researchers in the construction academia have adopted the CYCLONE model and have been successful in improving and diversifying its use for the simulation of many different types of construction operations (i.e., earthmoving operations, tunneling, pipelines, sewer systems, etc.). These include systems like INSIGHT, RESQUE, COOPS, STROBOSCOPE, and HSM among others.

This chapter presents discrete-event simulation models, their components and interrelationship, and three discrete-event simulation languages. The objective is to familiarize the reader with the concept of computer simulation studies for construction processes. In addition, general characteristics of construction operations simulation models, like the ones mentioned above are presented, as well as additional tools that have been developed to complement simulators for their implementation in the A/E/C industry.

4.2 DISCRETE-EVENT SIMULATION MODELS

Discrete event simulation concerns the modeling of a system as it evolves over time by a representation in which a set of state variables change only at a countable number of points in time. *State variables* are those that describe a system at a particular time relative to the objective of the study. These points in time are the ones at which an event occurs, where an *event* is defined to be an instantaneous occurrence that may change the state of a system (Law and Kelton, 1991).

A discrete-event simulation model is composed of various elements¹:

- 1) System state: Collection of state variables necessary to describe the system at a particular time.
- 2) Simulation clock: A variable giving the current value of simulated time.
- 3) Statistical counters: Variables used for storing statistical information about system performance.
- 4) Initialization routine: A subprogram to initialize the simulation model at time zero.
- 5) Timing routine: A subprogram that determines the next event from the event list and then advances the simulation clock to the time when that event is to occur.
- 6) Event routine: A subprogram that updates the system state when a particular type of event occurs (there is one event routine for each event type).
- 7) Library routines: A set of subprograms used to generate random observations from probability distributions that were determined as part of the simulation model.

¹ Refer to Law, A.M., and Kelton, W.D. (1991). Simulation Modeling and Analysis. New York: McGraw-Hill Inc. Pages 10 – 11.

- 8) Report generator: A subprogram that computes estimates (from the statistical counters) of the desired measures of performance and produces a report when the simulation ends.
- 9) Main program: A subprogram that invokes the timing routine to determine the next event and then transfers control to the corresponding event routine to update the system state appropriately. The main program may also check for termination and invoke the report generator when the simulation is over.

These elements or components of a simulation model are interrelated as shown in Figure 4.1. At time zero, the simulation run begins with the main program invoking the initialization routine which initializes the system state, statistical counters, and the event list. Right after, the main program invokes the timing routine. This routine determines which event has a higher priority of execution. As soon as an event occurs, the simulation clock is advanced to the time at which that event will be executed. Then, the main program proceeds to invoke the event routine. When this happens, the system state is updated to account for the occurrence of an event, as well as the statistical counters, and future events are generated and added to the event list. The statistical counters gather all information about system performance. Often, random variates are generated from probability distributions to determine the times of future events. Once these steps are completed, the main program or the event routine verifies if the simulation run is over. If the simulation is not over, the cycle is repeated until the stopping condition is satisfied. When the stopping condition is satisfied, the report generator is invoked to compute

estimates of certain performance measures of interest to the user. This element will produce a report.

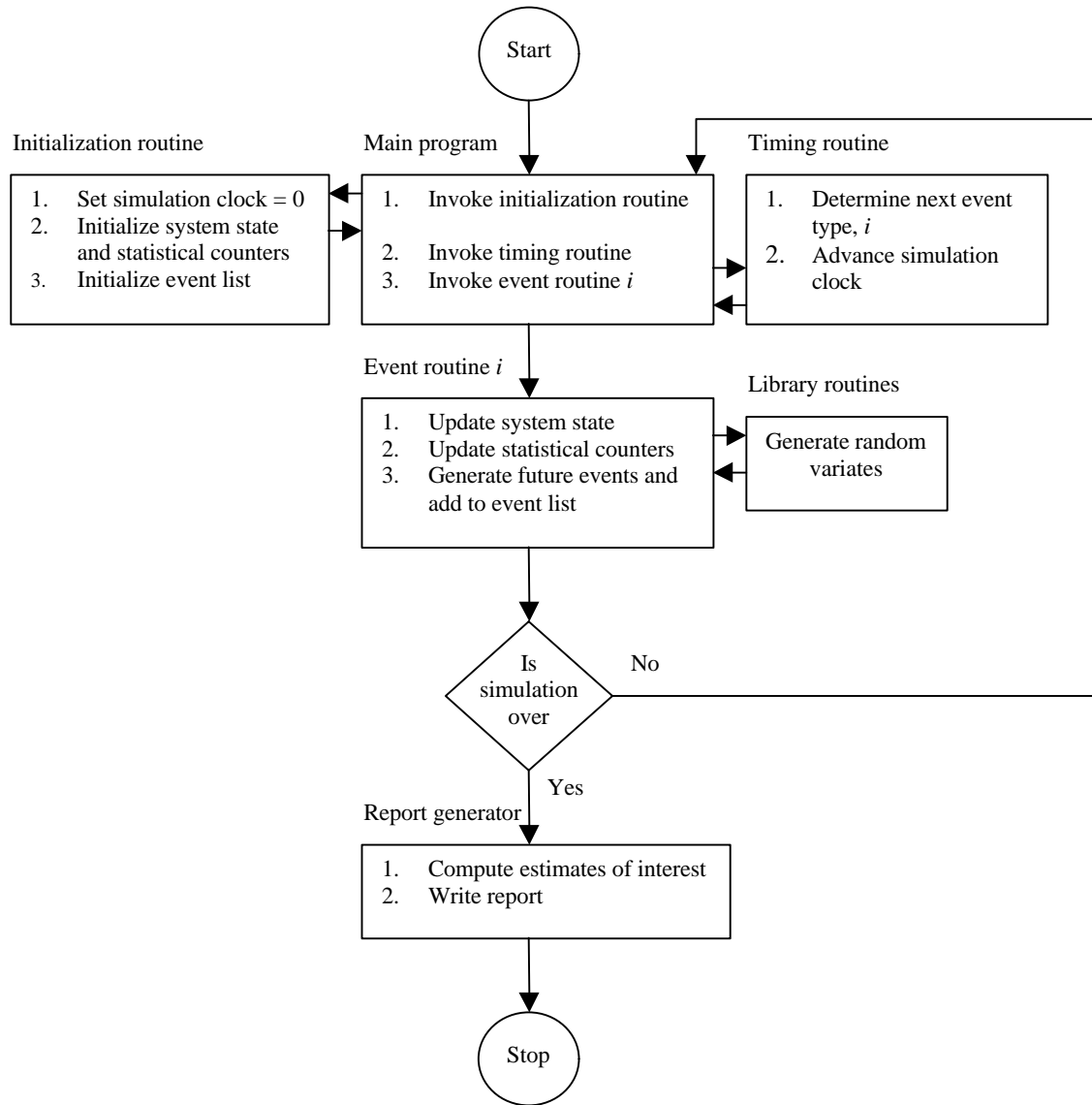


Figure 4.1. Components of a discrete-event simulation model²

² Adapted from Law, A.M., and Kelton, W.D. (1991). Simulation Modeling and Analysis. New York: McGraw-Hill Inc. Pages 10 – 11.

This modeling approach could be implemented in a computer system by means of a general-purpose language like FORTRAN, Pascal, or C. However, due to the complexity of some real-world systems using a general-purpose language could represent spending a considerable amount of programming time. This fact could cause a project to be unsuccessful if it is not completed on time. To address this issue, special purpose simulation languages such as SIMAN, GPSS and SLAM II have been developed. These languages provide features that facilitate the programming of a simulation model, as a result a significant amount of programming time is reduced. Making changes to a simulation model is easier if the model has been written using a simulation language. Also, simulation languages provide better error detection.

4.2.1 SIMAN

SIMulation ANalysis (SIMAN) is a simulation language that allows for the construction of event-oriented and process-oriented models, or a combination of the two. *An event-oriented model* is one in which the times of future events are explicitly coded into the model and are scheduled to occur in the simulated future. On the other *hand process-oriented model* is one in which the system is analyzed in terms of the individual entities involved.

The SIMAN model has two major components: a model frame and an experimental frame. The model frame contains all the information related to the logic of the process and resource interaction. This information is contained within modeling constructs called blocks, which can be combined in a top-down diagram. These blocks can represent

attributes, queues, and resources. This diagram describes the resources flow through the system. The experimental frame specifies the parameter values, which define resource types and quantities.

The report generator computes confidence intervals and performs hypothesis tests. It is capable of building time plots, histograms, and bar charts. Implementations of this language include analysis of work stations, transporters, conveyors, and automated guided vehicles.

4.2.2 GPSS

General-Purpose Simulation System (GPSS) is a process-oriented simulation language. It was originally developed for the modeling of queuing systems. GPSS models do not require the use of external routines. It consists of more than 60 statements represented by block diagrams. This block diagram has to be translated into a set of GPSS statements for the execution of the simulation model. The activities to be performed are called *transactions* and their attributes are called *parameters*. The resources performing the services are called *facilities* or *storages*, which could be a single server or a group of parallel servers. GPSS has been widely used for the analysis of manufacturing operations.

4.2.3 SLAM II

Simulation Language for Alternative Modeling (SLAM II) is a simulation language for event-oriented and process-oriented models, or a combination of both. This type of logic is very inconvenient for the process model. As a result, event routines are coded and then

are called from the process model.

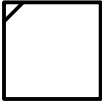
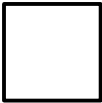

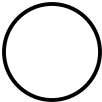

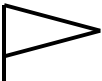
For this approach, a network diagram is developed by combining nodes and branches into a process network. Nodes are resources' pools or queues, while branches represent the passage of time. This graphical model is converted in a set of statements that will replicate the process and execute the simulation.

Based on the concepts above presented, which have been mainly used for manufacturing processes analyses, the research community in the A/E/C industry have adopted these concepts to simulate construction operations. Classroom sessions in many colleges have used simulation languages to model these processes, since others have developed their own modeling approaches. One of these approaches is the Cyclic Operations Network, presented in the next section.

4.3 THE CYCLONE MODEL

The CYCLic Operations NETwork is a discrete event simulation tool that is based on how the construction process is conducted at the operations level. When using the CYCLONE model, the user has to break the construction process into a series of repetitive activities that involve cyclic movements or sharing of resources and for which durations can be estimated (Lluch and Halpin, 1982). These activities are presented in a CYCLONE diagram. This diagram defines the flow of resources and equipment that is used or produced during construction operations. This diagram consists of a series of symbols that define the logic of the process. These symbols are presented in Table 4.1.

Table 4.1. The CYCLONE diagram modeling symbols³

Symbol Name	Symbol	Function
Combination activity (COMBI)		COMBI is always preceded by queue nodes. This node is logically constrained in its starting logic. Units must be available at each of the preceding queue nodes before it can commence. If units are available, they are combined and processed through the activity. If units are available at some but not all of the preceding queue nodes, these units are delayed until the condition for combination is met.
Normal activity (NORMAL)		The NORMAL activity is similar to the COMBI. However, units arriving at this element begin processing immediately and are not delayed. In other words, it is unconstrained in its starting logic.
Queue node (QUEUE)		The queue node precedes all COMBI activities and provides a location at which units are delayed pending combination. Delay statistics are measured at this element. It represents the idle or waiting state of resources.
Function node		This node is inserted into the model to perform special functions such as counting, consolidation, and statistics collection.
Arrow		This is the resource entity directional flow-modeling element.
Accumulator		System productivity is measured at this element. It is also used to define the number of times the system cycles.

There are two basic states that define every single work task. Resources could be either active or idle. A square node (NORMAL) defines the active state. On the other hand, a circular node (QUEUE) represents the idle state. In addition, arrows or processing lines link all these diagram nodes. These arrows route the resources or units between active and idle states. By combining the symbols presented in Table 4.1, the modeling of

³ Adapted from Lluch, J. and Halpin, D.W. (1982). *Construction Operations and Microcomputers*. Journal of the Construction Division, Proceedings of the American Society of Civil Engineers. Vol. 108, No. CO1.

work task sequences, processes, and assignments become possible (Halpin and Woodhead, 1976). Each one of these elements contributes to the development of a network system model of any construction operation that provides insight related to resources interaction. Figure 4.2 combines all these nodes to model a laborer filling a sandbox.

In this case, there are three resources involved: a sand stockpile, a sandbox, and a laborer. The activity is to take sand from the stockpile and shoveled it into the sandbox. In order for the laborer to become active, sand must be available in the stockpile. Also, in order for the sandbox to be filled, a laborer and a sandbox must also be available. For that reason, this task is represented using a COMBI. Three queue nodes precede the COMBI; for it to commence, all those three resources must be available.

As it can be observed, these three resources are represented by QUEUE nodes to establish resource availability. All QUEUE nodes are linked to the COMBI node defining the ingredience logic. Once the resources are available on every QUEUE, the laborer will be continuously filling sandboxes.

In this model, the CYCLONE model, system response in terms of productivity and the effective use of resources is monitored by statistics collected at all nodes (Lluch and Halpin, 1982). As the different approaches presented in Chapter 3, sensitivity analyses can be made by changing the initial conditions and the resources specifications until the user objectives are satisfied. This characteristic provides the user with the ability to compare between alternative methods and based on the experiment's results, select the most appropriate one depending on the user's needs.

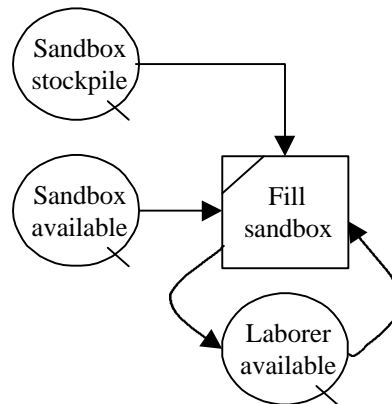


Figure 4.2. CYCLONE diagram representing a laborer filling a sandbox⁴

The analysis performed by the CYCLONE model provides information regarding operation productivity, system delays, and idleness of various construction resources. This approach is very useful in identifying areas of potential delays and bottlenecks. If these areas are identified, it becomes easier to take certain measures to avoid these problems before work begins.

This model is very powerful for cyclic processes. The CYCLONE networks are considered as sub-networks of the CPM network. Each operation in the model network is completed many times, while in the CPM all these repetitive cycles are represented by a single activity of the overall project. The results obtained from the CYCLONE simulations can be inputted into the Critical Path Method to obtain the total project duration.

Limitations regarding non-identical resources as well as very complex resource

⁴ Adapted from Halpin, D.W. and Woodhead, R.W. Design of Construction and Process Operations. (1976). New York: Wiley & Sons. Page 66.

flows have been identified by previous researchers (Liu and Ioannou, 1992; Salazar and Jimenez, 1998). To overcome these shortcomings a model known as RESQUE was developed by David Chang in 1986. Liang Liu and Photios Ioannou developed another CYCLONE-based model providing a graphical object-oriented discrete-event simulation, known as COOPS. This model combines interactive graphics and simulation functions, reducing inconsistency between the real system and the user's graphical representation of that system. This is possible by using object-oriented programming. These and other CYCLONE-based simulation models are discussed in the next section.

4.4 CYCLONE-BASED SIMULATION MODELS

4.4.1 INSIGHT

Originally developed at Stanford University in 1977, INteractive SIMulation using GrapHics Techniques (INSIGHT), is a conversion of CYCLONE that has extended the modeling capabilities of its predecessor. This simulation concept runs interactively and has been linked to a videotape data collection system and contains a graphical display that provides an alternative to tabular outputs. The combination of both systems eases the use of the CYCLONE model.

The video-data interactive processing (VIP) system records data in the field that is related to the logical relationships between the various elements that are part of the construction operations. Connecting a computer to a tape player allows extracting data in order to generate estimates of the system productivity. Once this data is collected, the user can proceed to build the simulation network that will replicate the performance of

the real-time system (Paulson et al., 1987).

The video system acts as a data acquisition system enabling construction people to obtain operational data from field. These operations are recorded using a video camera. A program code takes time counts. Time durations is then analyzed by means of two subsystems called the Video Interactive Extraction (VIE) and the Video-data Interactive Statistical Analysis (VISA). Histograms and distribution curves are generated by these subsystems.

An interface called the INSIGHT File Formatter enables the user to construct a simulation model. This simulation model will be the input for INSIGHT. The INSIGHT program has the same conceptual capabilities as CYCLONE with the advantage of providing graphical reports instead of a tabular output. Also, this simulator has the advantage of collecting productivity data by means of video methods that are linked to a computer for data extraction and analysis.

INSIGHT has been used for the analysis of concrete-placing construction operations in the late '80s. Since, other CYCLONE-based models have been developed with more updated capabilities.

4.4.2 RESQUE

The RESource based QUEuing network simulation system has been developed to simulate construction planning. The graphical representations used in RESQUE are very similar to those used in CYCLONE. These representations are composed of two parts: a process chart and process data. A process chart is essentially composed of the same

elements presented in Table 4.1 that were used in the CYCLONE model. Although, the modeling capabilities of this chart are different than the ones discussed before:

- 1) An arc connecting a QUEUE and a COMBI represents a calling relationship. The calling relationship means that a COMBI is calling resources from the preceding QUEUE nodes in order to commence the task. The called resources are identified in the arc or link (see Figure 4.3).
- 2) The COMBI node takes care of the resources called. The emanating link from the COMBI node shows the resource handling (see Figure 4.4).
- 3) The resources released from the COMBI node are routed to different destinations according to the rules established by the user. These rules are labeled in the COMBI's emanating link (see Figure 4.5).

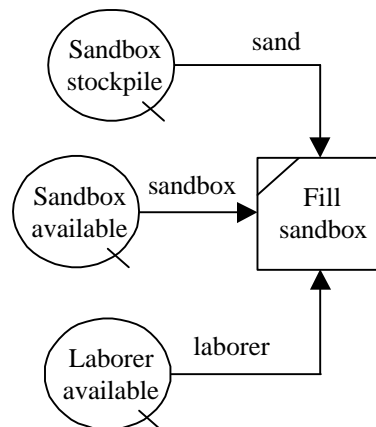


Figure 4.3. Resources calling

As mentioned before, RESQUE has the capabilities of analyzing processes with non-identical resources. In the example presented, two scenarios could be assumed:

identical resources, and non-identical resources. Table 4.2 presents the process data for the first case: identical resources. The RESLIST column contains the list of resources presented in the process chart (refer to Figure 4.5). In this column, there are three types of resources. However, there is only one type of sandbox used, one laborer, and the stockpile of sand. This list defines the resources by initial locations (Queue No.), resource type (i.e., STOCKPILE), attributes (optional), and quantities.

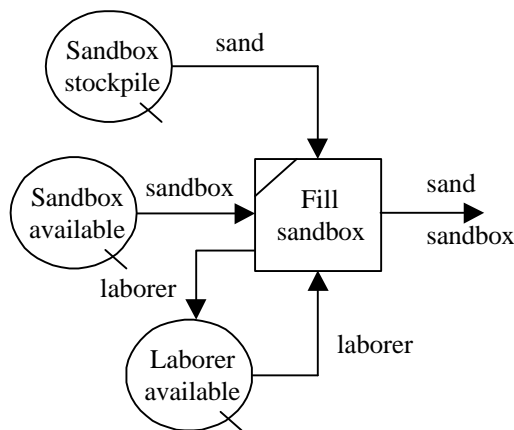


Figure 4.4. Resource handling

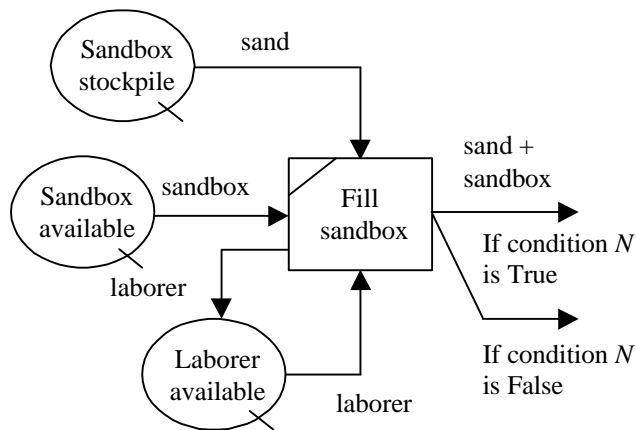


Figure 4.5. Resource routing

Table 4.2. Identical resources

RESLIST	COMBI	RDVLIST	DURLIST
Queue No., STOCKPILE,, 1cy	DUR, 5		5, 2, 5, 8
Queue No., SANDBOX,, 1			
Queue No., LABORER,, 1			

The COMBI column contains the information that represents the sandbox-filling operation. The duration of the COMBI element is given by the statement "DUR, 5", which means that the statement number 5 from the duration list column (DURLIST) will compute the duration of this operation. The DURLIST statement 5 considers that the time should be computed using a uniform distribution (code 2) between five and eight minutes. If the DURLIST statement includes a negative number in the statement number command, then the statement in the rules list (RDVLIST) will compute the duration of the COMBI element. This is shown in the second case as presented in Table 4.3.

In the case shown in Table 4.3, there are three resource types (stockpile, sandbox, and laborer), although there are two sandboxes of different capacity (non-identical resources). The first sandbox has a capacity to carry 16 cubic yards (cy) of sand, while the second one has a capacity of 25 cubic yards. The resources list of this case, for the sandboxes includes the attribute of sandbox-capacity, which is shown in bold. In addition, this case will use the statement number 10 of the rules' list to compute the duration of the COMBI. This rule establishes that the COMBI duration for the 16 cubic yards sandbox will be calculated using statement number 5 from the DURLIST. By

contrast, statement number 6 of the DURLIST will be used to compute the COMBI duration when filling the 25 cubic yards sandbox. For both, a uniform distribution will be assumed, taking from 5 to 8 minutes to fill the 16-cy sandbox and 8 to 12 minutes for the 25-cy sandbox.

Table 4.3. Non-Identical Resources

RESLIST	COMBI	RDVLIST	DURLIST
Queue No., STOCKPILE,, 1	DUR, -10	10, Queue No.,SANDBOX,5,16,6,25	5, 2, 5, 8
Queue No., SANDBOX,16, 1			6,2, 8, 12
Queue No., SANDBOX,25, 1			
Queue No., LABORER,, 1			

4.4.3 COOPS

COOPS is an object-oriented discrete-event simulation system. Liang Liu (University of Illinois) and Photios Ioannou (University of Michigan) originally developed it (Liu and Ioannou, 1992). Its modeling elements are designed as objects (e.g., nodes, links, and attachments) providing a user-friendly interface to build simulation models. This system address the issue of inconsistencies that may arise from developing separate simulation input text files as is the case of CYCLONE and INSIGHT. By using object-oriented programming, simulation modeling elements can be designed to contain the functionality of both interactive computer graphics and discrete-event simulation. This combination

allows building simulation directly and interactively, and simulation can be performed directly on the graphical network avoiding the need of building separate text files for model definition (Liu and Ioannou, 1992).

Similar to CYCLONE, the COOPS model is a precedence network consisting of three types of objects: nodes, links, and attachments. This network is constructed with four different nodes: activities, queues, consolidations, and routers. Links are represented as arrows, which define the flow of resources through the network. The attachments, of three types (specific resources, resource units, and flags), directly affects the characteristics of the elements.

There are two types of resources: generic and specific. *Generic resources* are identical and interchangeable, while *specific resources* are individually identified. During simulation, every resource is tracked down in terms of its units, state, flow, interactions, transformations, and queuing behavior.

As in CYCLONE, queues are storage areas for resources. Generic resources are stored as integer values. This value represents the quantities of those resources (i.e., number of resources, volume, etc.). The user is responsible for the compatibility of the units used.

The activities of the simulation network are the work tasks to be performed in the real-world system. The start of those activities is ruled by the availability of resources. The activity's duration is determined by six different types of probability distributions: deterministic, uniform, normal, beta, gamma, and triangular. Also, the concept of priority is introduced in this model. Every activity is assigned a priority value that will determine

which activity will be allowed to use a resource that could be required by another activity at the same time.

Routers are used to activate all links that lead to successor nodes in a specific path. These links are activated based on a probabilistic selection process. On the other hand, links specify the direction of resource flows and the precedence between nodes. They only allow the resources to flow through linked nodes.

Consolidations represent the transformation, combination, or consumption of resources. They only affect generic resources, which are merged to produce one unit of a finished resource.

Finally, there are flags that set the simulation stopping conditions. Once a queue node reaches the limit set by its attached flag, the simulation stops. Different that CYCLONE, multiple flags or counters could be used in the same model network.

This model uses a calendar system to control resource availability. This system defines the working schedule of all or individual resources in the same model. This feature takes break time as well as overtime into account for the determination of the activity completion time.

4.4.4 STROBOSCOPE

Developed by Julio Martínez at the University of Michigan (1994) under the advice of Photios Ioannou, STROBOSCOPE (STate and ResOurce Based Simulation of CONstruction ProcEsses) is a simulation programming language used for the simulation of processes common to construction engineering. It is used for resource tracking as they


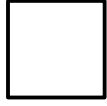
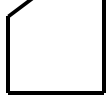


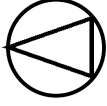

flow in a process network (Martínez, 1996).

As CYCLONE, STROBOSCOPE models are based on a network of interconnected modeling elements and programming statements. These statements define the behavior of the modeling elements as they control the simulation runs. The symbols used by this system are very similar to the ones used in CYCLONE. Table 4.4 shows a description of the symbols used by this approach.

These modeling elements have attributes that, as explained above, define how they behave during a simulation. These could represent activity durations, activity priority, discipline of a queue, and the amount of resource that flows from one element to another through the network links. The expressions that specify these attributes are composed of constants; system maintained variables that access the state of the simulation and the properties of resources; user-defined variables; logical, arithmetic, and conditional operators; and scientific, statistical, and mathematical functions (Martínez and Ioannou, 1994).

Elements' attributes enables the simulation models to consider uncertainty in any aspect (i.e., time and quantities). Also, they select the routing of resources as well as the sequence of the operations. In regard with resource availability, elements' attributes allocate resources based on complex selection schemes. These attributes have the capability to delay project operations due to conditions that are not related to resource availability, like space constraints and safety issues.

Table 4.4. Modeling symbols for STROBOSCOPE⁵

Symbol Name	Symbol	Function
Queue		Is a holding place (buffer) for 0, 1, or several resources waiting to become involved in the succeeding combination activity. The latter are distinct from one another and they can be traced as individuals through various network nodes during simulation. The logic describing the ordering of resources upon entry into a queue of characterized resources is termed a <i>discipline</i> .
Normal activity		Describes a certain type of work to be done, or delay, of a known (probabilistic) duration from start to finish. May require a single resource or no resource at all.
Combination activity		Like a normal, describes a certain type of work to be done, or a delay, of a known (probabilistic) duration from start to finish. Unlike a normal, required several resources in combination for its performance and draws what is needed from the queue(s) that precede it.
Consolidator		Acts as a counter up to n (n is an integer value specified with the node): after n resources have been released into the consolidator, the consolidated set will be released from it.
Link		Shows resource flow logic. Should be labeled to meaningfully describe the resources that flow through it. If the link emanates from a queue, a <i>draworder</i> may be specified to sequence resources being drawn from the queue.
Fork		Describes a split in a resource's flow path. Incoming resources are routed along one path or another in a probabilistic or deterministic fashion, so the node is called a probabilistic fork or a decision node respectively. Each link emanating from it carries a likelihood or a statement evaluating to true/false for being followed by any specific resource arriving at the fork during simulation. The resource's actual path is determined at run time.
Assembler		Shows that 2 or more resources are being assembled into a single unit resource which is of the compound (a special kind of characterized) resource type.

⁵ Adapted from Tommelein, I.D. (1998). Pull-Driven Scheduling for Pipe-Spool Installation: Simulation of Lean Construction Technique. Journal of Construction Engineering and Management, Vol. 124, No. 4.

4.4.5 HIERARCHICAL SIMULATION MODELING (HSM)

HSM is a simulation-based method that combines the concepts of work breakdown structure (WBS) and process modeling for planning of construction projects. Hierarchical and modular simulation constructs form the basis of this method (Sawhney and Abourizk, 1995). The objective of this method is to develop the project plan. For the development of this plan using HSM, four basic steps have to be followed:

- 1) The first step comprises the development of the WBS. Here the project is divided into three levels: project level, operation level, and process level. At the project level the focus is on management issues like project cost, schedule, resources, materials. Operation level is concerned with construction methods and strategies. The process level concentrates on the technicalities and sequence of work tasks. This WBS is developed using two modeling elements, the "operation-element" and the "process-element." The *operation element* focuses on the construction method. It can only have one parent object and multiple child objects. *Parent object* can only be another operation, whereas *child objects* can be either an operation or a process. On the other hand, the *process element* focuses on accomplishment of work tasks and flow of resources. It can only have one parent object that can only be an operation object. It does not have child objects. It defines the lowest level of the WBS.
- 2) Step two is the development of a resource library. All resources are initialized in this library. It contains details like resource name, quantity, variable cost, and fixed cost.
- 3) The third step sets up the sequence of the project operations listed in the WBS. All project activities are scheduled and linked to one another depending on the

construction process logic. All project activities are connected by four operation sequencing links defined in Table 4.5.

- 4) This last step comprises the development of process models. These are developed using CYCLONE modeling elements with additional elements for resource manipulation, process inter-linkage and inter-process constraining relations. These elements are shown in Table 4.6 below. Once the process models are set up, the simulation will take place.

Table 4.5. Operation sequencing links in HSM⁶

Link	Construction logic	Use
Serial	Operations can be implemented serially.	A predecessor operation is linked to a successor using a serial link. A lag in days can be assigned for any serial link.
Parallel	Operations can be performed simultaneously.	Links two operations that can be implemented in simultaneously. One operation is called the predecessor and the other is the successor. A lag in days can be attached to the link.
Cyclic	One operation or a group of operations need to be performed a given number of times.	One operation or a group of serially linked operations can be repeated by linking the last operation to the first operation. A counter is attached to the link to determine the number of cycles.
Hammock	Operation is not constrained by any other operation in the project.	A single operation is isolated from other operations by defining a hammock link. The hammock link is defined in terms of days relative to start time. Once an operation is defined as the hammock, no other links can be assigned.

This model provides the versatility of different level of details for planning purposes. This allows personnel at different levels to have access to the information needed at the appropriate level of detail. Also, the models developed can be reuse for

⁶ Adapted from Sawhney, A. and Abourizk, S.M. (1995). *HSM-Simulation-Based Planning Method for Construction Projects*. Journal of Construction Engineering and Management, Vol. 121, No. 3.

similar projects. The concept is completely based on WBS, while all the models presented before are based on CPM. As all of them, HSM allows for sensitivity analyses involving resource usage. Various strategies can be evaluated by altering the sequence of work operations.

Table 4.6. *Process modeling elements in HSM*⁷

Modeling Element	Description
Allocate resource node	Resource defined in the resource pool at the project level are attached to the process model using the allocate resource nodes. A single resource or a resource combination can be allocated at this node. The node captures the required quantity of resources from the resource pool and passes it to a COMBI.
Free resource node	It works in conjunction with the allocate resource node. A single resource or a resource combination can be released back to the resource pool using this node. It is essential to have a corresponding allocate resource node for every free resource node. In the absence of the free resource node the resources captured at an allocate resource node are not released back to the resource pool.
Predecessor node	This node in conjunction with the successor node is used to define process interdependencies. A predecessor node releases an entity to a succeeding process on the completion of a defined number of cycles of the current process.
Successor node	It works in conjunction with the predecessor for defining process interdependencies. It receives the entity released by the predecessor node in the preceding process. After receiving the entity the successor node allows the start of the succeeding process.

4.5 ADDITIONAL TOOLS COMPLEMENTING SIMULATION MODELS

The previous section was devoted to present existing computer simulation models that are currently used for construction engineering and management purposes. The CYCLONE

⁷ See note 8.

model has been successfully implemented in the construction industry by Dragados y Construcciones, Madrid, Spain in various of their projects for bridges construction.

In order to get more attention from the construction industry; advances in the simulation programs need to be made. These advances include a friendlier graphic user interface (GUI) for the preparation of the simulation-input data and graphic outputs.

First, one of the major factors for which simulation has not been widely used in the A/E/C industry is related to the difficulties in setting the simulation input. Also, simulation models rely on the assumption that the user has enough knowledge to establish the process model. However, if the data inputted into the program is not accurate, obviously the simulation results will not accurately predict the project duration.

Second, once the simulation is finished it will be very attractive to have the output in a bar chart format or some other graphic that would increase its visualization. Nowadays, most owners require that the contractor submits CPM schedules or bar charts. For this reason, simulation models should be able to develop bar charts, for the contractors to be willing to integrate these models to their planning tools. This is a key for the implementation of simulation models into the real world.

Recent studies trying to facilitate construction of simulation models include graphical model interfaces, model reusability or modeling libraries, and visualization and 3D-animation modules. Two examples are presented in this section; the Geotechnical Support Graphic User Interface (Brown et al., 1991) and the PICASSO system (Bolívar and Halpin, 1998).

4.5.1 GEOTECHNICAL SUPPORT GRAPHIC USER INTERFACE

The Geotechnical Support Graphic User Interface is an intelligent graphical user interface that encapsulates a tunneling simulation program known as SIMSUPER. This system provides parameter validation, as well as feedback about the quality of the simulation output (Brown et al., 1991).

The main benefit of having this GUI is that it removes the need for the user to have detailed knowledge of the parameters that SIMSUPER requires to run a simulation. This system enables novice users to operate the simulator, by monitoring the selections made by the program's user. The system is capable of guiding the user by:

- 1) Checking the user input and decisions
- 2) Addressing the possible consequences of the combination of the values given to the simulation parameters
- 3) Judging the goodness of the simulation output
- 4) Providing comments whenever the user shows the need or when the system detects the need

The interface displays information in a format that is familiar to the user. In this case the tunnel cross section and longitudinal section are shown in the computer screen. In this way the user visualizes the tunnel design through the diagrams provided. In addition, the knowledge base sends messages to the user through the interface in order to answer any request or to display the results of the user's actions. For example, during the setting of parameter values, a selection window pops up, waits for the user's value, and tells the user the acceptable range for the variable's value, its default value and the current

value. Figure 4.6 presents this user interface. In other words, the geotechnical support GUI is not only developed for data entry but for engineering work.

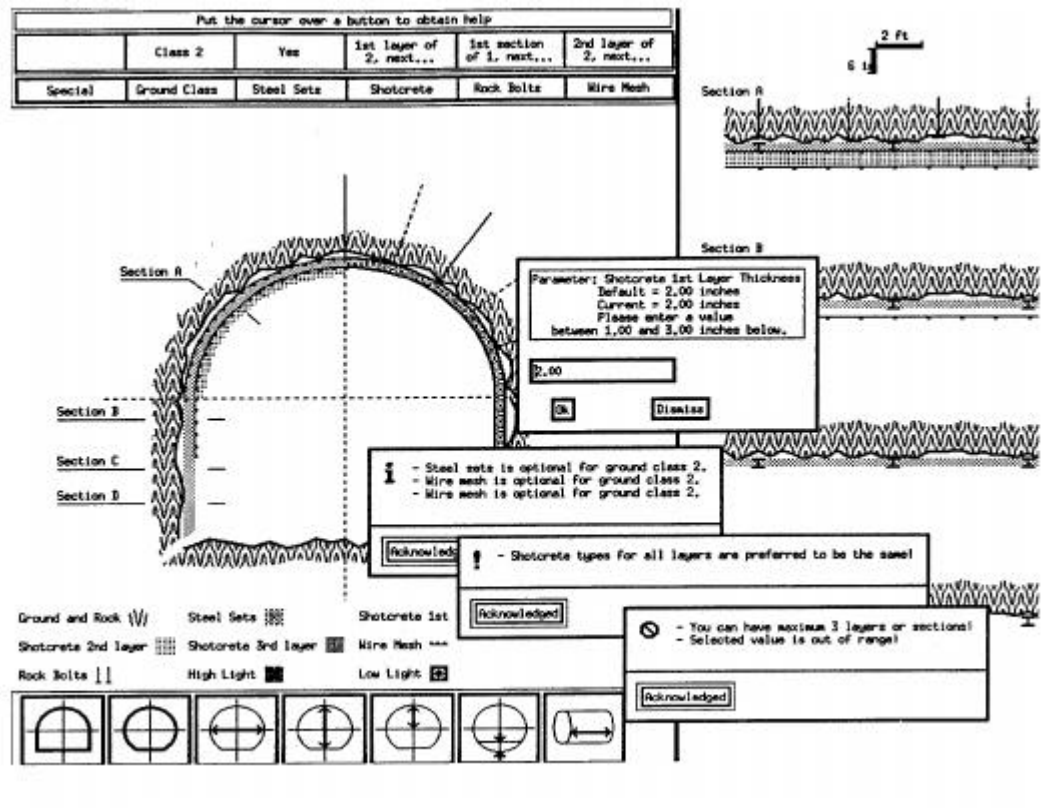


Figure 4.6. The geotechnical support graphic user interface⁸

The knowledge base has three components: the local component, the global component, and the analytical component. The first makes comments about the choices of individual parameters. The global component comments about the choice of set of parameters, and the analytical evaluates the results of the simulation and make

⁸ Adapted from Brown, D.C., Salazar, G.F., and Liu, S.X. (1991). An Intelligent Graphical Interface for Tunnel Support Specification. Proceedings of the World Congress on Expert Systems. Orlando, Florida, Page 741.

suggestions about which parameters to change. Figure 4.7 demonstrates how does the user receive feedback from these three components.

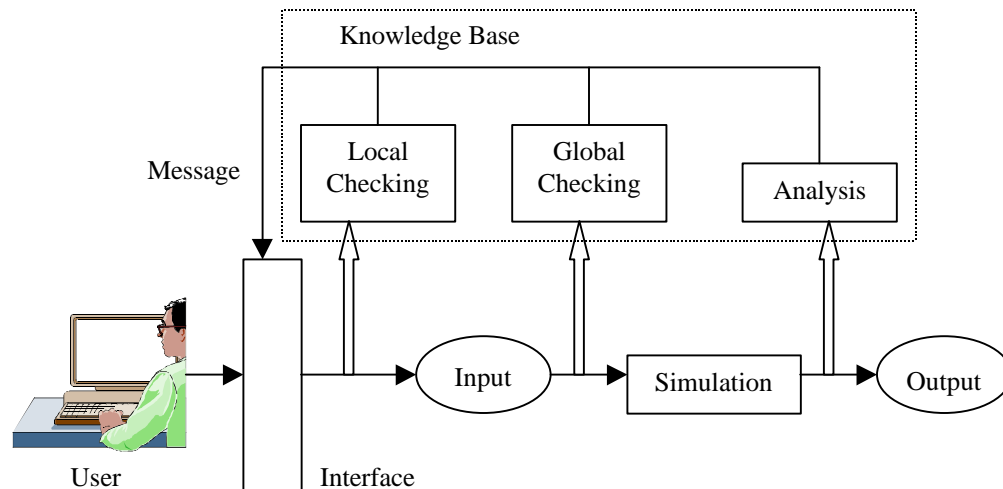


Figure 4.7. Knowledge base components

In summary, the Geotechnical Support GUI in combination with the knowledge base components ensures that the data provided by the program's user is acceptable. The system is able to detect unreasonable simulation results; case in which it will make suggestions about what information has to be changed to improve the accuracy of the simulation.

4.5.2 PICASSO

Developed by Bolivar Senior under the supervision of Daniel Halpin, PICASSO (Project-Integrated Cyclic Analysis of Serial System Operations) is a system that uses a simple modeling paradigm based on a combination of CPM and CYCLONE (Senior and Halpin, 1998). This scheduling algorithm is simulation-based but includes float information not

available in any of the previously described models.

This approach converts a CPM network into a CYCLONE network, which is used for simulation purposes. With the simulation output, an algorithm processes the output information to provide activity float information.

The first step consists in creating a PICASSO network. This network is composed of three elements: resources, activities, and links. The resource element represents the resource pool. This element is linked to the activity element. Finally, the link element specifies the sequence of the process and the relationship between resources and activities. Because every activity is linked to a resource pool and to other activities, their start up is constrained by the preceding activities and resource availability. This network is exactly a CPM network, to which resource flow has been added as well as repetitive subnetworks. As a result, once the resource pools and the subnetworks are taken off the PICASSO network, a CPM network is obtained.

Primavera Project Planner (P3) is used to develop the PICASSO model. The information obtained from P3 is automatically converted into a CYCLONE simulation network. This network is build on a graphics-oriented environment. From the results obtained from the simulation run, a separate algorithm is used to perform float calculations. The forward pass is computed using CYCLONE and a separate algorithm performs the backward pass. Finally, simulation results are presented in tabular and graphic formats by using templates on a computer spreadsheet program (see Figure 4.8).

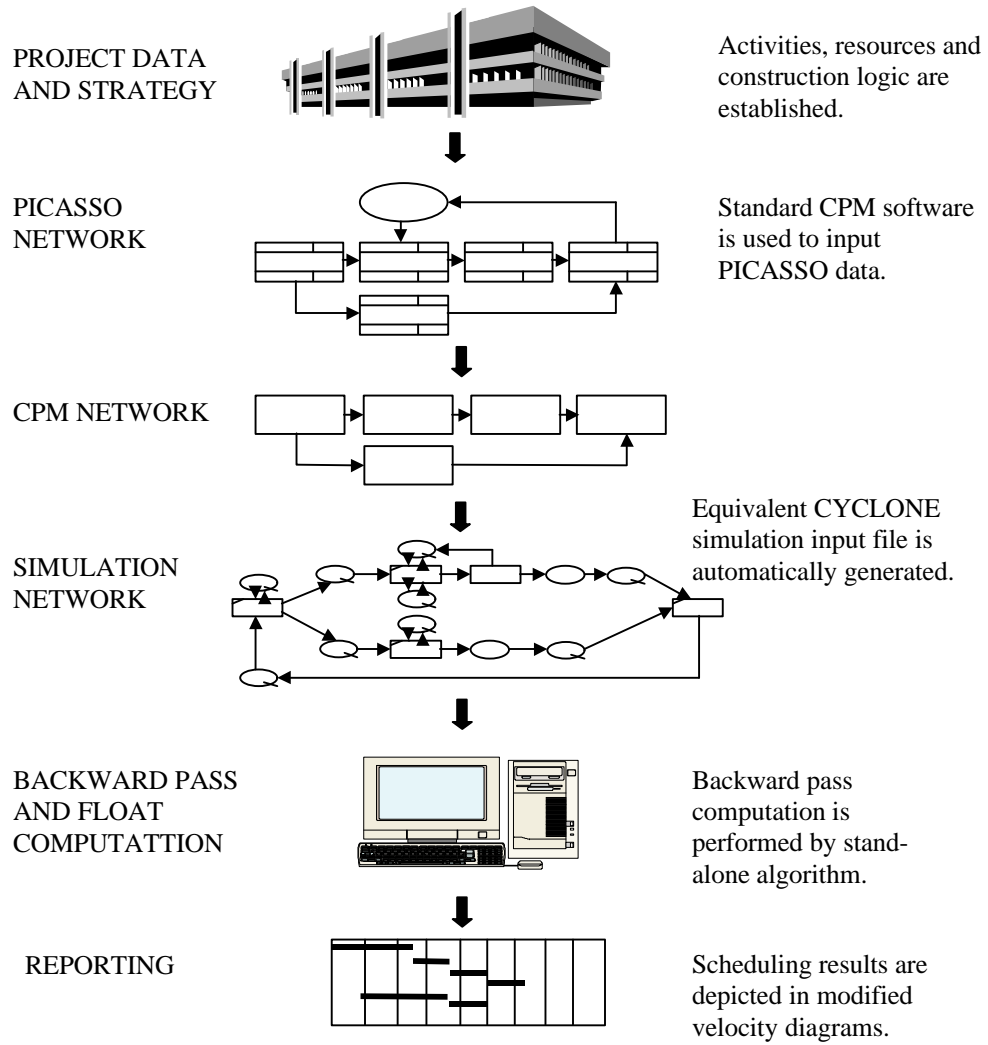


Figure 4.8. PICASSO implementation strategy⁹

⁹ Adapted from Senior, B.A. and Halpin, D.W. (1998). *Simplified Simulation System for Construction Projects*. Journal of Construction Engineering and Management, ASCE, 124(1), Page 73.

4.6 EXISTING MODELS AND RENOVATION PROJECTS

Due to the uniqueness of the characteristics of building renovation projects (refer to Chapter 2), specifically the impact of unforeseen conditions, the tools presented before have serious limitations that make them not suitable to effectively perform productivity analyses for building renovation projects (Novak, 1988). Contractors can make use of their own understanding of the work to estimate activity duration and resources required. This allows them to estimate project costs. However, due to the potential of unexpected events, the assessment made tends to be very conservative, with high contingencies.

Very easily, details can be missed. These details may cause changes in the dynamics of the operations, causing resources to be idle until the contractor is able to adjust its plan due to differences between the conditions expected and encountered conditions.

Network models also have a conceptual limitation that does not necessarily ensures that the plan is going to be an accurate one. This limitation is related to the lack of adaptability for network models or *hard-logic*. Basically, network models, like CPM and PERT, follows a hard-logic approach. This approach considers that conditions of work will remain constant throughout the entire project. For this reason, as soon as there is a change in the conditions of work, these network models developed during the planning stages of the project are not valid anymore. The computer models hereby presented also have the same limitation.

This issue raises the question of how to model this kind of project. What approaches are available for the analysis of building renovation projects? An existing

modeling approach called *soft-logic* allows modifying a predefined network as new sets of conditions appear. This approach is suitable for the modeling of building renovation projects.

Consider a particular process that requires a total number of six activities to be executed for the completion of a certain project (see Figure 4.9). In this case, activities 2 and 4 start after activity 1 is completed. Activities 3 and 4 follows activities 2 and 4, respectively. Then, the starting time of activity 6 is delayed until activities 3 and 5 are finished. This logic assumes an expected set of conditions. However, if this set differs from the conditions encountered, the original logic may not be valid. The new set of conditions may require that activity 4 must follow activities 2 and 3, and that the starting of activity 6 will proceed once activities 4 and 5 are completed. This ability of adapting to changes in conditions is called soft-logic.

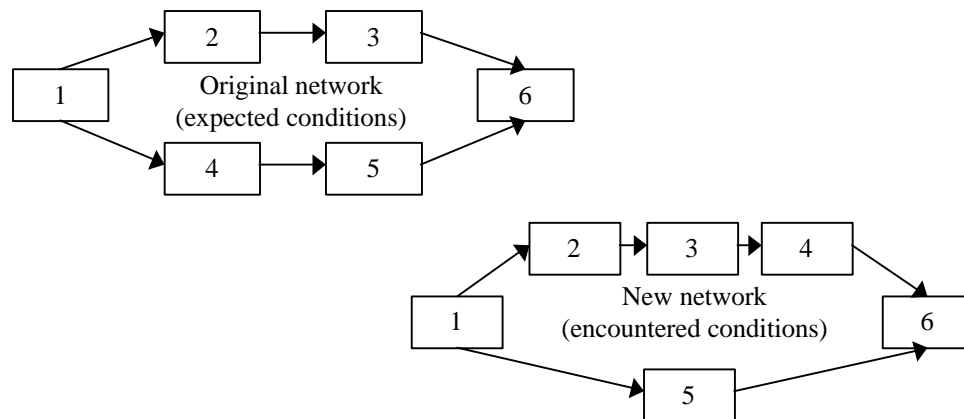


Figure 4.9. The soft-logic approach

As before mentioned, none of the existing computer simulation models presented in this chapter, provides the user with the ability of adapting to changes in conditions. The following chapter will introduce a computer simulation program that does include soft-logic as part of its simulation approach.

4.7 CONCLUSIONS

Within the research community, construction simulation has been very helpful in developing a better understanding of the construction process and in improving project planning and cost estimating. However, its use is not widespread in the industry due to the complexity in constructing the models and the amount of time required by the development and validation of these. This concern can be addressed by user interfaces and providing graphic outputs as well as computer animation to visualize the system's behavior. The studies presented in section 4.5 are an excellent example of existing systems that try to facilitate the construction of simulation models with GUI, knowledge base components, modeling libraries, and graphical outputs.

The simulation models presented in this chapter, as before explained, have been successful in replicating parts of the overall construction process. Although, none of the above mentioned has the capability to dynamically respond to changed conditions. This powerful modeling approach is known as soft-logic. CYCLONE-based models are mostly useful for cyclic construction operations at the process level. The models discussed were not intended to simulate the construction project as a whole. Therefore, they attempt to imitate the PERT/CPM techniques when modeling the project level,

resulting in a less efficient tool. Now, with the development of HSM, which is used as a simulation manager, different CYCLONE's libraries work together following the work breakdown structure packages. However, the fundamental structure of this model does not support a soft-logic.

In conclusion, there is a need of a computer simulation model able to analyze the construction process dynamically, considering conditions of uncertainty, with the flexibility of adapting the model as these conditions change. SIMulation SUPERvisor (SIMSUPER) is a simulation program that is capable of combining different networks for different external factors that impact the use of certain construction methods. The logic followed by SIMSUPER has the flexibility of selecting between networks depending on the conditions inputted. SIMSUPER has proven to be the only simulation model that satisfy this need for the simulation of tunneling excavation and initial support operations. This research explores the use of SIMSUPER in the prediction of construction productivity for building construction. Is the objective of this research to determine the level to which SIMSUPER can be adapted to simulate building renovation projects and to evaluate its potential benefits for the construction industry.

5 SIMSUPER: A SOFT-LOGIC SIMULATION APPROACH FOR ANALYSIS OF PRODUCTIVITY

5.1 INTRODUCTION

SIMulation SUPERvisor (SIMSUPER) is a discrete event computer simulation program that was originally developed to model tunneling excavation and initial support processes under conditions of uncertainty (Salazar and Einstein, 1986). In tunneling construction uncertain conditions exist mainly with regard to geologic conditions, and construction operations.

The program simulates the construction of the tunnel under varying geologic tunneling profiles. Excavation and initial support methods are selected on a round by round basis depending on the simulated geologic conditions. Within a given round, the program schedules a sequence of activities and then simulates their execution, the occurrence of random delays, and keeps track of time delays as well as of activity simulated time duration. Rounds are monitored in terms of their location within the tunnel alignment and their length of execution.

This simulation program has the ability to alter the sequence of execution based on specific conditions taking place during a simulation. This ability is known as soft-logic. The program is capable to determine the impact of changes in the sequence of construction operations and of construction methods on the advance rate and on the

corresponding utilization of labor crews and equipment. The program generates a range of possible values of advance rates and the chances of obtaining these values under varying ground conditions and constraints on the job. This information allows the contractor to select the most appropriate methods for rapid construction and better utilization of resources. It also aids the contractor in preparing estimates of labor and equipment costs as well as of time dependent job and home-office overhead charges. It also enables the contractor to establish reliable contingency figures on bids consistent with the company expectations and risk profile. This in turn permits to prepare probabilistic estimates of labor and equipment costs as well as of time dependent job overhead charges (Einstein et al., 1987).

This model is based in the Tunnel Cost Model developed at the Massachusetts Institute of Technology (MIT) in 1972 (Vick, 1974; Moavenzadeh et al., 1978). The Tunnel Cost Model, among other functions, produces estimates of construction time and cost for tunneling construction. Drew Tronvig, a graduate student at MIT, created the preliminary concept of SIMSUPER in 1979 to model the New Austrian Tunnel Method (NATM). SIMSUPER5, a newer version completed in 1983, was used extensively in the research of NATM for US practice (Salazar, 1983).

The original version of SIMSUPER5 was implemented in a mainframe computer environment using Honeywell Multics Fortran. Since then, several versions of SIMSUPER5 have been implemented for mainframes, workstations, and personal computers (Martin, 1988; Baeza, 1998), and rewritten in FORTRAN and C.

Since 1983, many features and capabilities have been added to the program by

graduate students at MIT and Worcester Polytechnic Institute (WPI) under the direct supervision of Professors Herbert Einstein (MIT) and Guillermo Salazar (WPI). Some of these changes include the integration of cost capabilities into SIMSUPER with the Cost Model by Chankyu Kim in 1991 at WPI (Kim, 1991). On that same year, Shawna Liu, from WPI, developed a knowledge-based system with an intelligent graphical user interface that enhances the system functions, helping the user to make design decisions (Liu, 1991). The inference engine of the knowledge base was developed using CLIPS, and the GUI using OSF/MOTIF.

In 1994, WPI's graduate student Kurt Ruchala used SIMSUPER to analyze operations that were not related to tunneling processes. Ruchala made a feasibility study for determining the usefulness of SIMSUPER in the modeling of fire suppression operations (Ruchala, 1994). At the same time, Brito at MIT developed SIMSECTION, a design module that shows stress and strain along the different sections of the tunnel cross-section (Brito, 1994).

In 1995, Vijaya Halabe, from MIT, developed the Resource Model and extended SIMSUPER capabilities for the modeling of multi-tunnel systems. Adding this feature to a system that now is called the Decision Aids in Tunneling (DAT), the program is able to model the global project on a real-time basis with distance association, following the fundamentals of the above mentioned features, with resource modeling (Halabe, 1995). Halabe's work provided the ability to simulate tunneling construction operations in different fronts. The Swiss Office of Transportation and the Engineering Coalition of Schools for Excellence in Education and Leadership (ECSEEL) sponsored this

development.

This simulation tool has been used for research and professional studies in engineering and construction planning by government and private engineering consultants like the Yucca Mountain project (Clem and Salazar, 1990). It has also been extensively used for educational purposes (Schwartz et al., 1992). This research project at WPI studies the feasibility of adapting the tunneling model for productivity analysis in building renovation (Salazar and Jimenez, 1998). The general requirements for the development of the Building Model are discussed in the next chapter.

This chapter presents a general review of the components of the SIMSUPER5 model and how these modules interact with each other. It also reviews operating procedures such as input requirements and run setups. It also describes simulation outputs. For details on how to use the computer program, please refer to Appendix A.

5.2 SIMSUPER AND THE DAT

In its most up to date version, SIMSUPER is a component of the Decision Aids in Tunneling (DAT). The DAT is composed of three major modules: a geologic module, a construction simulation module (SIMSUPER), and a resource allocation module. These three modules are combined with the purpose of simulating tunneling excavation and initial support operations on a real-time basis with distance association, considering resource availability and a variety of uncertainties. These uncertainties are mainly driven by the unknown geologic conditions as well as human and equipment performance and unforeseen events during construction.

These modules attempt to aid in the decision-making during the design stage of the project (i.e., selection of alternatives for different alignments, shaft locations, tunnel cross-sections, etc.), and during the construction planning stages (e.g., identification of feasible excavation methods, resource availability, resource centers, etc.). The following section describes in more details each one of these modules (see Figure 5.1).

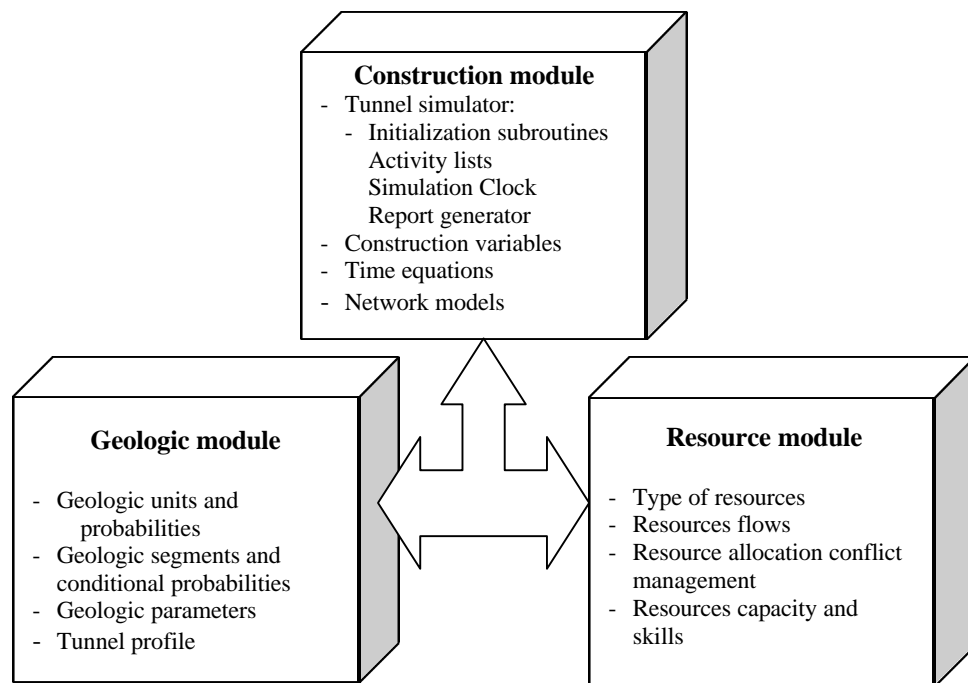


Figure 5.1. DAT modules

5.2.1 GEOLOGIC MODULE

The geologic module identifies the ground parameters of each tunnel segment along the tunnel profile, as well as the segment length (Chan, 1980). A *tunnel segment* is defined with a unique set of geology parameters that are constant throughout a certain length of tunnel. These parameters include compressive strength of the soil, rock quality

designation (RQD), foliation, gas, jointing, rock type, shear zones or faults, and water inflow (Vick, 1974).

All these parameters are integrated into a tree structure. Each path along the tree represents a unique geologic condition, which in turn defines a unique segment. Several geologic conditions per tunnel are possible and by assigning probabilities to parameter states, one obtains probabilities of the different conditions in each segment. Probabilities are subjectively estimated. Segment lengths and locations are also subjectively selected (Einstein et al., 1987). Figure 5.2 shows this concept.

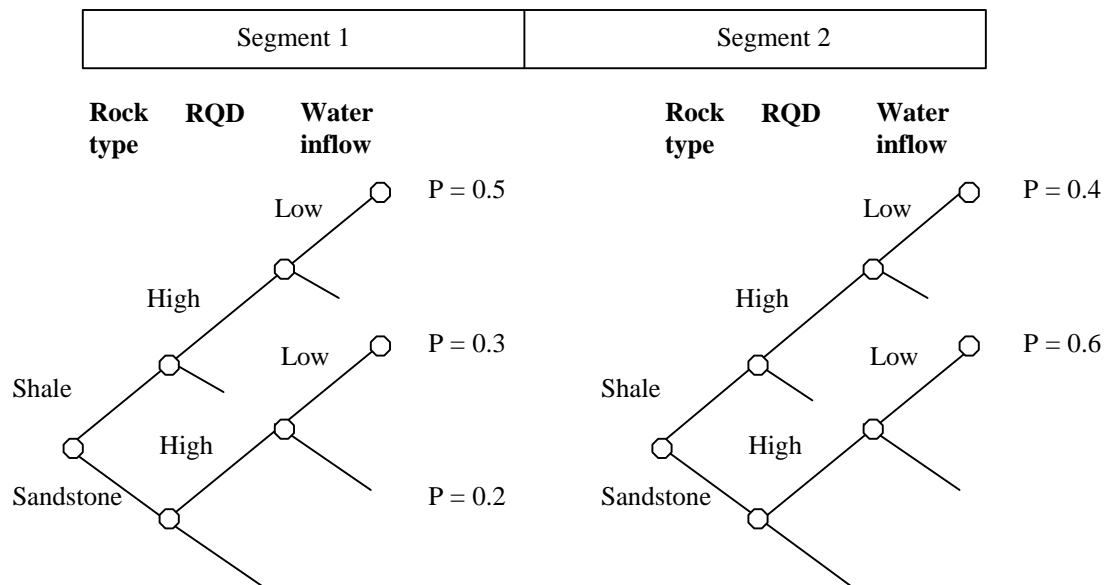


Figure 5.2. Segments with different combinations of parameter states and associated probabilities¹

¹ Adapted from Einstein, H.H. et al. (1987). Computer Based Decision Support Systems for Underground Construction. Proceedings of the Rapid Excavation and Tunneling Conference, New Orleans, LA.

The resulting combination of unique values or data sets defines a *ground class*, which is associated to a specific method. In other words, several tunnel segments may share similar characteristics and be part of the same ground class. For instance, segments and ground classes are associated to one construction method that is feasible for those conditions. Probabilities and deterministic values are associated with these ground parameters among the tunnel segments through a Markovian model. An *interface* is defined as a change of ground classes and change of construction method.

The average extent and a transition probability matrix estimate the average length for which a parameter value will remain constant and the probability that each parameter state will become a different parameter state given that there is a parameter state change, respectively. Experts in this field estimate the values for the average extent and for the transition probability matrix.

All the data related to the ground conditions is stored in the geologic module input files. Once this data is entered into the module, the program generates a *tunnel profile*. This profile is defined as the percentage of all ground classes in the tunnel as well as the number of interfaces. In other words, this tunnel profile indicates the probability of finding certain geologic conditions at a particular location given the subjective assessment of experts in the field. Figure 5.3 shows the relationship among the tunnel segments, segment's length, geology parameters, ground classes, and tunnel profile. In the case shown below, there are three different ground classes, three different construction methods and at least four tunnel segments. Segments 1 and segment n share the same ground conditions and as a result the same construction method. Throughout the

length of a segment, soil conditions do not change.

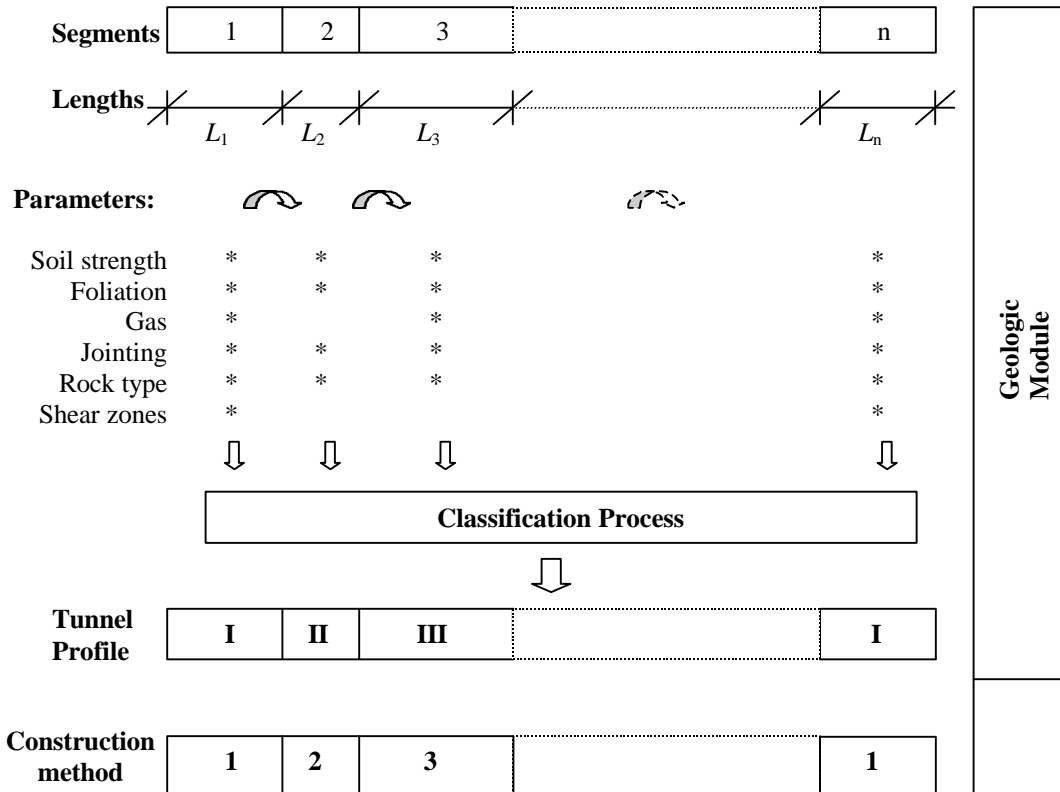


Figure 5.3. Ground class tunnel profile²

5.2.2 CONSTRUCTION MODULE

This module is used to perform the simulation of the construction operations through the different ground classes along the tunnel profile. It relates the ground classes to one or more construction methods (see Figure 5.4). These construction classes define the tunnel cross-sections or layouts (tunnel geometry), initial and permanent support, as well as

² Modified from Baeza, J.R. (1998). Computer Based Hybrid Model for Estimating Tunneling Excavation Productivity. Ph.D. dissertation. Civil and Environmental Engineering, Worcester Polytechnic Institute, Worcester, MA. Page 82.

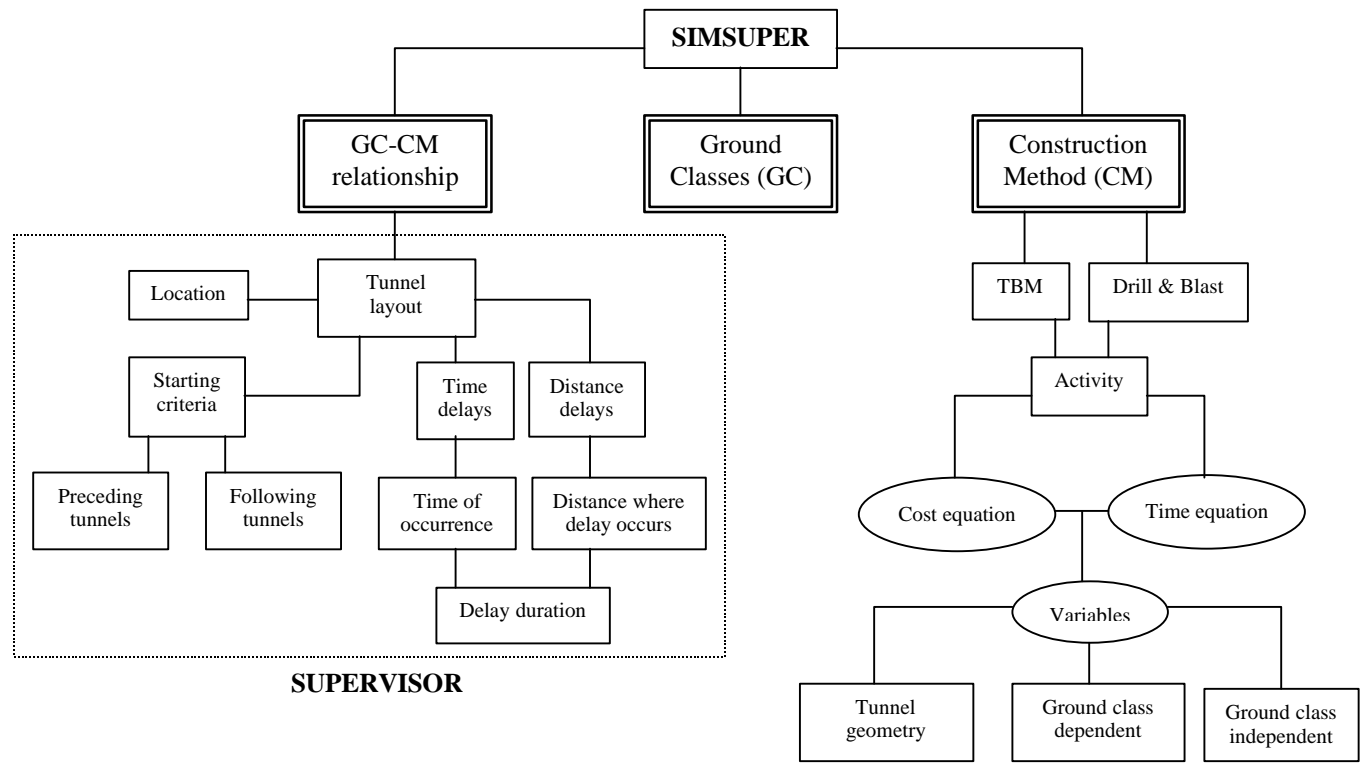


Figure 5.4. Construction simulation module structure⁴

⁴ Adapted from Halabe, V.J. (1995). Resource Modeling for DAT. Ph.D. dissertation. Civil and Environmental Engineering Department, Massachusetts Institute of Technology, Cambridge, MA. Page 11.

excavation methods that are best suited for a particular ground class (e.g., tunneling boring machine method or drill and blast). For each one of the activities that are part of the different construction methods there are two associated equations: cost equation and construction time equations.

The construction time equations are defined in terms of construction variables like the drill penetration rate and the length of the drilled face holes (Minot, 1974). The user, depending on experience and data availability, defines these equations. The ground and construction variables files store sets of values that correspond to either ground dependent or ground independent variables (e.g., drill penetration rate and advance round, respectively). The ground dependent variables values can be generated from probability distributions. These values are given in terms of three point estimates (most optimistic, most likely, and most pessimistic).

In addition to the construction time equations, SIMSUPER also determines construction cost by a set of predefined construction cost equations. For each round or cycle the simulator selects a cost-time pair by adding the cost and time, from the cost and time equations assigned to each single activity. Cost and time required to finish each round are combined to determine the total cost and time required excavating and supporting the segments until the simulation of tunnel excavation is completed for the entire tunnel length.

Prior to the simulation, the user establishes the relationships between ground classes and construction methods. A construction method is represented by means of network diagrams. These networks graphically display the sequence for all the activities

that have to be executed to complete construction operations within a round of excavation. These activities are performed on a round-by-round basis, until the total tunnel segment length is excavated and supported. Every time that a round is completed, construction operations advance in the direction of the tunnel stations allowing the user to keep track of the location where the operations are taking place (i.e., spatial tracking). Referring back to Figure 5.3, consider segment 1 to be 30 meters long as well as the length of face holes. Once the first round is finished, the excavation crews have moved from station 0+000 to station 0+010, at the completion of the second round the excavation crews are in station 0+020, and so on.

Tunnel layouts can be associated with ground classes, which in turn are associated to a specific construction method. Different tunnel layouts may prevent the use of certain methods, for this reason a particular tunnel layout may have a bearing in the selection of the excavation method.

The SUPERVISOR of the construction module allows the user to model multi-tunnel systems (refer to Figure 5.4). This modeling concept allows for the simulation of excavation operations at various locations at the same time. In other words, the SUPERVISOR has the ability to replicate simultaneous operations in different fronts. The user can specify the sequence at which these tunnels will be excavated by establishing starting criteria for preceding and following tunnels. Also, it allows for the modeling of random delays that may occur during the excavation process. These delays may be distance or time related. Time delays allow for the modeling of predefined interruptions like workers resting time or machine downtimes. On the other hand, distance related

delays could represent interruptions related to safety concerns.

The construction module also has the capability of redefining the sequence of execution of the activities within a given round if certain conditions are met during the simulation of the process. This ability was already introduced in Chapter 4 and is called *soft-logic* (refer to section 4.6). The ground conditions of subsequent segments are tested continuously during the computer simulation, allowing the module to select the appropriate excavation method to use in the next segment.

SIMSUPER uses discrete event simulation to control the events that take place during the simulation (Salazar, 1983). When a round is specified, a number of blocking conditions or constraints for execution is assigned to each activity depending on the number of immediately preceding activities. As the preceding activities are completed, the number of blocking conditions decreases until it becomes zero. Then, the activity is placed in the Pending Activity List. The Pending Activity List provides the system with a decision-making capability to alter the network flow in case there is a conflict of resources between two competing activities. If this is the case, the blocking condition for the activity with the lower priority is increased by one and removed from the pending list. Once an activity clears for any potential conflict, it is placed on the Active Activity List. The Active Activity List controls the interaction with the construction module by adjusting time duration for those activities that have been interrupted due to safety issues controlled by a set of preempting rules. Finally, the Event Activity List maintains the schedule for the future activities. This system also has a simulation clock, an initialization subroutine, statistical counters, and a report generator. These features are encountered in

most simulation programs that use the event schedule approach. Figure 5.5 below presents a system flowchart for the simulation of a single activity.

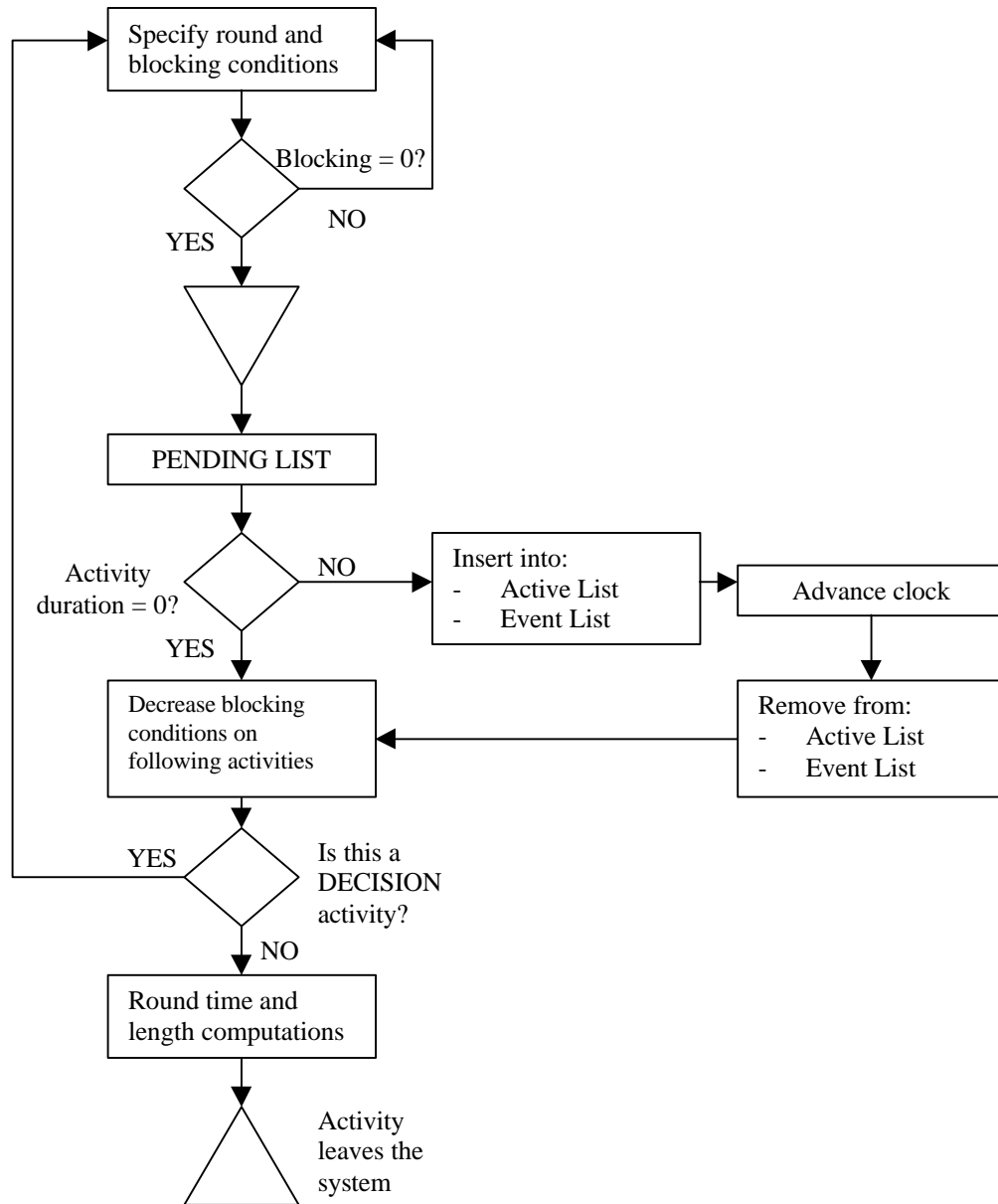


Figure 5.5. Simulation system flowchart³

³ Adapted from Salazar, G.F. and Einstein, H.H. (1986). SIMSUPER5: Tunneling Construction Simulation. Proceedings of the Fourth Conference of Computing in Civil Engineering, Boston, MA.

5.2.3 RESOURCE MODULE

This module manages manpower, material, financial, energy, and equipment resources during the simulation of construction operations (Halabe, 1995). This management includes storing, queueing, sharing and competing of resources. The objective of this module is to link the construction simulation module to resource availability and resource handling issues (resource production, consumption, disposal, etc.). Resources are available from resource centers, which are very similar to queue nodes as in CYCLONE and CYCLONE-based models. These resources are either produced during construction operations (i.e., aggregate material from crushed rock) or used during the execution of the process activities (e.g., manpower, tunneling boring machine, etc.). All tunnels and resource centers are associated with the geologic, construction simulation, and resource modules' data.

This resource module defines the type of resources, their quantities, flow properties, and values. The resources could be of different types: labor, material and equipment. They are available in certain quantities, like crew size for labor, cubic yards for materials, and number of units for equipment. The project resources move to different locations to perform the activities for which they have been assigned. These resources, as in the case of manpower and equipment moves from a resource center to a particular tunnel, at a certain location. In contrast, resources generated by the operations performed within the tunnel moves from the tunnel to a location in which it is classified and properly disposed or recycled for other purposes and uses. In addition, an identification number is assigned to each resource. This number differentiates resources in terms of

their capacity, skill level, and cost. Adding this component to the Supervisor of SIMSUPER, the model structure looks as presented on Figure 5.6.

As described before, a tunnel is associated with one or more construction methods, which are represented by network diagrams. Depending on the ground conditions of the tunnel, certain methods could be more attractive than other methods. Remember that different locations may have different ground conditions. Similarly, a tunnel is also associated with a resource center or with various resource centers that are able to execute certain operations.

The project resources contained in these centers are related to the construction method activities in the construction simulation module. Each activity requires resources for its execution. Also, an activity may generate resources during its execution. The amount of resources either required or produced is pre-established by constant values or determined by resource equations. These equations consider the productivity and capacity of each resource, among others. These values can vary according to the ground conditions, tunnel dimensions, and type of resource.

Figure 5.7 shows the connection between resources and construction activities. For an activity to be executed, specific resources have to be available to perform the required task. The resources required are taken from preceding completed or active activities or from the closest resource center relative to where the task is going to be executed. The resources used or produced by the preceding completed activities that are not needed by the subsequent activities are sent back to a resource center. The ones sent to a resource center are considered to be in idle state and are available to be utilized or

SUPERVISOR

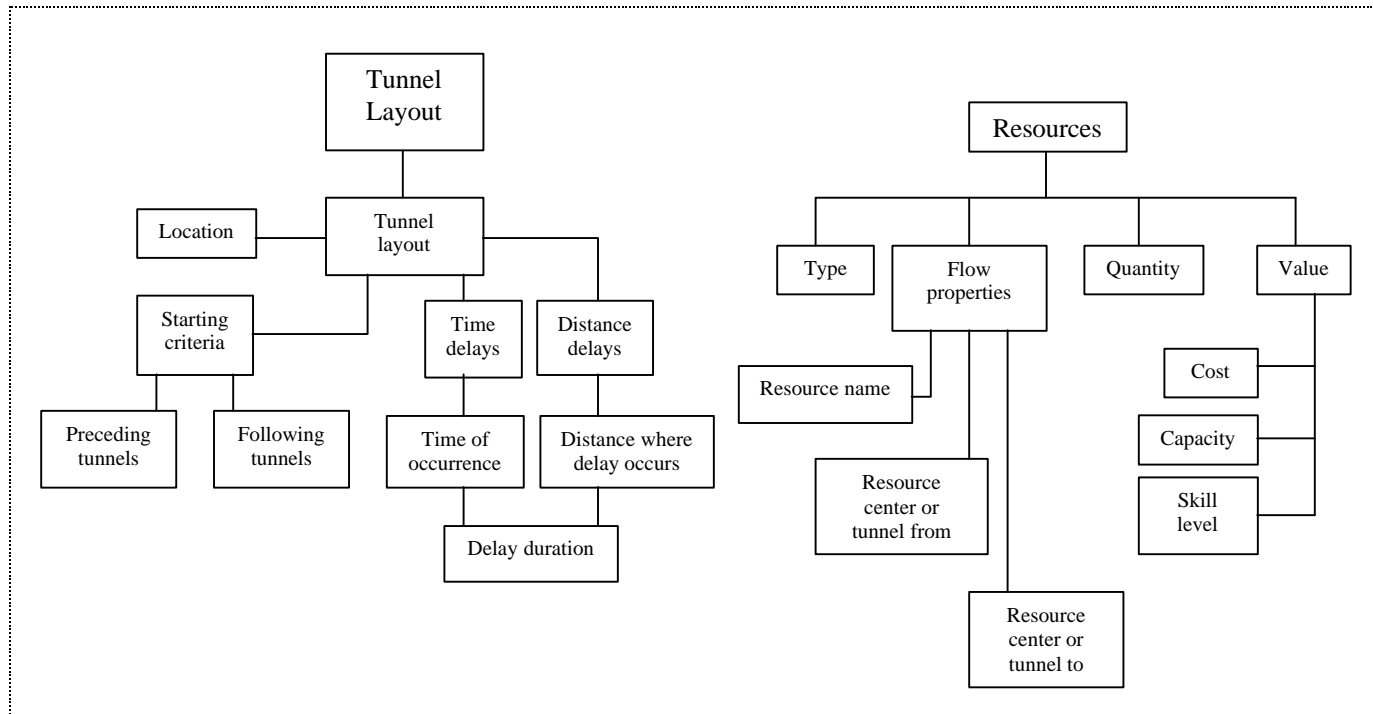


Figure 5.6. The SUPERVISOR for multi-tunnel systems and resource modeling⁵

⁵ Adapted from Halabe, V.J. (1995). Resource Modeling for DAT. Ph.D. dissertation. Civil and Environmental Engineering Department, Massachusetts Institute of Technology, Cambridge, MA. Page 68.

disposed by other occurring activities in the same tunnel, different tunnel, or resource center (see Figure 5.7).

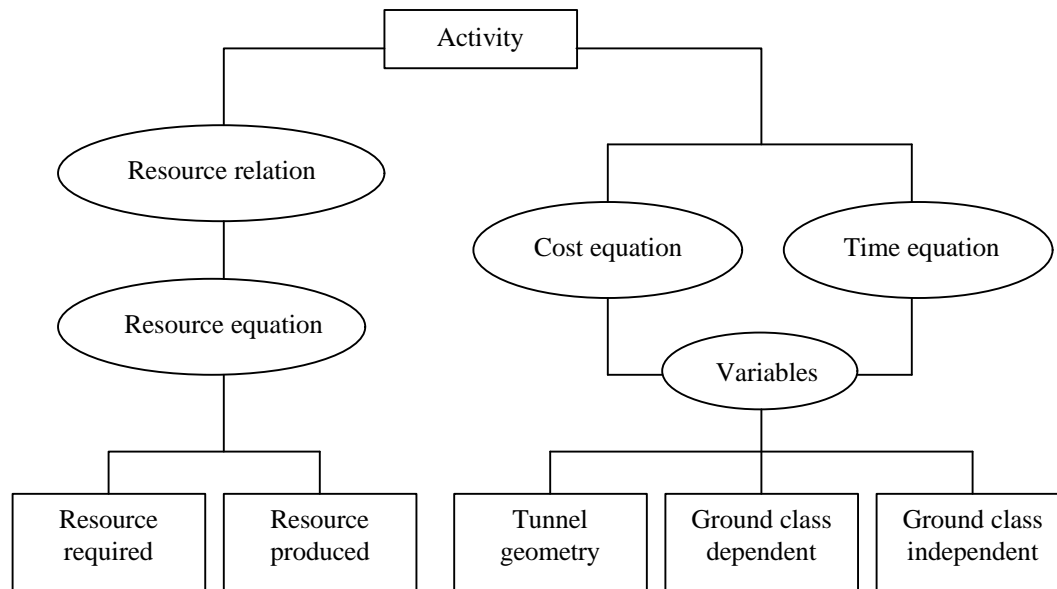


Figure 5.7. Resource-activity relation

In summary, the following four basic steps are followed by the system when a simulation is running:

- 1) The geologic module, GEOLOGY, determines the probability of finding different ground conditions throughout the tunnel length. The tunnel is then segmented based on tunnel lengths for which the ground conditions stay constant. Based on the Monte Carlo simulations the module generates a tunnel profile with various ground classes.
- 2) The construction simulation module, SIMSUPER, based on the data contained on the Supervisor component, starts running the simulation of those tunnels

for which there is no initial delay. The construction method is selected based on the ground classes of the tunnel segment for which the first round is going to be executed. In order to start with the first activity of the construction method, in addition to the checks reviewed in Figure 5.5, SIMSUPER verifies that the resources required to execute that task are available. If the resources are available, then the construction process starts. In contrast, if resources are not available, the start up time is delayed until the required resources are idle.

- 3) The quantities of resources generated by the activities are computed in order to determine construction time and cost, using the time and cost equations defined by the experts. Steps 2 and 3 are repeated until the round or cycle is completed. Once the round is finished, SIMSUPER verifies if the tunnel has been completed. If the tunnel excavation and support have not been finished, the simulator proceeds to run the next round using the specified construction method. If there is no change of ground class, the same method is used. Otherwise, a different method is selected depending on the conditions of the new tunnel segment. This process is repeated until the tunnel is finished. If the tunnel is finished, SIMSUPER verifies the relationship of the executed tunnel with the following tunnels, if any, or with other tunnels that may have been constructed in parallel. If all tunnels have been finished, total construction time and cost is computed, and the simulation stops.
- 4) The program output is generated in terms of time-cost scattergrams.

5.2.4 ADDITIONAL COMPONENTS

In addition to the three basic modules discussed above (sections 5.2.1 to 5.2.3), the DAT has four auxiliary components: Exploration, Geologic Updating, Construction Management, and the Geologic Support GUI. The first three have not been developed to the same detail level as GEOLOGY, SIMSUPER, and the Resource Module.

Exploration allows the user to evaluate the value and feasibility of a planned exploration by conducting soil tests from borings. The results obtained from these tests provide information about the probable geologic conditions to be found during excavation. These tests could provide more information to the decision-maker for construction method selection. The user compares the cost of excavation based on the assigned construction method before exploration versus the selected method once the exploration has been performed. This comparison produces the value of exploration. If the reduction of the construction cost and time due to exploration is greater than the cost of this planned exploration, it is worthwhile to actually perform the exploration (Halabe, 1995).

Once construction operations start, it is likely to find differences between the predicted geologic conditions and the encountered ones. For this reason, the information inputted for the simulation must be updated, and must represent the actual conditions in site. The *Geologic Updating* module is used to perform these updates. These updates will also affect the predictions for the tunnel sections that have not been excavated yet. Obviously, this will result in changes of logic because different sequences could be followed for the excavation of those segments to come. This module has not been

completely developed.

The *Construction Management* module is used for decision-making purposes. This component provides the user with the ability to decide whether construction methods should be changed once the encountered conditions improve (Kim, 1984). It uses dynamic programming to rank the value of alternative choices. This module has been developed but not incorporated into DAT yet.

Finally, the *Geotechnical Support GUI* module which objective is to remove the user's need to have detailed knowledge of the parameters that SIMSUPER requires to run a simulation. As discussed in section 4.5.1, this system enables novice users to operate the simulator, by monitoring the selections made by the program's user. This component checks the user input and decisions, addresses the possible consequences of the combination of the values given to the simulation parameters, judges the goodness of the simulation output, and provides comments whenever the user shows the need or when the system detects the need. For more details refer to section 4.5.1 of this report.

5.3 THE MULTI-TUNNEL SYSTEM

SIMSUPER provides the user with the ability to simulate tunneling construction operations of entire tunnel systems consisting of several tunnels and shafts. This concept was introduced for the modeling of railroad tunnels (e.g., double track and service tunnels, and multiple single-track tunnels with service tunnel). These tunnels could be related to each other depending on the configuration of the overall project excavation. For this purpose, there are seven basic tunnel types defined in the program. Some of these

types are dependent of other tunnel types. These dependencies define the precedence of operations among tunnels and the conditions that have to be met for the construction process to be started in the different fronts. Table 5.1 presents and defines each one of these tunnel types.

Tunnels of type 1 are not associated to any other tunnels. The simulation of a tunnel type 1 will always start at time zero or after an initial delay specified by the program user. The simulation stops when the entire tunnel length has been excavated. A tunnel of type 2 is a variation of a type 1. The construction activities of this type of tunnel are started from two opposite ends. Construction operations end once resources coming from both ends meet.

Tunnel type 3 is associated to at least one tunnel of type 1. In the case of a tunnel type 3, its construction operations and of its associated tunnel start independently and as specified by the user. Once the type 1 tunnel reaches a convergence point, the two original tunnels become a single tunnel of type 2. The resources of the original tunnel of type 1 are sent to assist in the construction operations of the remainder tunnel length of the previous type 3 tunnel.

Tunnel types 4, 5, 6 and 7 are associated to at least two tunnels. The starting time of the construction operations of tunnel types 4, 5, 6, and 7 is delayed until their associated tunnels reach a convergence point. For tunnel types 4 and 6, all of their associated tunnels must have reached the convergence point in order for their excavation to start. By contrast, tunnel types 5 and 7 construction starts as soon as one of their associated tunnels reached the convergence point. The main difference between tunnels 4

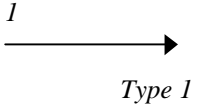
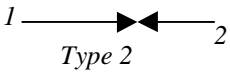
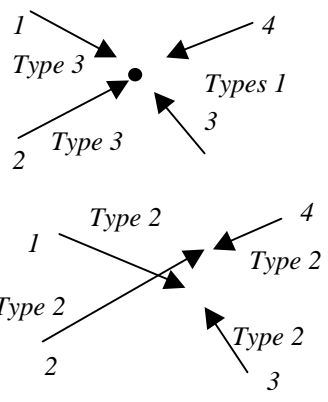
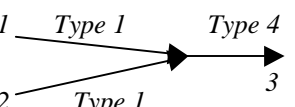
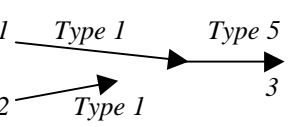
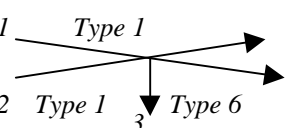
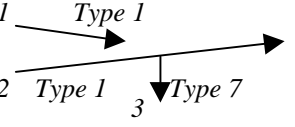
and 5, and tunnels 6 and 7, is that the associated tunnels of tunnels 4 and 5, once converging become only one tunnel. This new tunnel can also take the form of a tunnel type 1, 2 or 3. On the other hand, for tunnels 6 and 7, a new tunnel is added to the entire tunnel system when their associated tunnels reach the convergence point. They also become tunnels of type 1, 2, or 3.

The simulation of tunnel types 3 to 7 finishes when all operations within all tunnels that compose the entire system are completed. These concepts have been summarized in Table 5.1 that includes figures of all these tunnel types.

The multi-tunnel concept introduces systematic delays to the simulation process. There are two types of delays that can be specified by the user: delays by time and delays by distance. *Delays by time* are delays that occur at a certain time relative to time zero after construction begins. The user specifies the time at which the delay will occur, as well as the length of the delay. On the other hand, a *delay by distance* is a delay that will occur when operations have reached certain point in the tunnel length or excavated certain tunnel length.

In addition to the features presented above, SIMSUPER allows the user to choose different geometry for each tunnel. Every tunnel in the multi-tunnel system is associated with a *geometry number*. This number is used when, along the tunnel profile, changes in geometry occur. When a change in geometry occur, a new tunnel is define and is categorized by this geometry number.

Table 5.1. Basic tunnel types

Tunnel Type	Description	Tunnel Diagram
<p>Type 1</p>	<p>A tunnel type 1 is independent of any other tunnel. Its construction begins at time zero or after a specified initial delay. Its beginning and end points are known.</p>	
<p>Type 2</p>	<p>Construction of this type of tunnel begins from two opposite ends. It is complete when the two tunnels meet.</p>	
<p>Type 3</p>	<p>This type is very similar to a tunnel type 1 until a convergence point is reached. When a tunnel reaches this point, the simulator verifies the location of the associated tunnels and sends resources from the type 3 to help in the completion of the tunnel that is further from the convergence point. At this time, the type 3 and its associate are declared tunnels type 2. Once they meet, the simulation stops. If by the time that the type 3 reaches the decision point all of its associated tunnels have also reached it, the simulation stops.</p>	
<p>Type 4</p>	<p>Construction operations within this tunnel begin when all of its associated tunnels reach a convergence point.</p>	
<p>Type 5</p>	<p>Similar to a tunnel type 4, the starting time of the construction operations in this tunnel is delayed until one of its associated tunnels from the complete set of tunnels reaches a convergence point.</p>	
<p>Type 6</p>	<p>Similar to type 3 and 4 combined, tunnel type 6 waits until all of its associated tunnels reach a convergence point before its construction operations begin.</p>	
<p>Type 7</p>	<p>Similar to type 5 and 6 combined, tunnel type 7 waits until only one of its associated tunnels reaches the convergence point before its construction operations begin.</p>	

5.4 HEADING AND BENCH OPERATIONS

In addition to the two main construction methods already provided by the system (TBM, and full face drill and blast), the user could simulate tunnel partial face excavation by heading and bench methods (see Figure 5.8). The user must specify a set of operations to be performed in the head and bench of the tunnel as well as the *head-bench distance*. The operations in the head starts at time zero, relative to the starting time of the round, and continue to be simulated until they traverse the head-bench distance. Then the operations in the bench start simultaneously with the head operations.

The time delay for the start up of the bench operations is known as the *head-bench time lag* (Salazar, 1983). When the head-drift reaches the end of the tunnel segment, operations continue on the bench-drift only until the full face of the tunnel is excavated.

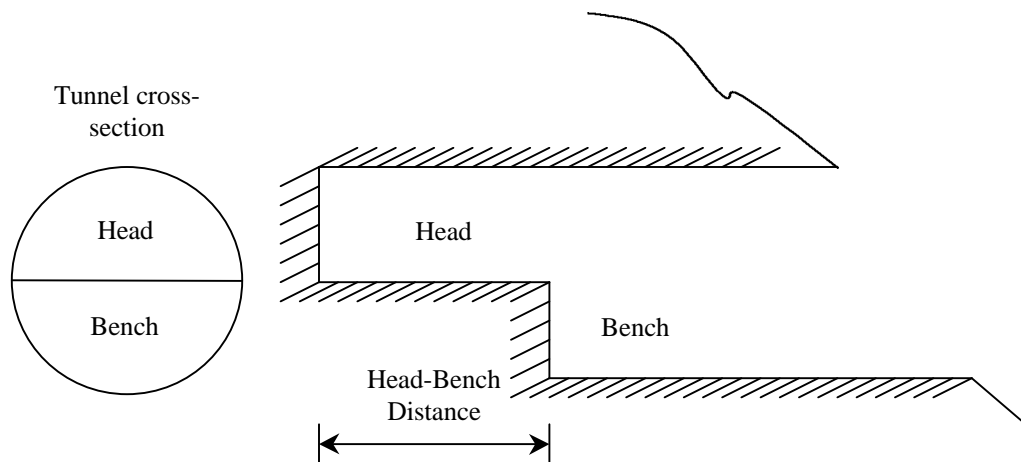


Figure 5.8. Partial face excavation

Partial face could also be performed in multiple drifts. This operation is similar to heading and bench but the user specifies additional drifts. These may include heading, left and right bench, and invert, or crown, heading, upper left (UL) and upper right (UR) bench, lower left (LL) and lower right (LR) bench, and invert (see Figure 5.9).

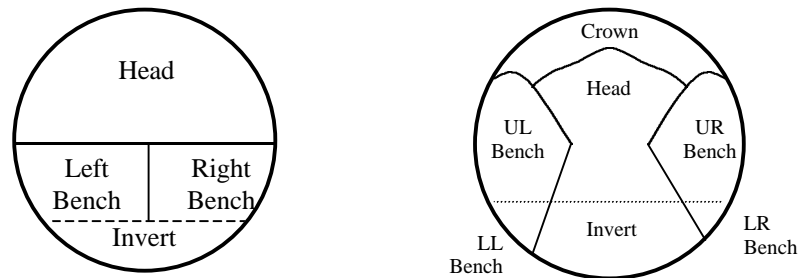


Figure 5.9. Multiple drifts

5.5 SOFT-LOGIC RULES

SIMSUPER soft-logic is controlled by internal rules. This allows the user to assign different degrees of priorities for the execution of construction activities whenever a resource or technical conflict arises. For example, consider the network diagram shown in Figure 5.10. This diagram represents the original plan prepared by a project manager for the excavation and initial support operations of a tunnel segment, by means of partial face. The top portion of the network contains the activities taking place at the segment's head, while the bottom portion contains the activities of the segment's bench.

There are certain factors that control the starting time of execution of each one of the activities contained in this network. These factors could be related to safety requirements or resource availability. During the simulation run, SIMSUPER is able to

consider these factors by a set of rules embedded in the program which are called preempting or soft-logic rules. Table 5.2 shows an example of these rules. For safety reasons, when blasting operations need to be performed, all activities in the surrounding areas of the tunnel are preempted and the tunnel segment must be evacuated. A higher priority of execution is assigned for blasting, resulting in a delay or interruption of other activities. Another case will be when the same resource is required to perform two or more activities that are going to occur at approximately the same time. Based on the priorities assigned by the user to every single activity, the resources will be routed to the activity with the higher priority. Then, the starting time of the other conflicting activities with lower priority are delayed until the needed resources become available.

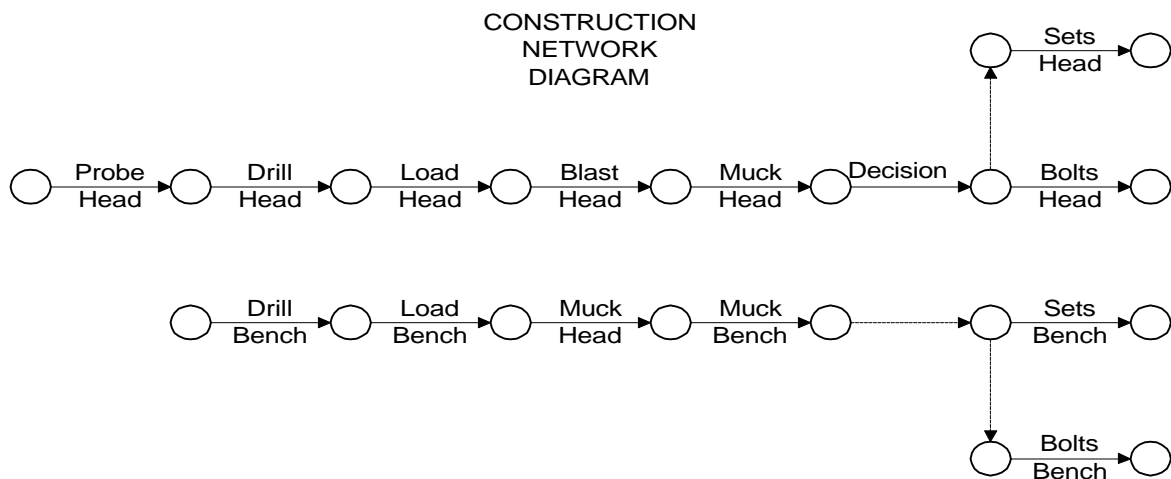


Figure 5.10. A network diagram for tunneling excavation

Figure 5.11 shows the simulated events, demonstrating how activities get interrupted and rescheduled. When activity 4 (blast head) takes place, other tunnel

activities are delayed due to safety issues. For that reason, it is observed that activity 10 (load bench) gets interrupted as soon as blast head starts. On the other hand, the activity muck head (activity 5) is also interrupted when blasting operations take place in the segment's bench. Once the blasting is completed, the activity muck head is restarted and completed.

Table 5.2. Soft-logic rules

Activity No.	Description	Duration	Preempt	Conflict
1	Probe Head	5	-	-
2	Drill Head	36	-	-
3	Load Head	49	-	-
4	Blast Head	23	All	-
5	Muck Head	84	-	Muck Bench
6	Decision	-	-	-
7	Sets Head	147	-	-
8	Bolts Head	35	-	-
9	Drill Bench	49	-	-
10	Load Bench	52	-	-
11	Blast Bench	22	All	-
12	Muck Bench	79	-	Muck Head
13	Sets Bench	94	-	-
14	Bolts Bench	32	-	-

Another observation that can be made from this figure is the resources conflict among activity 5 (muck head) and activity 12 (muck bench). Although both activities were originally scheduled to occur independently, there is only one crew available to muck. For that reason, the crew can only perform one activity at a time. This forces the start of activity 12 to be scheduled after activity 5 is done. The reason why they are executed in that order, 5 followed by 12, instead of 12 followed by 5, is because activity 5 had already started when the blasting of the bench took place. Then, it was finished as

soon as the blasting ended.

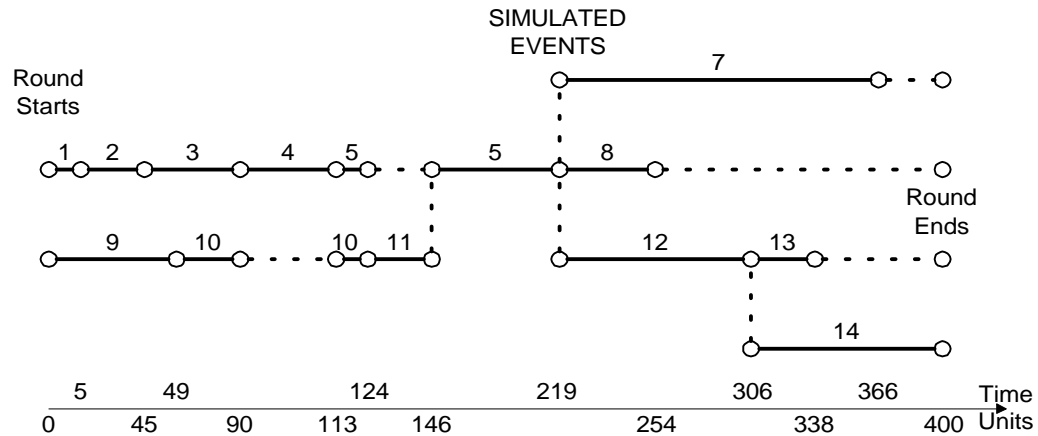


Figure 5.11. Simulated events

5.6 CONCLUSIONS

This chapter has presented the characteristics and capabilities of SIMSUPER, a simulation program that makes use of a soft-logic approach for the analysis of productivity of construction operations. These capabilities have proven their effectiveness for the analysis of tunneling construction and fire suppression operations.

The modules that compose the program allow the user to relate different construction methods with different tunnel segments in which the conditions of work may be different. The tunneling operations advance in the direction of the tunnel on a round-by-round basis. This allows the user to have definite knowledge of the location of the resources as construction progresses. This capability is known as *spatial tracking*.

Each construction activity is associated to the proper resources that are required

for its execution. This association, in conjunction with the soft-logic rules provided, enables the program to handle conflicts that may arise due to resource availability and safety or code requirements or some other reason.

Finally, the multi-tunnel system soft-logic allows the user to simulate construction operations that occur simultaneously at different fronts. Each one of these fronts can be associated, in order to allow resource sharing. Also, their associations determine the way that resources are routed when tunnels are completed.

Chapters 6 and 7 of this report present the use of SIMSUPER for building renovation projects. These two chapters are dedicated to study the feasibility of using the features above mentioned for building renovation projects.

6 SIMSUPER IN BUILDING RENOVATION

6.1 INTRODUCTION

SIMSUPER is a computer simulation program that has been used to conduct research on the tunneling construction processes like the New Austrian Tunneling Method (NATM) and conventional methods. The soft-logic approach developed for this model deserves further study and implementation into areas other than tunneling construction. This approach may be valuable for the simulation of construction processes for which conditions of uncertainty causes dramatic changes in the logic of the project plan. Many of the characteristics of building renovation projects, presented in Chapter 2, are analogous to the ones that occur in tunneling projects. For that reason, the approach provided by SIMSUPER may make this tool a suitable one for the modeling of building renovation projects.

This assumption is critically reviewed in this chapter. If the program is able to successfully model building renovation projects, SIMSUPER could also be extended for the simulation of new building construction or other non-linear construction processes. Previous research with SIMSUPER has demonstrated that indeed the program can be used in contexts other than tunneling (Ruchala, 1994; Halabe, 1995). However, some of its essential features have not been fully explored in these cases. The objective of this research is to study the feasibility of SIMSUPER for simulating building construction

processes. This will be tested using real data obtained from a real building renovation project.

6.2 SIMSUPER MODULES IN BUILDING RENOVATION

In order to use SIMSUPER for simulating building renovation activities such as demolition work, sitework, concrete work, and plumbing among others, certain changes have to be implemented. These changes are not necessarily related to the structure of the model. They are related with the way data is entered to the program for the simulation runs.

The current versions enable the program user to enter data that does not necessarily relate to tunneling projects. Even though SIMSUPER was originally developed for tunneling projects, it provides enormous flexibility as to whether the user must restrict to model tunneling projects. The running version at WPI provides adequate throughput and response time. However, there are limits in the amount of memory available in the computer server where the program is stored. This may limit the size of the projects to be modeled.

This section also documents the assumptions that the user must make while operating SIMSUPER for the modeling of building projects, particularly renovation projects. This document may well reduce the potential resistance that a user may experience while simulating non-tunneling projects due to the perception that the program is only reliable for the modeling of tunneling excavation processes.

However, it should be make clear that this research only tests the system's

adaptability. The goal is to identify the program areas that are useful or not for the objective previously discussed. The concern is to test if the technology available is flexible enough to be applied for renovation projects.

6.2.1 USING THE GEOLOGIC MODULE FOR RENOVATION PROJECTS

As discussed in section 5.2.1, the Geologic Module represents the conditions in which the tunneling process is conducted. Each condition is characterized by the specific values of a set of parameters. A combination of different conditions that may be encountered on site defines a ground class. Associated to each one of these ground classes there is a set of feasible construction methods that could be used to excavate and support a tunnel segment. The program provides the user with the flexibility to assign one or more construction methods to a given ground class according to the encountered conditions.

The excavation and initial support operations progresses along the tunnel going from one tunnel segment to another. If the conditions encountered in each one of these segments are different, the construction method used in the previous segment may not efficiently perform the excavation of the new segment. This forces the contractor to make changes in its approach, forcing changes in equipment and labor crews.

In building renovations, different building areas or rooms (i.e., hallways, stairways, roof, etc.) have their own characteristics and deficiencies. These deficiencies will determine which areas of the facility have to be improved and how will they be rehabilitated. Based on these deficiencies, different activities will have to be executed in different rooms. There may be many ways on how to perform these activities; however,

the actual conditions of an area will determine the logic to be applied. These conditions could be specified as the parameters that characterize every single room or building area (i.e., space limitations, asbestos presence, etc.). Each one of these parameters could be assigned various states (e.g., confined or ample space, congested or uncongested space, high asbestos presence, low asbestos presence, etc.).

For example, the presence of asbestos as well as the characteristics of an area will determine the logic to be followed in order to renovate this area. In other words, depending on the amounts of this material and its location within the room, two basic methods could be used for its removal: Total Isolation Removal, also known as Gross Removal, or Glove Bag Removal. Glove bags may be used as an alternative to gross removal or in conjunction with gross removal. It is used in areas identified in the scope of the work for pipe insulation removal or in confined rooms, but only if the room area will be unoccupied during all phases of the abatement.

A building module for renovation projects could be defined in an analogous fashion as the geologic module in tunneling. The profile generated by this module could be used to identify all the construction methods that are going to be combined to perform the renovation of the entire facility.

In order to build and validate such module, further study is recommended to identify the most critical uncertain condition sources that mostly impact the plan in renovation projects. These sources may vary from building to building, depending on the type of building, year in which it was built, construction materials used and suppliers, among others. A sample population of facilities used for similar purposes and constructed

in certain years could be surveyed. From the conditions encountered in this population of buildings, a probabilistic model could be built with the purpose of determining the likelihood of finding similar conditions in a building for which a renovation project has been proposed as has been done for the soil conditions in the tunneling case.

The actual version of the DAT's Geologic Module cannot be used in order to obtain a profile of the different building areas. This limitation does not prevent the user from providing the program with a set of conditions present on every room and from selecting the construction methods that are more appropriate and feasible. In this case, the "tunnel segments" are user-specified or *directly segmented*. In other words, when using SIMSUPER, the user has the option of not using the geologic module for the prediction of the conditions to be encountered in the different tunnel segments. The user may already have accurate information about these conditions. In this case, there is no need to use the module and geologic module, so the user may proceed to build the simulation and directly associate tunnel segments with construction methods.

In renovation, the user can specify the building classes (previously called ground classes) that characterize different building areas (previously called tunnel segments). Then, the user would also have to specify the construction method that applies for each building area. The building parameters that compose each building class can be obtained after a thorough investigation of the facility.

In summary, a development of a "Building Module," analogous to the geologic module, and able to identify a set of building parameters for each work area, which could include asbestos presence, level of disruptiveness, size of work area, and space

congestion must be considered. All these parameters will also have to be integrated into the tree structure with paths representing a combination of values that will be evaluated for these parameters. In addition, each path will have to be associated with one or more construction methods that are feasible for those conditions. Probabilities will also have to be associated with these building parameters. Once the module is able to analyze building conditions, then the user will be able to perform the building segmentation through specification of building ground classes using the new module. The building classes will then describe the conditions along the entire building. They will determine the construction methods required to renovate different building areas, and will provide the building conditions profile (refer to Figure 6.1).

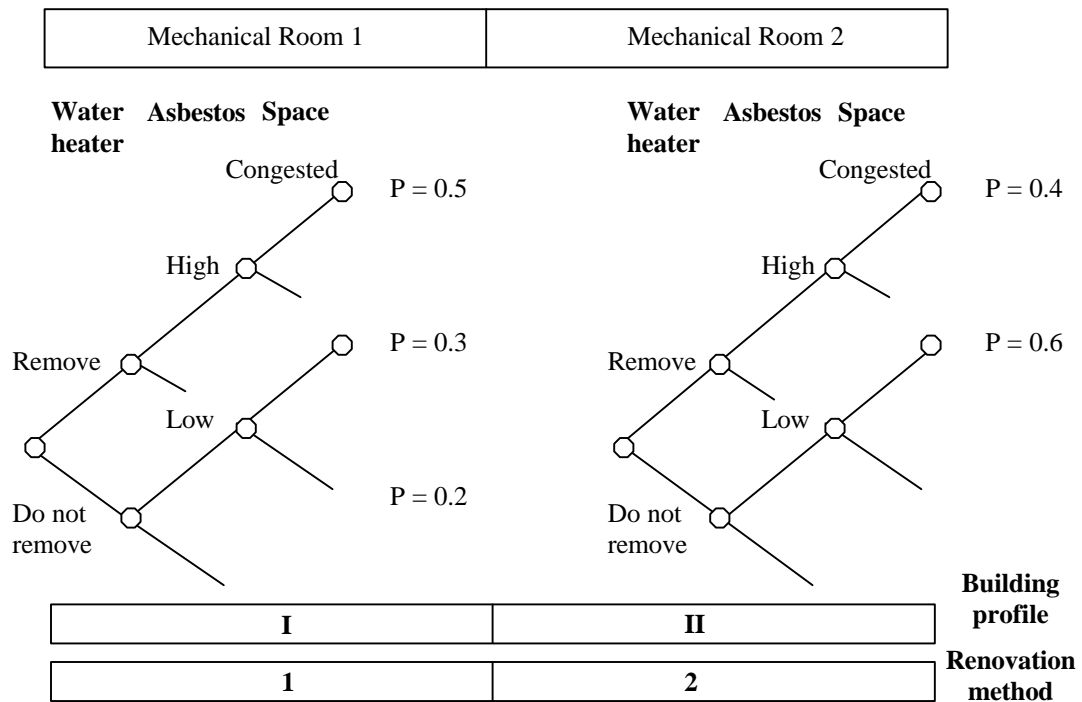


Figure 6.1. Rooms with different combinations of parameter states and associated probabilities and building profile

6.2.2 USING THE CONSTRUCTION MODULE FOR RENOVATION PROJECTS

SIMSUPER provides the user with very powerful capabilities that are not included in the computer simulation models presented in Chapter 4. These features could improve existing models' reliability for the simulation of construction processes. This section discusses in thorough detail the advantages of making these features available for the simulation of building renovation projects.

6.2.2.1 Combination of Different Construction Methods

SIMSUPER has the ability of relating construction methods with the conditions under which work is going to be executed. Basically, contractors have to plan how different building areas are going to be built, who is going to be in charge of those tasks, when those tasks are going to be performed, and what is the logic that will be applicable to the existing conditions. The method to be used for delivery will be a function of the constraints encountered in the different areas of the facility. For this reason, a combination of different activities will be necessary to finish the work tasks in the different building areas.

Figure 6.2 presents two network diagrams that describe the tasks scheduled for two different dormitory building bathrooms. In this particular case, the conditions or deficiencies encountered in the first floor bathrooms are different than the conditions in the bathrooms located in the second, third, and fourth floor. These main differences are a function of the uses given to these two areas. For example, the first floor bathrooms only provide toilet rooms, while the second, third, and fourth floor bathrooms are the

dormitory bathrooms. These provide toilet and shower rooms.

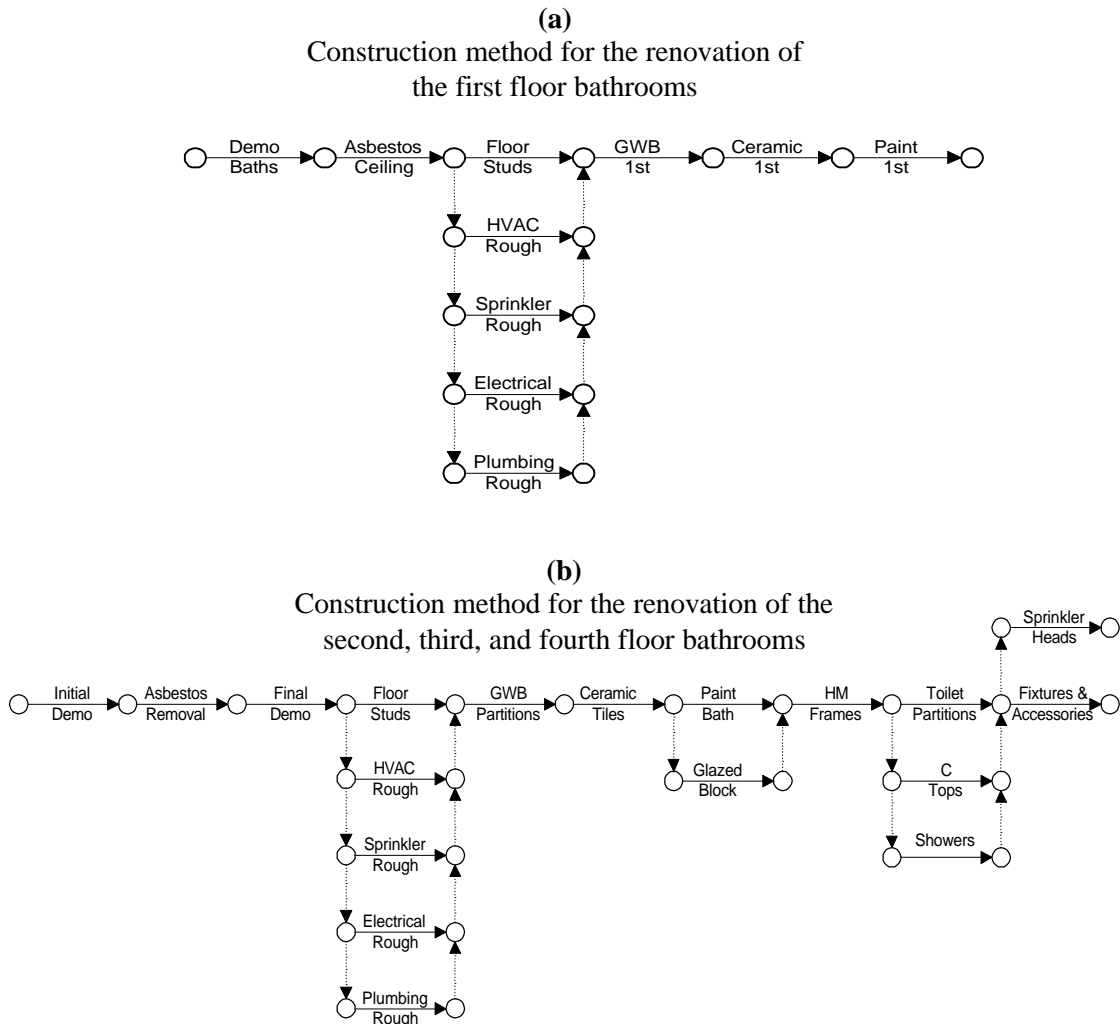


Figure 6.2. Network diagrams for two different building areas

Two different plans are required to renovate these two building areas. As the conditions change between building areas, the contractor is forced to alternate the construction logic. Because the program's input is entered in terms of network diagrams, the user can generate as many networks he or she needs to model the execution of the

project. Even though SIMSUPER is a tunneling simulation program, the construction networks entered to the program do not need to be defined in terms of tunneling operations. This allows the user to model any kind of construction project using the concepts provided by the program. Also, it is very important to understand that the user controls the level of detail in which a project will be modeled. The activities included in the networks presented in Figure 6.2 can be broken down into sub-networks that would increase the level of detail of the simulation study.

As the project advances and conditions change, different methods are selected in order to complete the planned work tasks. SIMSUPER is able to model these changes in logic and it is able to adapt through the simulation of the project. The soft-logic of this module is able to modify a pre-defined sequence of construction operations if certain conditions are met during the simulation (Salazar and Einstein, 1986). The program has the capability of selecting the construction method for the following round while the simulation of the current round is still in progress. By contrast, existing modeling techniques like PERT/CPM and CYCLONE-based models does not provide this flexibility. Both techniques assume that the conditions of work will remain constant throughout the entire project, from start to finish.

6.2.2.2 Construction Equations and Variables

Each one of the activities entered in the program is associated with a pair of construction time and cost equations. The program provides the user with the flexibility of defining these equations in the terms of the project under study and in as much detail the user

wants (i.e., tunneling project, road construction project, renovation project, etc.). It is important to mention that the GUI of the DAT is a knowledge-based tool that advises and monitors the input entered by the user, including values for the equations' variables (refer to section 4.5.1 for more details). However, this interface has been programmed for tunneling design and construction projects. As a result, a specific GUI defined in terms of building renovation projects must be designed.

6.2.2.3 Preempting Rules

As presented in section 5.5, preempting rules are a set of rules in the program that assign different priorities to each network's activity. This set of rules allows the flow of construction operations to be altered in the event of any resource conflict or any other event that triggers a change of logic. These preempting or soft-logic rules are continuously tested during the simulation.

As an example, there are certain restrictions that apply to the execution of blasting operations in urban areas. In addition to the disruption issue, there is a safety concern that forces any other activity taking place within a specified distance from the blasting area to be interrupted.

In the case of building renovation projects, this concept is very valuable. For example, consider that a masonry crew needs to sawcut the bathroom entrances to relocate a wider door. Due to space limitations and excessive dust dispersion, workers performing operations inside the bathroom at the time that the mason arrives to do the wall cuts will have to leave the room. This activity could be considered as an analogous

process to blasting operations in tunneling construction. The same situation could apply to asbestos found in plumbing pipes. If the plumbers find asbestos at the time that they reach the pipes, their operations have to be stopped in order to proceed with the appropriate abatement and disposal of this hazardous material. Depending on the priorities pre-established by the contractor, sawcutting operations and asbestos removal could preempt any other operations that are going or have already been started at the time the sawcutting or asbestos removal resources are ready to execute their task.

6.2.2.4 Spatial Tracking

One of the most valuable SIMSUPER's features is its ability to identify the location where the work tasks are being performed in a real-time basis. This feature is called *spatial tracking*. In tunneling construction, for simulation purposes, the total tunnel length is divided into segments of unique and constant geology conditions. Based on these conditions, particular construction methods are used to perform the excavation and initial support operations. Basically, for every tunnel segment, the operations start at an initial station and finish once the operations reach the final station (i.e., from station 0+000 to 1+000, segment length = 1,000 ft).

The program has knowledge of the location of resources within the tunnel length, and how fast do they move within the segment and complete their tasks. This rate at which the operations are completed is known as the *advance rate*. Now, with the implementation of the recently developed Resource Module, the program is also able to identify the location of the resources required and generated by the tunneling operations.

Remember that each activity that is part of a construction method has resources associated to it, required and generated for or during its execution (refer to section 5.2.3).

Figure 6.3 below shows the relationship that exists between building areas and the renovation methods, including resources. Each building area is associated with one or more construction methods, depending on the building class of the room. When a round is initialized, the operations in area number 1, which are defined by construction method 1, start being executed. When these operations are finished, the resources are ready to move to segment 2. By this time, area 1 is completed. Once work in area 1 progresses, the simulator selects the renovation method for area 2, in this case method 1 is selected and the process is repeated. This cycle will go on until the last area of the building segment is finished. In this context a building story could be defined as a building segment, which in turn may be considered as one "tunnel" of the entire building system. As long as the operations are executed from station 0+000 to station N+NNN, the resources also move with them. As a result, the user can track how the resources move within the tunnel.

For the spatial tracking of building projects, a two-dimensional space could be considered for a more realistic modeling of resources flows. It would be very useful to track resources flowing within a building story (horizontal displacement) and from floor to floor (vertical displacement). This may prove very useful in middle and high rise building projects. More details on resource modeling are presented in section 6.2.3.

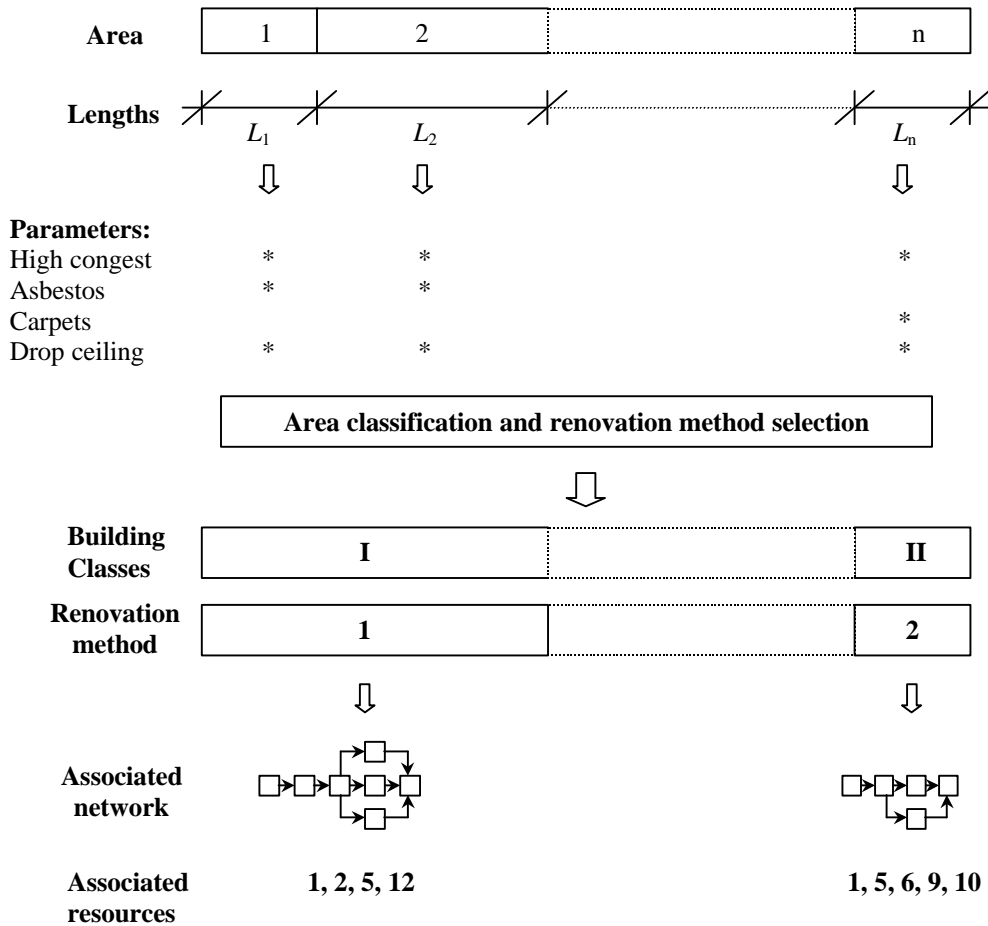


Figure 6.3. Relationship among building areas, building classes, renovation methods and resources

6.2.2.5 Heading and Bench Operations

As presented in section 5.4, SIMSUPER is able to simulate partial face excavation as well as multiple drift methods. This feature is also relevant for the monitoring of resources and for the determination of the advance or productivity rate. Both of these features, the spatial tracking and the multiple drift are key for the simulation of

renovation processes.

In the particular case of renovation processes, different operations take place in the same area or room. In other words, different crews have to go into the same rooms and perform different tasks. These operations can be simulated using the concept of multiple drifts. In this case, the area will not be finished until all trades have performed the required tasks. For example, consider the renovation of a bathroom of a dormitory building. Figure 6.4 below, presents a network diagram with the activities to be performed inside the bathroom and the logic of the process.

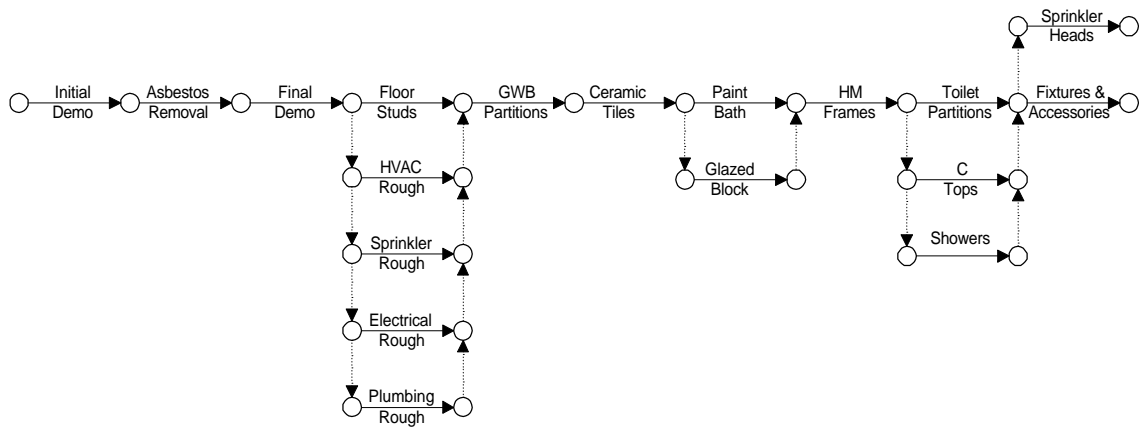


Figure 6.4. Sample of a network diagram for the renovation of a dormitory bathroom

The first activity, *Initial Demo*, refers to the demolition and removal of all bathroom furniture, mirrors, toilet partitions, sinks, toilets, urinals, and drop ceiling. Based on a thorough investigation of the actual building conditions, the contractor and the owner are aware of the presence of asbestos. These have been used as insulation for plumbing pipes. For that reason, before any demolition of existing walls is started, a specialized asbestos abatement subcontractor is responsible for the removal of all the

asbestos covering plumbing pipes that are enclosed by the existing walls. After the asbestos is removed and the air quality test results demonstrate that the room does not represent any hazard for laborers, the contractor's crew come back for the demolition of existing walls, heating and ventilation ducts, and plumbing pipes, among others (e.g., final demolition). Once all demolition work has been completed, then all trades can proceed to install new electric systems, new heating and ventilation ducts, new partitions and bathroom furniture, etc. Basically, all these crews follow the logic presented in Figure 6.4, entering and leaving the room until all the planned activities are completed.

As described above, every time that these crews finish their part of the plan, another crew comes in and performs their part of the schedule. Even though there is progress, there is a continuous motion in and out of the same room. The fact that a crew exits the area does not mean that the area or "segment" has been completed. In other words, there are many cycles to be executed in the same "segment of the tunnel." For this reason, the multiple drifts approach is the best way to simulate these operations' flow in order to get the advantage of the soft-logic that is only provided by SIMSUPER.

6.2.2.6 Multi-Tunnel System

During the renovation of a building, many activities take place in different locations at the same time. For example, during asbestos removal operations in a dormitory bathroom, other activities like demolition of old furniture, demolition of old electric systems as well as old heating and ventilation systems removal, may take place in the dormitory bedrooms, lounges, and hallways. Each one of these different locations can be

simulated as different tunnels of the same system. A tunnel type 3, as discussed in section 5.3, is a very powerful representation of this process and it can be used to replicate how renovation operations take place in the interior and exterior of the building under the rehabilitation process (see Figure 6.5).

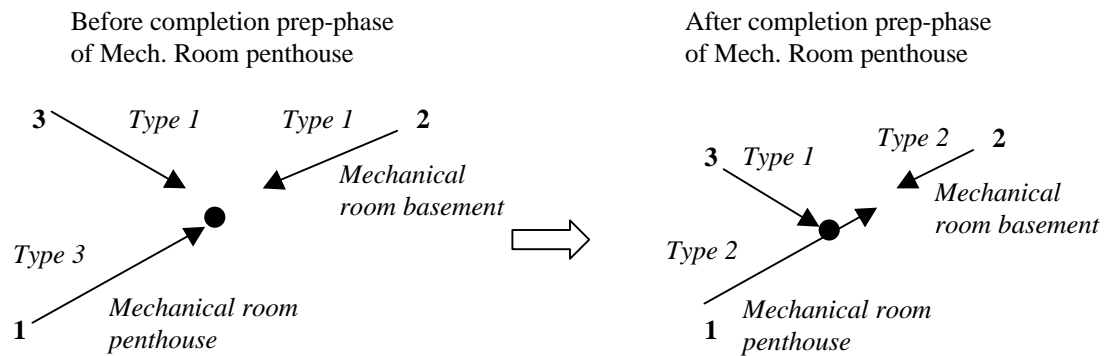


Figure 6.5. Resource flow between the mechanical rooms during the preparatory phase of the asbestos abatement process

The preparatory phase of the asbestos abatement process consists of the installment of sheeting, decontamination unit and HEPA machine in a room from which ACM will be removed. As it can be observed from Figure 6.5, these activities started independently at both rooms, the mechanical rooms in the penthouse and basement floors. Once this phase was completed in the penthouse mechanical room, its associated resources were sent to the basement to speed up the preparation of the mechanical room.

This tunnel type essentially allows the user to simulate various operations in different locations. All areas can start at the same time. However, as discussed before, the user can specify initial delays if necessary. Once the work starts been executed in different parts of the building, as the crews get out of their first assigned areas, they could

go on help finishing the activities in other areas that work is also being performed.

For example, consider two HVAC crews that have been assigned to demolish the ducts in the second floor bathroom (Crew 1) and to perform demolition work in the mechanical room (Crew 2), respectively. The project manager has determined that once the first crew finishes their tasks in the second floor bathroom they will be assigned to help the second crew in finishing the demolition in the mechanical room. The logic presented in Figure 6.5 is recommended for this analysis.

In the previous example, the penthouse mechanical room is considered as one tunnel and the basement mechanical room as a second tunnel. The penthouse mechanical room is defined as a tunnel type 3, while the basement mechanical room could be defined as any tunnel type except a type 2. The basement mechanical room is considered to be the associated tunnel of the penthouse mechanical. Once crew 1 finishes their work in the penthouse, it is automatically sent to the basement, following the associative rules of the multi-tunnel system for a type 3 tunnel.

Different combinations of the tunnel types provided in SIMSUPER could be used in order to better simulate the process. Depending on the user's needs, several tunnels could be specified, with different types of relationships among them (refer to Figure 6.6). In this figure, there are four tunnels representing four building areas. Two of these areas, 1 and 2, share the same resource center (RC), while the other two have their own. Areas 3 and 4, however, are associated with each other in terms of the resource allocation rules. When area 3 is completed, all resources allocated on its associated resource center are

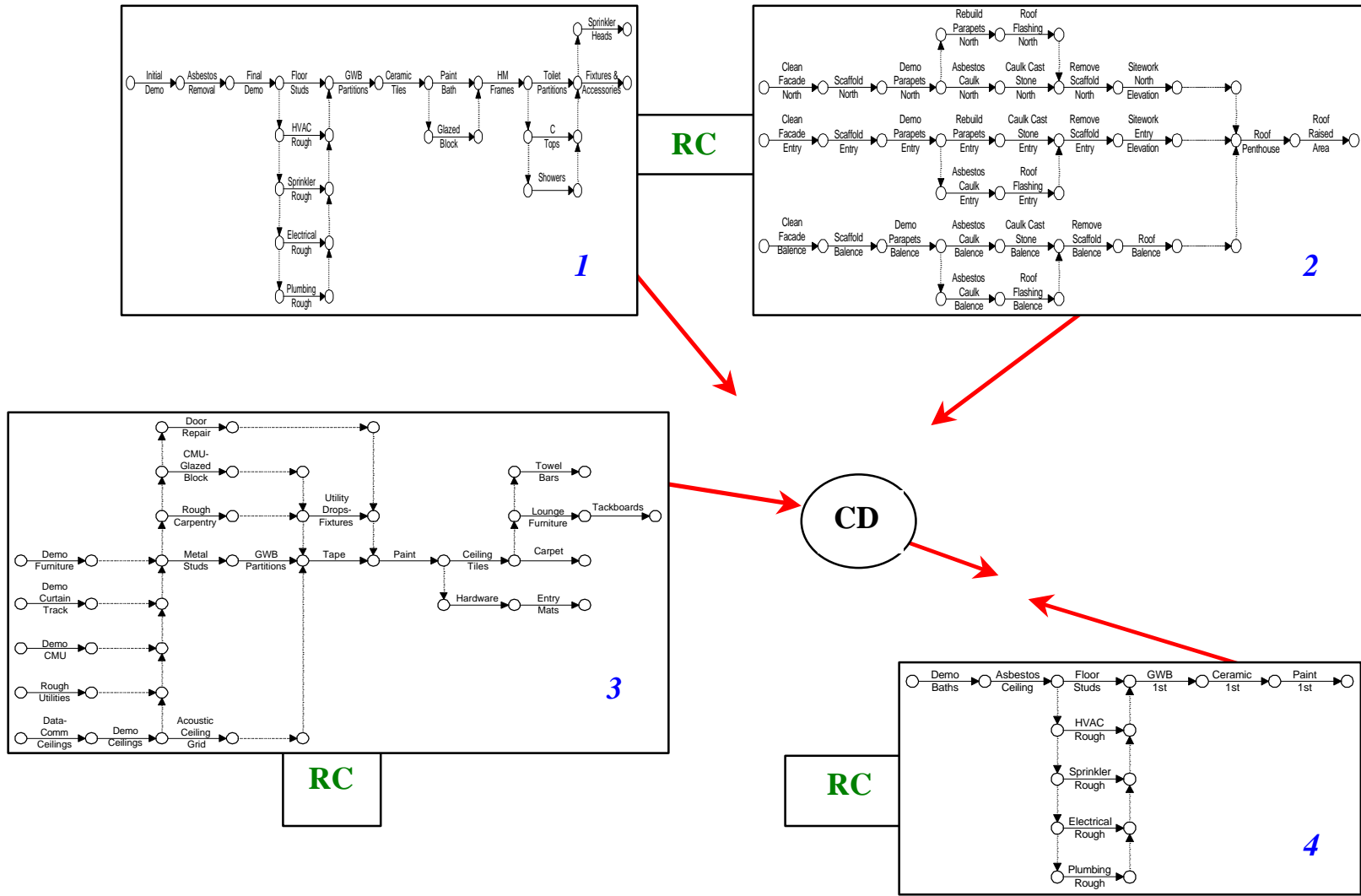


Figure 6.6. SIMSUPER modeling of renovation operations at different locations

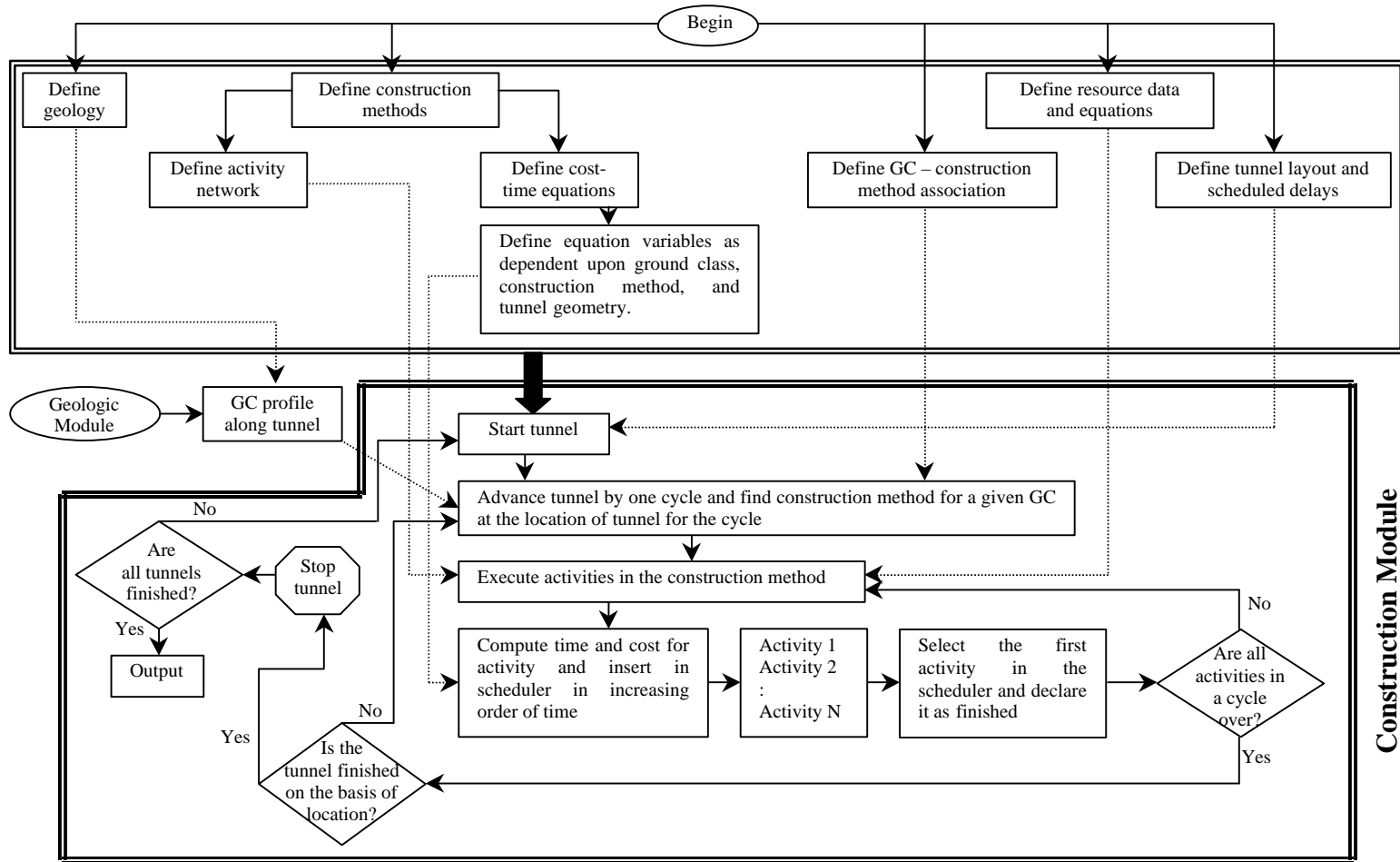
routed to the resource center of area 4. By contrast, because areas 1 and 2 share the same resource center, they act as competing areas. The entire project is finished when all areas are completed. The time that it takes to complete the work in all four areas will determine the project estimated completion date (CD). This flexibility of simulating the entire project as a whole is only provided by this program. By contrast, all models presented in Chapter 4 are focused on specific processes that are only part of the entire project.

6.2.3 THE RESOURCE MODEL

The monitoring of resources in renovation projects is very challenging in terms of simulation modeling. This is specially true in early stages, like the demolition phase, is very challenging in terms of simulation modeling. The reason is because there are many "degrees of freedom" or possibilities of flow, and because of tasks duration, which are very short in length, as discussed in Chapter 2.

To properly address this issue, the use of a simulation model that is able to keep track of the location of resources in a real-time basis throughout the completion of the project is necessary. The Resource Module addresses this concern. Figure 6.7 shows how the simulation program models the tunneling construction process considering resource modeling.

In order to start an activity, the program verifies the resource data and determines if the required resources are available in the resource center associated with the tunnel in which the activity will be executed. The condition specifies that if there are enough



Construction Module

Figure 6.7. SIMSUPER computer simulation with resource modeling¹

¹ Adapted from Halabe, V.J. (1995). Resource Modeling for DAT. Ph.D. dissertation. Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA. Page 89.

resources in the resource center, then activity X starts being executed. On the contrary, if the number of resources required is higher than resources available, activity X waits until the condition is satisfied. For instance, if the resources are being used by activity Y, which has a lower priority than activity X, then they are routed to activity X. Activity Y is then interrupted and waits until these resources complete activity X. If activity X and activity Y have the same priority level, then the activity with the higher idle time gets the resources first. If there are not enough resources for the activity that has the higher idle time, then the activity with the second higher idle time gets the resources. The activity with the higher idle time continues to be idle until enough resources are freed. If an interrupted activity has the same priority as an activity that has not yet been started and that is also competing for the same resources, the activity that was interrupted has a higher priority.

These priority rules work in conjunction with the preempting rules discussed in section 6.2.2.3. Basically, the activity priority level defines the allocation of resources for activities that are occurring in parallel or approximately at the same time. By contrast, preempting rules interrupt occurring activities when a specific activity is being executed and safety requirements establish that all laborers should be kept out of the area where the work is being performed. Figure 6.8 shows how do resources are distributed based on the level of priority assigned to an activity.

In addition to resources required, this model also considers resources produced by the active operations. The amount of resources produced by an activity is computed based on the size of the tunnel. Each project activity is associated with resources required (i.e.,

equipment, material, and manpower) and resources produced (e.g., material). The amounts of the resources utilized or produced can be directly entered to the program by the user or can be calculated from the resources' equations.

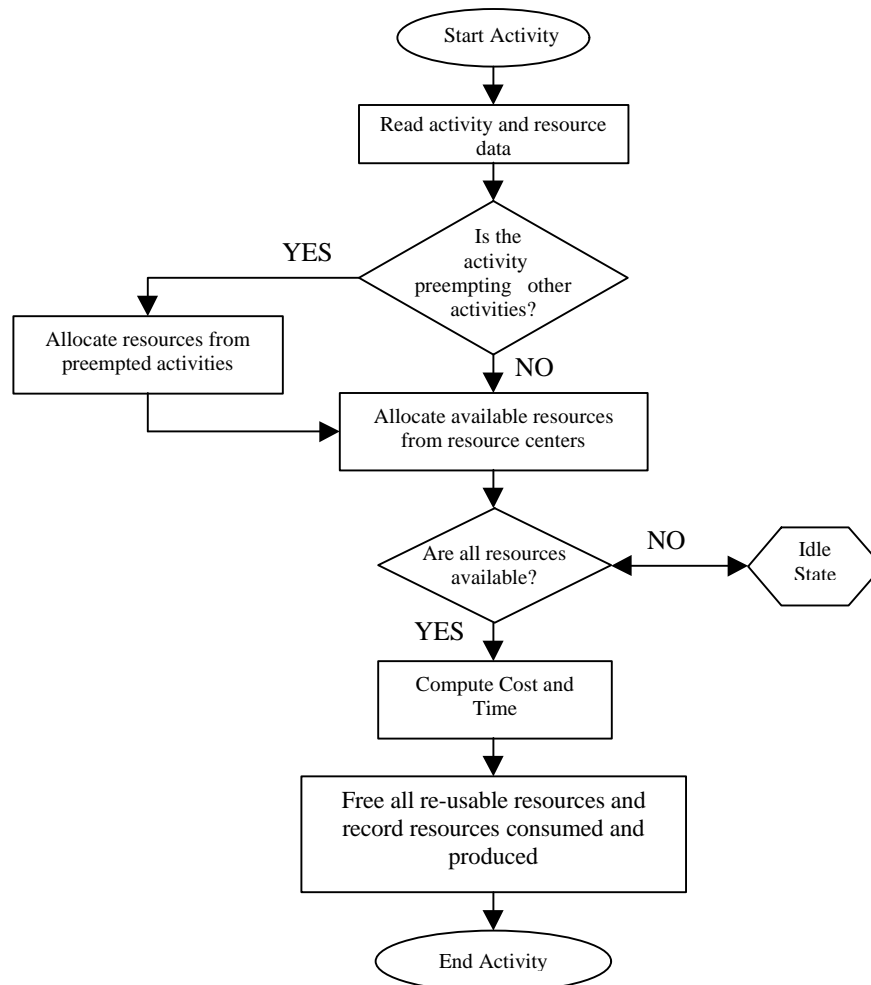


Figure 6.8. Resource model flowchart¹

¹ Adapted from Halabe, V.J. (1995). Resource Modeling for DAT. Ph.D. dissertation. Civil and Environmental Engineering Department, Massachusetts Institute of Technology, Cambridge, MA. Page 102.

Each tunnel of a tunneling system can be associated with more than one resource center. These centers are situated at different locations. Depending on their closeness to the tunnel station in which activities are being performed, these are sharing its resources with the activities within the tunnel section. The availability of these resources depends on the level of resources in each associated tunnel and the resources flow. For example, resources may flow from a resource center to another resource center or tunnel.

As it has been described, resources arrive to a tunnel from the closest of its associated resource centers. This distance, the *path distance*, is defined as the linear distance between a resource center and a station in the tunnel. This distance is defined in a Cartesian coordinate system. Therefore, resource centers are used in order of increasing path distances. In other words, this distance is computed every time that a resource is requested by taking the linear distance from the location within the tunnel at which the resource is needed to the resource center. Also, the user is able to predefine that for certain tunnel, only resources of a particular center are allowed to execute the tunneling operations.

The Resource Model provides SIMSUPER with the ability of analyzing different resource flows, resource competition among different tunnels' activities, and resources location within the tunnel in a real-time basis during simulation. These three conceptual features make the program suitable for the simulation of renovation projects. Consider the example of the demolition phase of a dormitory bathroom (refer to Figure 6.9).

Resources are sent to the dormitory bathroom, considered as a single tunnel, from the closest resource center. Every resource or crew is associated to a construction method

or network diagram and linked to certain activities that the crew is capable of executing in the bathroom. The execution of these activities will be possible if all the required resources are available in the resource center. In addition, the bathroom could be associated to another resource center that will represent the dump center for the disposal of all debris produced by the demolition operations.

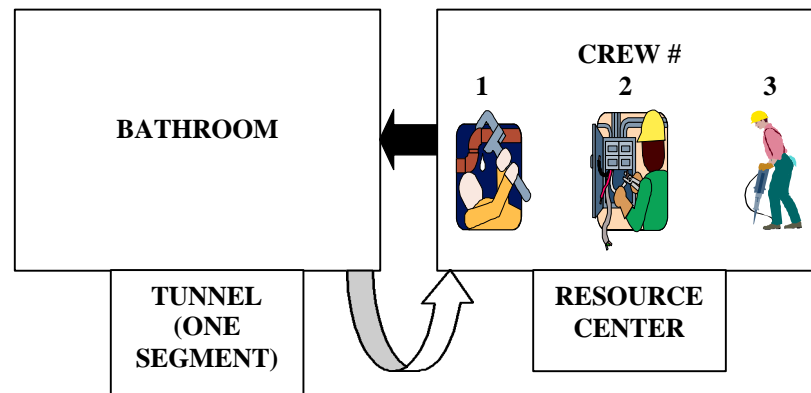


Figure 6.9. Resources flow

Priority rules will establish the usage of the resources when competing activities that are executed in parallel are in conflict. For example, during the preparatory phase for the asbestos abatement in the dormitory bathrooms, crews are sent to isolate the area, set the decontamination unit and install the HEPA filters. However, in the event that not enough resources are available, the bathroom isolation will preempt the installation of the decontamination unit and the HEPA filter. As a result, the priority level assign to the installation of the polymer barriers will be higher than the level assign to the other two activities.

Consider an analogous case but between two different building areas. Activity X is ready to be executed in bathroom 1. However, the required resource for bathroom 1 is executing an activity in bathroom 2. The start up of the activity X in bathroom 1 is delayed until the required resource finishes the task that is taking place in bathroom 2. Once the required resource finishes his/her task in bath 2, then is routed to bath 1's to start the activity that was pending, assuming that baths 1 and 2 share the same resource center. If the preemption rules had established that activity X in bathroom 1 had a higher priority of execution, then the activity in bath 2 would have been interrupted and the resource released to perform the activity in bath 1.

Another analogy between resources produced in tunneling construction operations and building renovation is related to blasted rock disposal and asbestos abatement processes, respectively. Asbestos could be considered as a resource produced by the abatement operation. The amount of asbestos to be removed are estimated by the subcontractor, and based on these estimated quantities, the time and cost of the operation is determined by the pair of related time-cost equations. Once the asbestos produced by the abatement process are removed, they are placed in the disposal bags and sent to the disposal center. If required by the user, this step could also be considered for simulation purposes as the blasted rock disposal operation is considered for the tunneling simulation.

In regard to the location of resource centers, for building renovation projects, the use of various resources centers and their locations could be considered as a function of the building size. If the building is a small facility, the use of only one resource center per building area could be sufficient to accurately replicate the process. On the other hand, a

multistory building may require the use of various resource centers for every certain number of floors. Also, resource centers could be defined by building trades. In other words, one center for the general contractor resources, a second center containing the asbestos subcontractor resources, a third with the HVAC subcontractor resources, and so on.

As all the planned activities inside a room are finished, then the tunnel segment or room is completed. As the crews finish their part, they are sent to the associated resource center, from which they could be sent to another center to help finishing another tunnel or building area. The user, in the Supervisor module, has the ability to specify these details. This module defines the relationships among the tunnels that compose the system (i.e., the dormitory building rooms).

6.3 CONCLUSIONS

This chapter has discussed how to apply the SIMSUPER model, developed for tunneling construction processes, to building renovation projects. This discussion included an operational feasibility assessment on the use of each one of the different modules presented in Chapter 5 for the simulation of building renovation projects. One of the three major modules, the Geologic Module, proved not to be useful for these purposes. However, the soft-logic approach included in the Construction and Resource Modules seems effective for this type of simulation. Specifics on the use of these two modules will be presented in the next chapter.

The following chapter presents the implementation and testing of the SIMSUPER model in a building renovation project. For this study, the author was allowed to be on site, making observations that helped to understand the process and to collect data to the simulation study. The results obtained from the simulation runs are also presented in Chapter 7 and compared with the project plan prepared by the job's contractor and the data gathered on site.

7 THE CASE STUDY

7.1 INTRODUCTION

This chapter illustrates how the concepts developed in the previous chapter are implemented in SIMSUPER for the simulation of building renovation operations. For this purpose, the current SIMSUPER version running in the WPI's UNIX network has been used.

The renovation of Daniels Hall, a four-story dormitory facility at Worcester Polytechnic Institute (WPI), Worcester, Massachusetts, is used as the case study of this research (see Figure 7.1). The structure has suffered damage to masonry and roofing from water penetration. Its renovation intended to correct these damages. Newly enacted building codes required making the building accessible to the ambulatory handicapped. The building needed to be adapted to today's requirements for entry, egress and toilet facilities for the physically handicapped.



Figure 7.1. Daniels Hall

The information required for the simulation runs of this project was acquired from the project owner, general contractor, and subcontractors. In addition, the author was provided with the opportunity of being in site for the first two weeks of the construction operations (demolition phase). This allowed the researcher to obtain practical experience, reliable knowledge and data of how does the plan logic is implemented once the construction process begins.

This chapter is divided into four major parts. The first part of the chapter (section 7.2) presents a general overview of the major requirements for the renovation of Daniels Hall. A second part, section 7.3, introduces the input and output files of the program. The third part of the chapter presents a detailed description of the assumptions made to perform the computer simulation. Finally, section 7.5 presents a discussion of the results obtained from the simulation.

A total of three simulation runs were performed. A first run tries to replicate the general contractor's plan, considering all project phases (section 7.5.1). The input for this first run are the activity duration times that were estimated by the contractor for the project overall schedule. A second run integrates data obtained from field observations during the demolition phase (section 7.5.2). A final simulation tests the resource allocation concepts presented in Chapters 5 and 6 (section 7.5.3).

7.2 CASE STUDY SCOPE OF WORK

Two major existing problems in Daniels Hall required its prompt rehabilitation. First, water penetration had damaged the building masonry and roofing. This required repairing

exterior windows, roofing, flashing and exterior masonry wall. Second, the building did not meet the Building Code requirements for handicaps' accessibility and fire protection. For this reason, all entry and egress means as well as toilet facilities had to be adapted.

The scope of the work addressed the following major requirements (refer to Figure 7.2):

- 1) Building elevator must meet the Americans with Disabilities Act (ADA) requirements and to have Fireman's Recall.
- 2) Building stairways had to be modified to meet current code requirements.
- 3) Deteriorated built-in furniture from bedrooms needed to be removed and replaced.
- 4) Deteriorated existing carpet and flooring needed to be removed and replaced.
- 5) Plumbing and HVAC systems needed to be upgraded.
- 6) Fire protection and alarm systems needed to be upgraded.
- 7) Electrical and data communication systems needed to be modified.
- 8) Toilet and shower rooms needed to be reconstructed for handicaps' accessibility.
- 9) Existing roofing membrane needed to be removed and replaced.
- 10) Exterior brickwork needed to be rebuilt.
- 11) Existing windows needed to be replaced with new aluminum units.
- 12) Building entries needed to be modified.

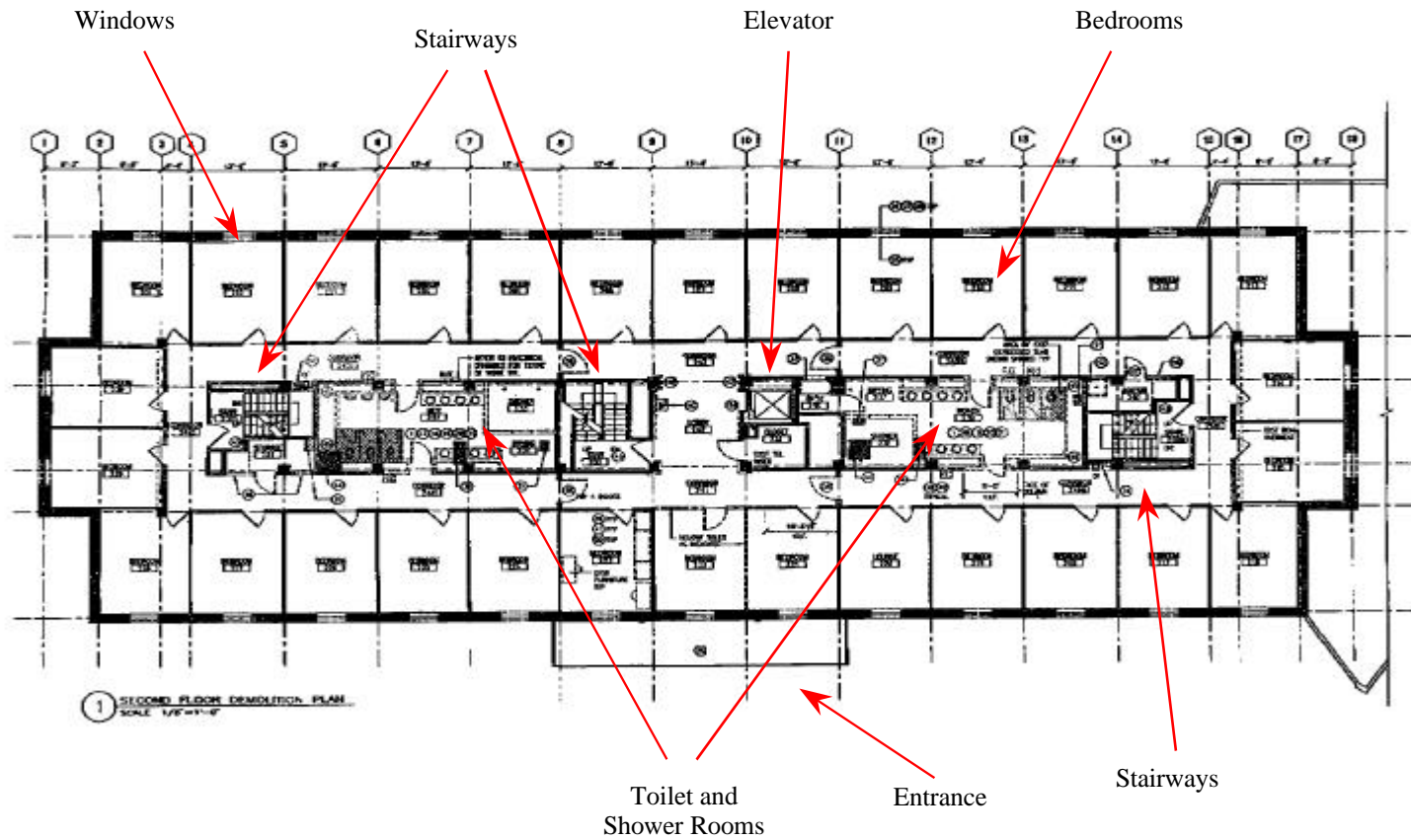


Figure 7.2. Plan view of a typical dormitory floor of Daniels Hall

The type of contract for the renovation of Daniels Hall included a base bid price with alternate prices and unit prices. A traditional contracting arrangement (i.e., design/bid/build) was followed (see Figure 7.3). For instance, the general contractor, Francis Harvey & Sons, Inc., was responsible for the planning and cost estimating of the construction operations. The general contractor subcontracted specific work tasks like asbestos abatement, plumbing, fire protection, heating and ventilating, electrical, and elevator rehabilitation. The total project cost was \$3.4 Million. Construction operations began on May 4, 1998 and the owner, WPI Plant Services, expected the completion of the project to be before August 4, 1998.

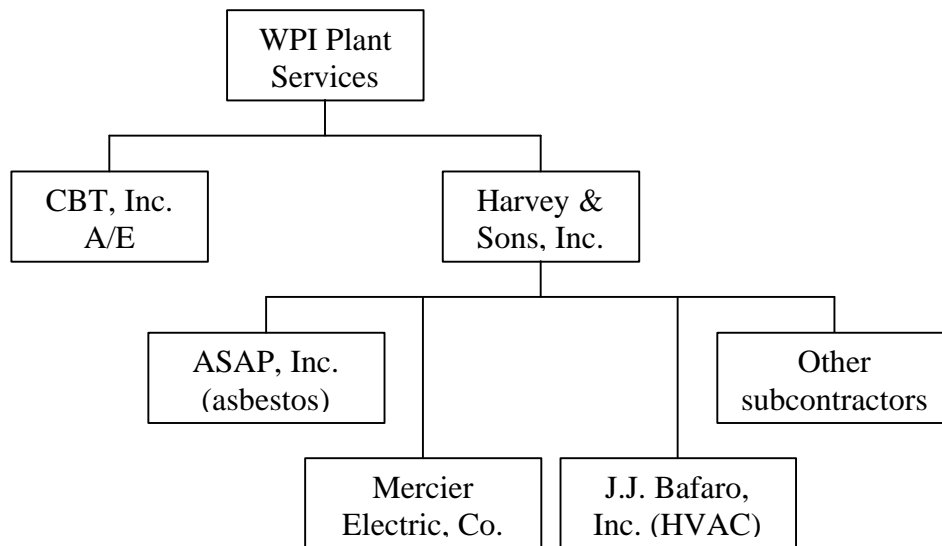


Figure 7.3. Daniels Hall renovation project contracting arrangement

7.2.1 ASBESTOS ABATEMENT

In addition to the work tasks mentioned in these twelve points, it was needed to follow an asbestos abatement process to clean contaminated materials at the job site. New building

requirements prohibit the presence of asbestos. This abatement process had the intent to remove all asbestos-containing materials (ACM) that can be impacted by the proposed renovation work.

The general contractor had to schedule the work with the asbestos abatement subcontractor in order to protect all project laborers. The abatement process in the building interior was scheduled to start on May 3, 1998 and its completion date was May 9, 1998. The exterior abatement was scheduled to begin on May 15, 1998 and was expected to be completed by May 26, 1998. The building interior ACM removal had a higher priority than the exterior cleaning in order to allow the general contractor to proceed with the demolition of partitions, and HVAC and plumbing systems.

The majority of all ACM found in the facility functioned as insulation for hot water tanks, water heaters, and pipe and fitting insulation. Also, asbestos was found in ductwork seam cement, clothes vibration dampers, floor tiles, and window caulking. It was also found that the cove base molding was contaminated by ACM mastic.

Different combinations of these ACM were found in the basement and penthouse mechanical rooms; first floor janitor's closet; second, third and fourth floor elevator lobbies; second, third and fourth floor bathrooms; second, third and fourth floor lounges and resident's rooms; and second, third and fourth floor stairwell landings. Since the presence of ACM vary from room to room, the logic of the work to be performed by the contractor for asbestos abatement was different on many of them. As a result, the asbestos abatement required operations plan changed from room to room.

7.2.2 TEMPORARY SERVICES

Some other tasks that had to be considered for planning purposes included all temporary services to performing renovation operations (i.e., temporary lightning and electricity, temporary heat and ventilation, temporary water, temporary fire protection, etc.). For example, the electricity contractor had to provide the necessary wiring and distribution boxes that allowed service in specific building areas. Basically, the electricity contractor had to provide lightning for construction operations. This lightning was provided by a combination of permanent and temporary lightning.

Other temporary construction activities included the provision of security and safety barriers that prevented public entry to construction areas. These barriers also helped to protect existing facilities from damage from the renovation operations. In terms of enclosures, the contractor had to provide temporary insulated weather-tight closures of openings in exterior surfaces to exclude rainwater, to provide acceptable working conditions, and to allow for temporary heating.

7.2.3 SITEWORK

The demolition phase of this project included the removal of designated building equipment, furnishings, and fixtures. These included the removal of electrical and plumbing fixtures, bedrooms' furniture, and others. Also, the demolition of designated partitions, ceilings and floor coverings and finishes.

Cutting activities that were part of these demolition phase included the cutting of toilet room floors for recessing accessible shower pans, the cult of glazed tile walls for

recessing electric conduit, and the cut of toilet room floors for recessing accessible ADA showers. Cutting of brick, concrete and glazed tile had to be done by abrasive saw method.

These demolition activities had to be conducted in a way that would have minimized interference with functioning offices on the first floor of the building, and protecting existing supporting structural members. When the demolition phase was completed, it was required to vacuum cleaning of all interior surfaces.

Excavation and filling was required to produce new contours, including grading work for pavements, walks, structures and relocation of existing utility covers (raising or lowering). Existing trees had to be protected. Special excavation was required to accommodate ramps, and stoops. All required pumping and dewatering necessary to maintain excavated spaces free of accumulated water was also part of the scope if necessary. Temporary earthwork included the installment of fences, barricades, guardrails, and street plates.

7.2.4 CONCRETE

The scope of all concrete work included formwork, reinforcement, cast-in-place, and underlayment and patching. The formwork consisted of providing shoring, bracing and anchorage for cast-in-place concrete, and the installation of all formwork accessories and formwork stripping. Cast-in-place concrete was required for light pole bases, sidewalks, and all other site cast concrete items. Also, cementitious floor underlayment and patching over existing concrete subfloors under new carpet and resilient flooring was required.

7.2.5 MASONRY

The masonry work included the installation of mortar and grout for masonry unit. Exterior masonry parapets were rebuilt (refer to Figure 7.4). These pre-cast concrete parapets were removed, cleaned and reinstalled. Once the parapets were removed, 15 courses of brick at top of exterior walls were also removed. These were later replaced with new bricks. All masonry unit back up at the parapets was also removed and a new concrete masonry unit (CMU) was used as masonry back up. In the building interior corridors and alcoves, a new ceramic glazed concrete unit was installed. All holes and chips in existing glazed masonry units were patched with mortar and painting.



Figure 7.4. Pre-cast concrete parapets and bricks to be removed and replaced

7.2.6 FINISHES

Gypsum drywall finishes include the installation of steel suspension systems for ceilings and soffits, and installation of interior partition framing with screwable steel stud.

Installation of screwable steel stud framed and furred enclosures at columns and beams. In addition, blocking and attachments for fixture supports, and gypsum wallboard finishes for interior ceilings, walls, partitions, ceiling edgings, soffits, column enclosures, and beam enclosures, including interior faces of exterior steel curtain wall framing. Also, acoustical ceiling and acoustical insulation of gypsum wallboard finishes, at steel stud framed partitions and furring, were required.

In addition to the drywall finishes, ceramic tiles at floors, walls, bases and marble thresholds needed to be finished. At the ceilings, suspended acoustical ceilings metal grid panel systems had to be installed, as well as the acoustical panels and perimeter trim.

In regard to flooring, substrate surfaces were prepared, resilient flooring was applied, and all floor surfaces were cleaned. Then, sheet carpeting and related items were installed.

Finally, all surfaces that required painting were prepared to receive finish. All exposed interior and exterior surfaces, except factory finished items and interior woodwork, were painted.

7.2.7 FIRE PROTECTION AND PLUMBING SYSTEMS

All existing fire protection systems needed to be demolished except the basement and first floor sprinkler systems that were connected to the new sprinkler main. These ran through the basement ceiling to be furnished with a new tamper and flow switch. A new floor control assembly was furnished and installed at each first floor stairwell. Additional parts include a wall-mounted fire department inlet connection, a backflow preventer, hose

and isolation valves and a new wet-pipe alarm check valve.

Plumbing work included the removal and demolition of existing plumbing fixtures, equipment and piping. New domestic hot, cold and hot water return water distribution system, and a complete waste and vent system for the new bathroom core connecting to existing services at the first floor ceiling was installed. Installment of new plumbing fixtures, trim, carriers and accessories throughout the new bathroom core. A new roof drainage system was required. Also, two new steam/gas water heaters were connected to existing capped services.

7.2.8 HEATING AND VENTILATING SYSTEMS

In general, the HVAC work consisted, in the building penthouse, in the removal of existing bathroom exhaust fan and associated ductwork. In the basement mechanical room, existing circulation pumps and selective piping, existing expansion tank, and a transfer pump, were removed.

In other building areas, miscellaneous piping, ductwork and equipment were removed. New flues, breeching, and associated combustion air ductwork for new hot water heaters were installed. New exhaust fans, associated ductwork and appurtenances, new circulation pumps, associated piping and were also installed. Some other new fixtures included a expansion tank, a condensing transfer unit, control valves, fin-tube enclosures, roof mounted air cooled condensing unit, ductless split air conditioning units, and steam traps. For insulation, duct and pipe insulation at all new heating hot water piping and ductwork were installed. All existing cabinet unit heaters were removed and

reinstalled. Finally, all existing ductwork, heating hot water piping and steam piping were tied up.

7.2.9 ELECTRICAL SYSTEMS

Electrical work included work in the electric service underground primary distribution, installation of unit substation and wiring of motor starters and controls, panel boards, circuit breakers, safety disconnect switches, fuses, lighting fixtures, conduits, raceways, and wires. A new telephone/data system was installed as well as a fire alarm system, and emergency lighting system. All HVAC and plumbing system electrical parts were connected. All existing electrical fixtures were demolished and new fixtures were installed.

7.3 SIMSUPER INPUT AND OUTPUT FILES

The characteristics of building renovation projects, as previously discussed in Chapter 2, makes the modeling of renovation processes a very complex one. For such reason, it was proposed before that a soft-logic approach as the most appropriate existing approach to replicating the complexities encountered in this type of projects. Soft-logic is a better way to assess productivity because it can adapt and reflect more "faithfully" to changes in the original work conditions. Of all the existing computer simulation programs that are available for the modeling of construction operations, SIMSUPER is the only candidate that uses soft-logic. For this reason SIMSUPER was selected as the computer-modeling tool to simulate the building renovation process.

Once SIMSUPER was selected, the input required for the program was based on a set of network diagrams. These networks represented different plans to be used on site. In order to develop these networks, the general contractor and subcontractors were interviewed. From the project owner, the researcher obtained the general contractor's schedules (e.g., bar charts). These presented the contractor's estimates of the duration of the project activities. The researcher was also given access to the site during the actual execution of these activities. This experience was very important for data acquisition purposes.

During such time, specifically during the demolition phase of the project, time and process observations were made. Activity duration times were recorded, as well as the location and number of workers within different crews. All these data was then organized and entered into the different input files as required by SIMSUPER. These simulations were conducted with data collected from the contractor's plan and from field observations. The results of both were compared against each other to assess the ability of SIMSUPER to replicate what really happened on-site.

7.3.1 INPUT FILES

SIMSUPER has a main input file that defines the different input and output files that are read and generated when performing a simulation run. A sample of this file, called "*monitor.dat*", is shown in Figure 7.5 (refer to Appendix B for the input files of Daniels Hall project). The first six files listed in bold letters are the basic input files that the user needs to be familiar with to perform the simulation runs. As previously discussed, the

simulation input of this program is based on network diagrams. Every process to be simulated has to be modeled in a network format. These networks are stored in the "activities.def" file. This file contains a list of the activities that conforms each one of these network diagrams. This activity list specifies the activity number, activity type, time-equation associated with the activity, level of priority, general and detail section of which the activity is part of (e.g., heading, bench, crown, right bench, left bench, etc.), and the activity name. Also, this file specifies where are these different networks or construction methods going to be used within the tunnel. In other words, in which tunnel segments are the different methods inputted going to be invoked.

Daniels Hall Renovation Simulations	; name of simulation run
1 Maxsim	; maximum number of simulations
6	; number of tunnels
3 Monitl	; level of detail for real-time output
1 Rpoutl /var/tmp/simN.rep and /var/tmp/simN.stat	; statistics level
1 Twoutl /var/tmp/simN.timw	; time-way level
0 Coutl	; level of detail of cost output
1 seed_flag	; seed flag
0 Moutl 4 next lines only if Moutl != 0	
activities.def	; connections or networks input file
ground	; ground dependent variables input file
construction	; ground independent variables input file
equations.dat	; time-equations input file
multinfo.dat	; tunnel system description input file
tunlocation.dat	; tunnel location input file
93_interface_delay.dat	; interface time delays file
../Geology/seed	; seed file
zonelengths.res	; zoning input file
output.dat	; real-time output file
test.b	; bug file
daniels.rep	; round-wise output file
daniels.stat	; segment-wise output file
daniels.restime	; time-way output file
daniels.res	; statistics output file

Figure 7.5. Sample of WPI's SIMSUPER version main input file

A second input file, the "*ground*" file has a list of variables that are dependent on the conditions encountered in the tunnel segment. The variables listed in this file are part of the time and cost equations. The values given to each one of these variables can be obtained from various sources like RS Means, historical databases, tests, etc. On the other hand, the "*construction*" file contains a list of variables that are not dependent on the tunnel segment conditions such as the round length.

The "*equations.dat*" input file contains the set of time and cost equations that are used to determine the time duration and cost of every single activity, so the total completion time and construction cost can also be computed. This file makes use of the variables contained in the *ground* and *construction* files.

The "*multinfo.dat*" and the "*tunlocation.dat*" input files contain the characteristics of the different tunnels that compose the tunnel system. For example, in the "*multinfo.dat*" file the user can specify the tunnel type of each one of the tunnels in the system (see section 5.3 for more details on different tunnel types). The user can also establish the association that exists among these tunnels. Here, the program allows the user to specify any sort of initial delays and or distance related delays that may occur in the construction process. For instance, the user could well include delays as lunch breaks that will always occur at a certain time of the day. On the other hand, the "*tunlocation.dat*" file contains the tunnel lengths, with their respective heading and bench distances if applicable, and the different combinations of construction methods that could be invoked to execute the required activities in the different tunnel segments.

7.3.2 OUTPUT FILES

Referring to Figure 7.5 again, there are three major output files that produce reports of the simulations runs. They are also listed in bold letters at the bottom of the figure. "Daniels.rep" presents a table that contains information about the duration of activities occurring at a tunnel segment. This report includes spatial details like the round location, number of rounds in a tunnel, and length of the round in time units. It also presents the elapsed time that was required to perform the operations in the tunnel segment, the net elapsed time for the operations in the total tunnel length, and the duration of every single activity per round. In the case shown in Table 7.1, only one round was ran, as well as one tunnel segment and one tunnel. The report shown is called a round-wise report.

Table 7.1. Sample of the simulation statistics round-wise report

***** TUNNEL 1 *****			
Segment	1	Ground Class	1
Method	1	Method Type	1
Method	1	Elapsed Time (minutes)	1771
Round	1	Net Elapsed Time	1771
Round Length (ft m)	36.0	Waiting for Blasting	NA
Round Loc. (End) - ft m	36.0	Head / Bench Deferred	NA
ACTIVITY DURATIONS (minutes):			
Remo_mirrors	15	Save_toilet_partit	265
Remo_shwr_fixtures	135	Remo_drop_ceiling	75
Temp_lights	20	Disc_sink_pipes	25
Remo_toilets	20	Remo_sinks	28
Debris_drop_ceilin	45	Install_sheet	120
Install_HEPA	10	Install_DECOM	40
Wall_opening	35	Inspect_debris	15
Remo_asbestos	45	Air_test	180
Remo_sheet	10	Uninst_HEPA	6
Uninst_DECOM	8	Shwr_walls_demo	60
Wall_demo	265	Shwr_roof_demo	95
Debris_wall	305	Remo_floor_tiles	90
Debris_floor_tiles	18	Single_shwr_roof	45
Remo_wall_tiles	55	Debris_wall_tiles	35
Pipes_demo	155	Remo_duct	62
Decision	0	Advance_round	0

The "*daniels.stat*" output file presents a report with the same list of activities as the one shown in Table 7.1, but this list includes, in addition to the simulated times, the average time, the standard deviation, and the highest and lowest activity time duration. The last report, the "*daniels.res*" file (refer to Table 7.2), presents the average advance rate at which work was performed in the different tunnels of the system. Also, this report presents a cost summary. In this particular project, no effort was made to obtain cost figures. The scope concentrated in data gathering for productivity rates. Although, from this analysis is possible to determine labor and material costs in function of the total completion time.

Table 7.2. Sample of the simulation statistics output file

Run No. 961		Simulation No. 1		14-10-1998 12:02:08								
Tu Nr	Ar Nr	Gm Tp	Beg-X [m]	End-X [m]	Length [m]	Beg-T [hr]	End-T [hr]	Duratn. [hr]	Idle [hr]	Ad.Rt [m/hr]	Cost [MF]	Cost/m [KFr/m]
1	1	1	0	36	36	0.0	29.5	29.5	0.0	1.22	0	0.0
2	1	1	0	36	36	0.0	51.9	51.9	0.0	0.69	0	0.0
3	1	1	0	36	36	8.0	39.0	31.1	0.0	1.16	0	0.0
4	1	1	0	36	36	8.0	39.8	31.8	0.0	1.13	0	0.0
5	1	1	0	36	36	16.0	54.1	38.1	0.0	0.95	0	0.0
6	1	1	0	36	36	16.0	46.1	30.1	0.0	1.20	0	0.0
Total Time :		54.08 hrs.										
Total Cost :		0.00 M.										

Section 7.4 of this report provides more specific details on how to simulate renovation projects by presenting a set of sample runs of the renovation activities that took place in Daniels Hall. This section discusses all the assumptions made to replicate the operations executed in the different building areas.

7.4 SAMPLE RUNS

Three sets of sample runs, the contractor's plan, the observed process, and a final simulation that tests the resource allocation concepts presented in Chapters 5 and 6, are discussed in this section. These plans were simulated and compared with the data obtained from the contractor and from the time study performed on-site by the researcher.

7.4.1 THE CONTRACTOR'S PLAN

The contractor's plan divided the building into three major areas: bathrooms, building interiors, and building exterior. The general contractor presented a bar chart for each one of these building areas (refer to Figures 7.6, 7.7 and 7.8). These estimates are generally based on the contractor's judgement and his/her understanding of the work. As it can be observed from the figures, the level of detail is minimum, not showing productivity rates or alternative sequence of activities, among others. The contractor may provide the owner with a plan that most likely includes contingency to account any unexpected situation.

In this particular case, the contractor has planned to start the renovation operations in the bathrooms, building interiors and building exteriors on May 2, 1998. The contractor expects to have the bathrooms and exterior job completed by July 10, 1998, while the building interiors completion is scheduled for July 18, 1998. In the building interiors, the first project phase or demolition phase is expected to be finished by May 22, 1998. However, this estimate is subject to change, depending on the existing conditions of the building that could have not been anticipated, as well as change orders, weather conditions, and absenteeism, among other sources of uncertainty.



Figure 7.6. Contractor's plan for the renovation of Daniels Hall bathrooms

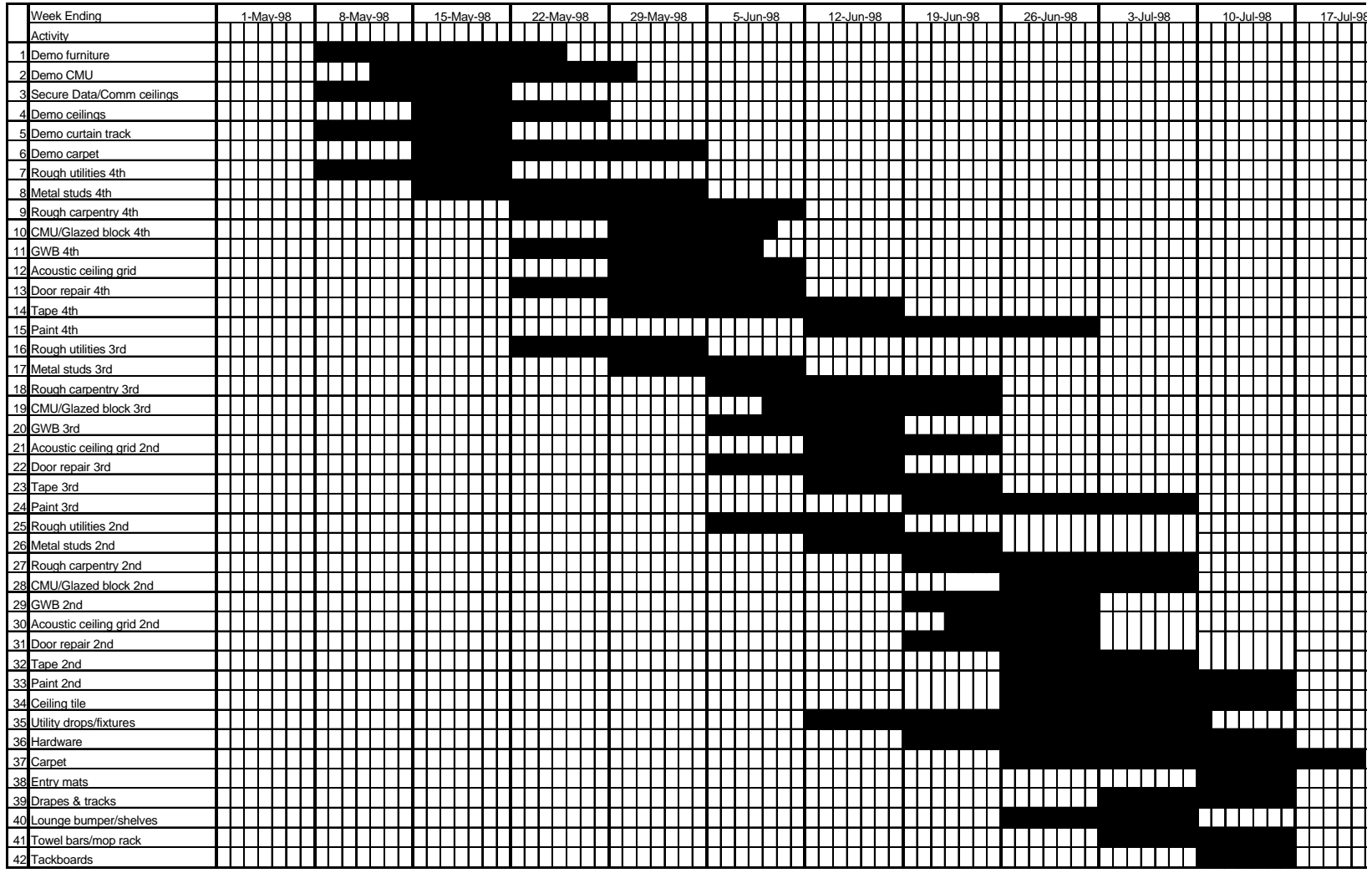


Figure 7.7. Contractor's plan for the renovation of Daniels Hall interiors

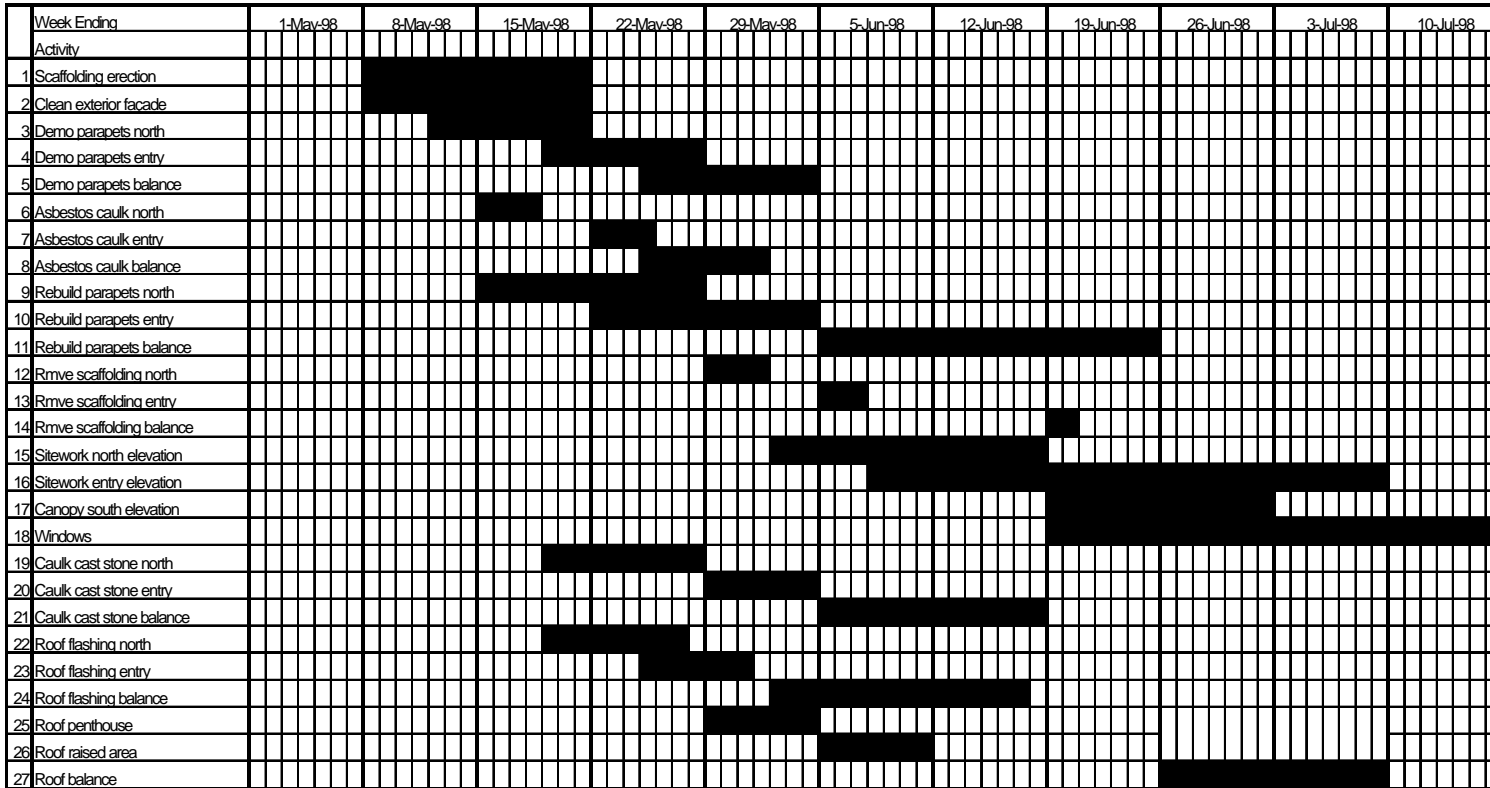


Figure 7.8. Contractor's plan for the renovation of Daniels Hall exteriors

In order to input the data presented in the contractor's plan into the computer program, it is necessary to translate these bar charts into network diagrams. These networks present the interrelationships or dependencies that exist among various project activities. For this reason, the researcher developed project networks for each building area with the purpose of simulating the contractor's plan (see Figure 7.9). The sequence of the activities presented in these networks represents the process logic that was observed on site by the researcher.

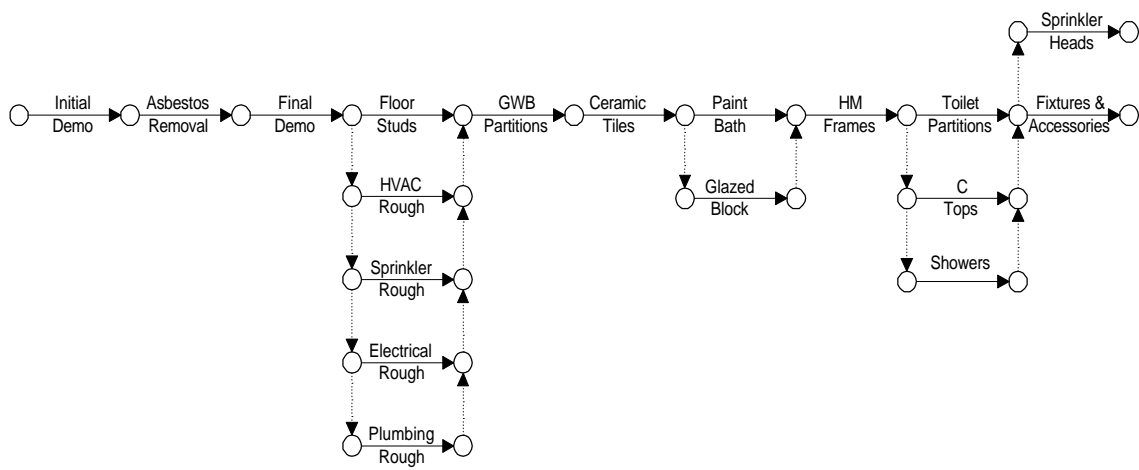


Figure 7.9. Sample of the contractor's bathrooms plan as a network diagram

The network shown in Figure 7.9 is a sample of the contractor's plan for a single bathroom. It includes the activities presented in the bar chart that correspond to the work that will be executed in the building bathrooms located at the second, third, and fourth floor. The advantage of translating the bar chart into a network diagram is that it allows to studying the relationships existing among the different project activities. Also, this diagram eases the data entry process.

For the *contractor's plan simulation run*, the schedule shown in Figure 7.6 was divided into four networks that represent the logic for the execution of the renovation operations in the first, second, third and fourth floor bathrooms respectively. These four networks are similar to the network shown in Figure 7.9. Due to data storage limitations of the WPI's Hornfel Server, these building areas were the only ones considered to be included in the computer analysis.

To perform the simulation runs, several assumptions were made:

- 1) Each one of these networks represents the activities to be performed in an independent tunnel. In other words, the tunnel system representing the renovation work of these areas consists of a total of four tunnels: first floor bathroom tunnel, second floor bathroom tunnel, third floor bathroom tunnel and fourth floor bathroom tunnel.
- 2) The renovation processes were simulated as a full face excavation method. It was recommended before (refer to section 6.2.2.5) that a multiple drifts or partial excavation method was the best approach to model this type of project, however, the existing version of SIMSUPER at the UNIX network in WPI does not provide this capability.
- 3) The tunnel length was taken as the length of the bathroom. For example, for a bathroom size of 36' x 15', 36' would have been taken as the tunnel length.
- 4) Each bathroom (tunnel) was considered to have only one segment. And the work to be performed in a bathroom required only one round. The work to be performed in a bathroom, to the level of detail modeled, is not repetitive. For

that reason, it would not make any sense to define more than one round.

- 5) The program version currently available in the UNIX network does not provide a resource module. For that reason, resources were not included in the modeling of the Daniels Hall project.
- 6) Initial delays were included in the input of the program. For example, the demolition phase of the third floor bathrooms is supposed to start two days after these operations start in the first and second floor bathrooms, as estimated by the contractor. Because each building area can be simulated as single tunnel, SIMSUPER is capable of delaying the start up of the operations at a certain location.
- 7) Activities time duration were taken from the contractor's plan as single value. This number is stored in the ground variables that are part of the time and cost equations.
- 8) Activity equations were not developed since it was not considered part of the scope of this project.
- 9) Two construction variables were defined. These are the length of face holes and the advance round. These are factors that in the context of a tunnel establish the round length and the rate at which an excavation process is progressing (i.e., advance rate). These two variables have no physical meaning for renovation processes but they are needed to run the simulation. It was previously explained that the modeling of renovation operations only requires a single round per room. For this reason, the length of face holes is defined as

the length of the room and the advance round as one.

These nine points summarize the basic assumptions that were made to allow the modeling of a non-tunneling project in the SIMSUPER environment. Basically, the user translated the data obtained from a building renovation project into a tunneling based input. The results obtained from the simulation runs are discussed in the next section (section 7.5).

7.4.2 THE OBSERVED PROCESS

A second computer simulation run concentrates in the first phase for the renovation of Daniels Hall bathrooms, the demolition phase. This run is identified as the *observed simulation run*. This second run tries to replicate the operations observed by the author during the first two weeks of the project. This phase can be divided into three sub-phases: pre-asbestos demolition, asbestos abatement and post-asbestos demolition. The pre-asbestos demolition includes the removal of toilet partitions, toilets, sinks, and other equipment which demolition do not disrupts asbestos contaminated areas. The post-asbestos demolition sub-phase refers to the demolition of partitions, plumbing pipes, and HVAC ducts. Bathroom partitions, plumbing pipes and some parts of the ductwork, were contaminated by asbestos containing materials. Its demolition would have easily spread such material representing a potential hazard to all laborers. For this reason, the demolition of these types of equipment had to follow an asbestos abatement process.

The assumptions made for the contractor's plan simulation run are valid for this run also:

- 1) The network diagrams developed for this run represents the activities to be performed in six building areas: east and west bathrooms second floor, east and west bathrooms third floor, and east and west bathrooms fourth floor. This simulation run consists of six "tunnels."
- 2) As in the contractor's plan run, the processes were simulated as a full face excavation method.
- 3) The tunnel length was taken as the length of the bathroom.
- 4) Each building area was considered to have only one segment. And the work to be performed in a bathroom required only one round. The level of detail of this run summarized the work to be performed in the demolition phase. As shown in Figure 7.10, the demolition phase was decomposed into a set of "microscopic" activities. These were expected to take place between May 2, 1998 and May 22, 1998 as estimated in the contractor's schedule.

Figure 7.10 presents a typical network diagram relating the demolition activities at a bathroom. This particular network shows the logic for the activities that were executed in the second floor bathrooms. This network was built based on the information gathered on site by the author during the actual execution of the demolition phase.

- 5) Resources' availability was not considered as part of the input data for this run due to the limitations discussed in section 7.4.1.
- 6) Initial delays were also included in the input of the program, as presented in the contractor's bar charts.

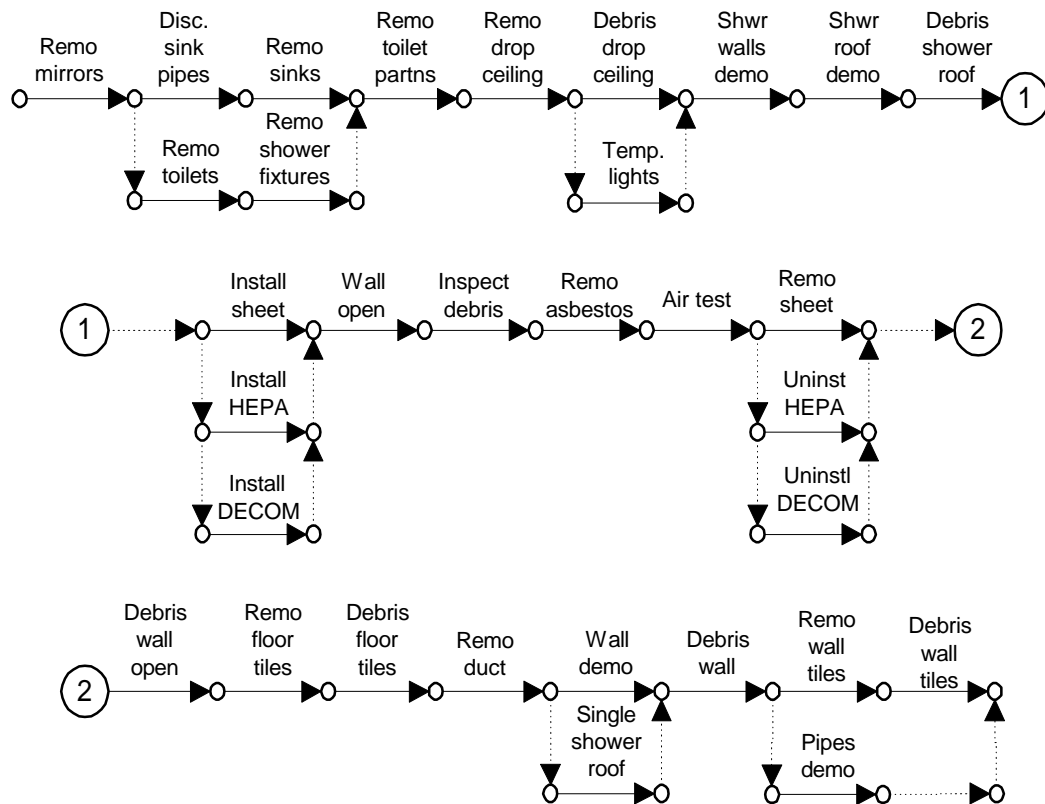


Figure 7.10. East bathroom second floor network diagram

- 7) Activities time duration were obtained on site by the researcher. The researcher recorded the time duration of the activities being observed. This time duration was entered to the program as a single value.
 - 8) Activity equations only included the actual duration of each one of the activities that are part of the network diagrams.
 - 9) The two construction variables defined before, length of face holes and advance round, are equal to the length of the room and one, respectively.
- As explained before, these network diagrams as well as the assumptions made

were entered into the program following the format of the input files shown in Figure 7.5. Once this translation is completed, the program is ready to perform the simulation analysis. The results obtained from these runs are discussed in section 7.5.

7.5 SIMULATION RUNS RESULTS AND DISCUSSION

7.5.1 THE CONTRACTOR'S PLAN SIMULATION RESULTS

Figure 7.11 shows a bar chart that contrasts the contractor's plan with the output obtained from simulating his/her plan with SIMSUPER. The contractor's estimated duration are shown by the black bars, while the SIMSUPER output is shown by the gray bars.

To simplify the reading of the bar charts and to make ready comparisons among the planned schedule versus the simulation output, several activities were grouped and they constitute one single activity. For example, the demolition and the asbestos activities were grouped into a single activity called "*Demo & asbestos N bath.*" The plumbing rough, electrical rough, sprinkler rough, and HVAC rough activities were reduced into an activity called "*Plumb, elec, spr, HVAC N bath,*" and so on. A more detailed representation of the simulation outputs is shown in Appendix C.

As can be observed from Figure 7.11, there are some differences between the starting and completion dates of the planned activities and the output. For example, consider the case of the "*Plumb, elec, spr, HVAC 2nd bath*" activity. As it can be observed, the output presents this activity occurring one-week before than as planned. The network diagrams that were constructed for input purposes only consider the technical dependencies that exist among each one of the project activities.

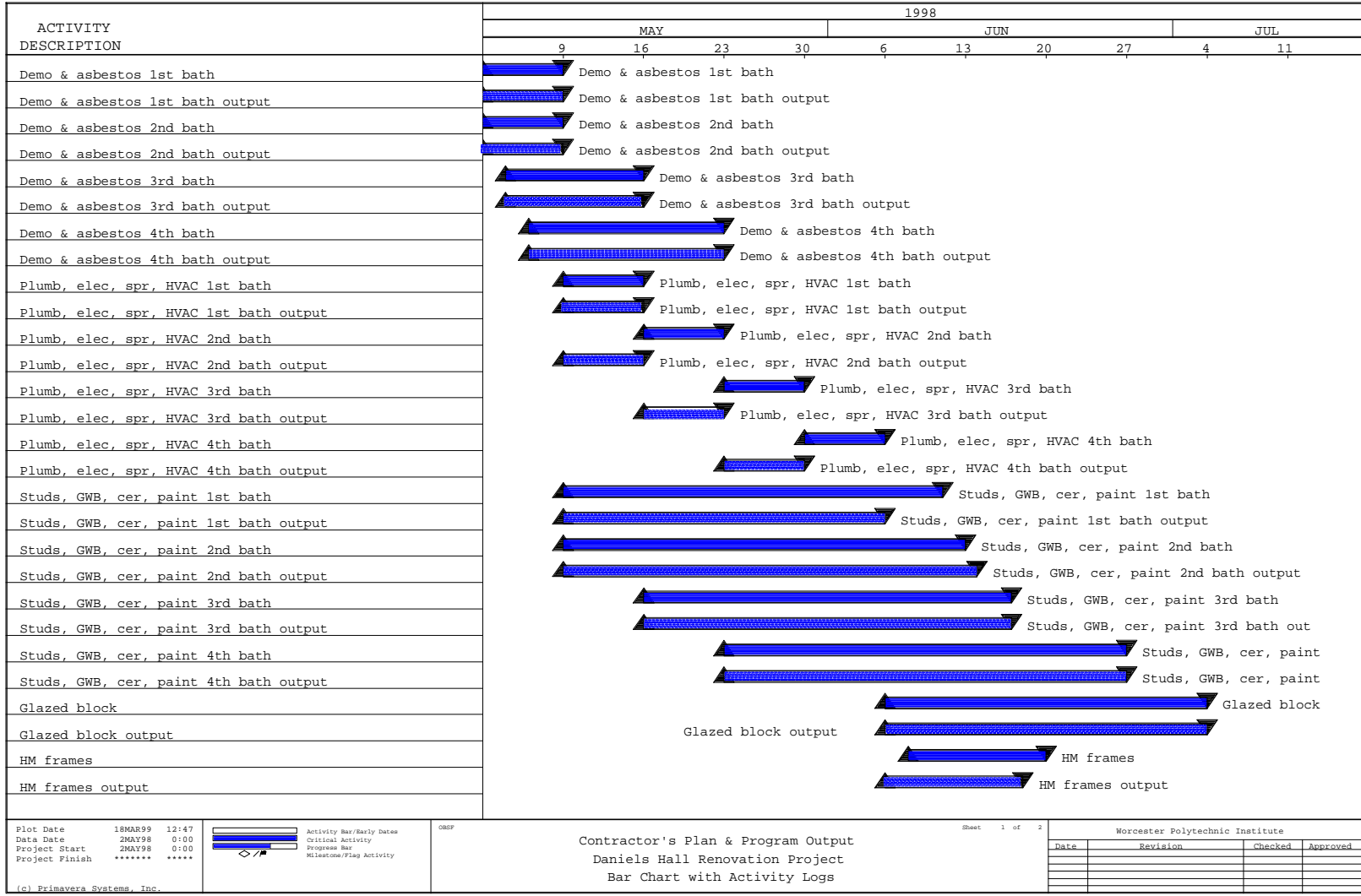


Figure 7.11. Contractor's plan simulation output

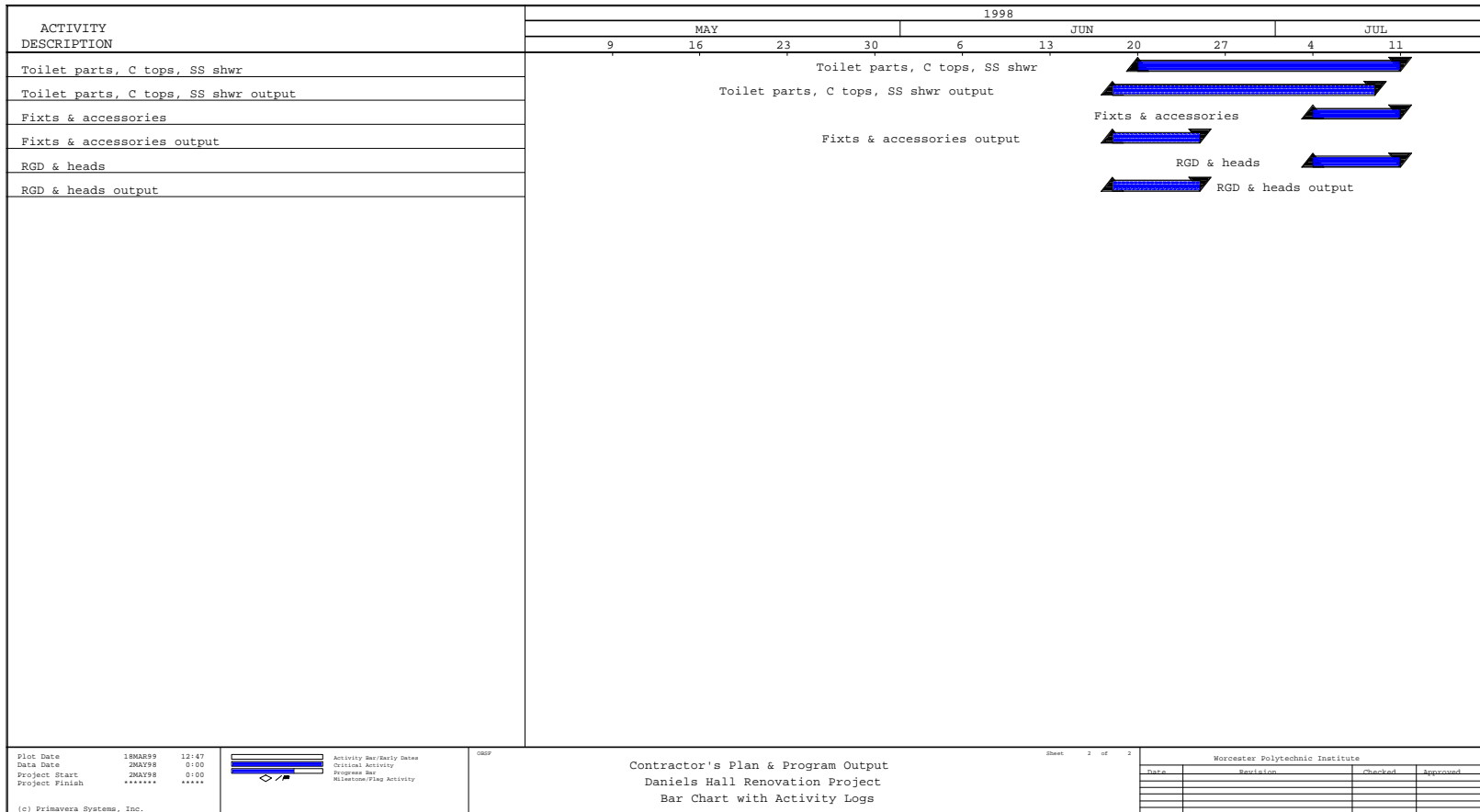


Figure 7.11. Contractor's plan simulation output

This scenario assumes that resources will be available at the time that the activities are ready to be executed. Also, there is no interaction among the different building areas that are part of the whole system (i.e., each building area is considered as a tunnel type 1).

On the other hand, the contractor's plan does not only consider the technical aspects but also resource availability. Due to the limitations discussed before, regarding the use of the resource module, this issue of resource availability was not included in the program input. One way to overcome this constrain is to create artificial delay activities that can be included in the network whenever the activities in a certain building area are going to be delayed due to resource constrains. As a result, it is obvious that the simulation output will present an earlier completion date than the contractor's plan.

The completion date obtained from the program is July 8, 1998, while the plan estimated project completion for July 10, 1998. Due to the relative short duration of this project, this difference is not significant. However, in a major extension project, this difference could easily be greater.

7.5.2 THE OBSERVED PROCESS SIMULATION RESULTS

Figure 7.12 presents a comparison between the computer simulation output built from the observations made in site and the actual execution for the demolition phase of the Daniels Hall renovation project. As it can be observed, the project activities for each bathroom have been grouped into three major activities: "*Pre-asbestos demo*," "*Asbestos abatement*," and "*Post-asbestos demo*."

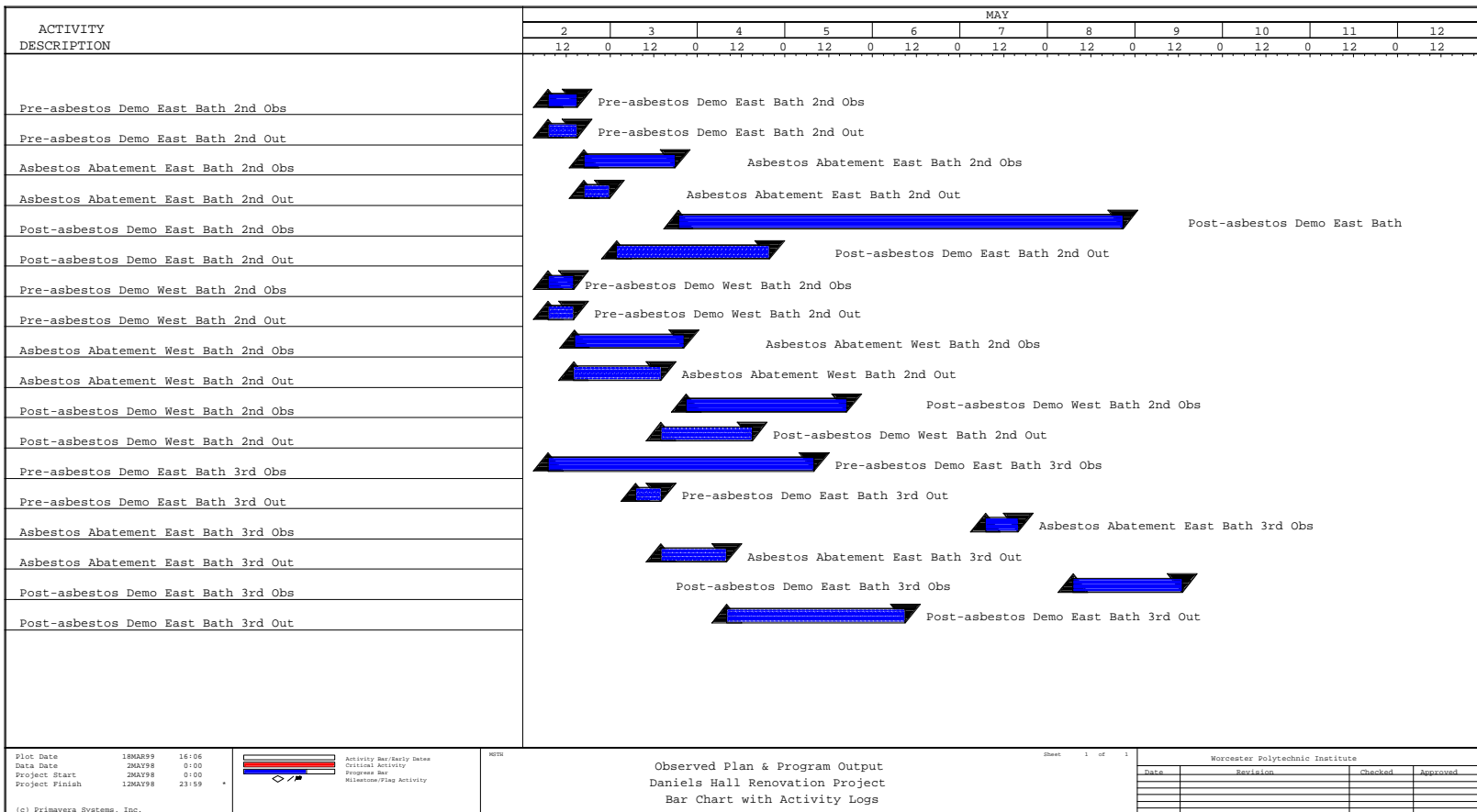


Figure 7.12. Observed process simulation output

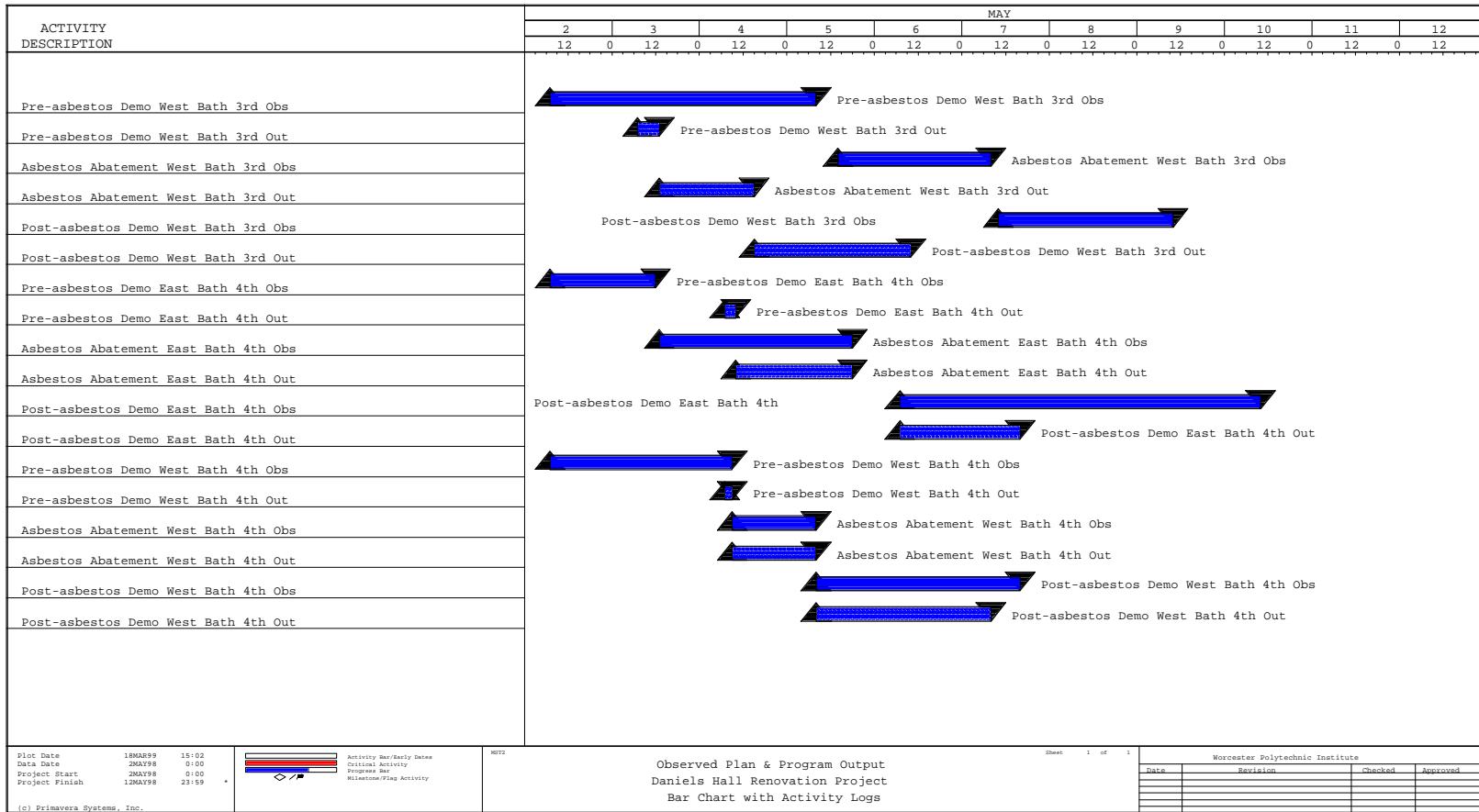


Figure 7.12. Observed process simulation output (continued)

As in the previous case, for each building area (e.g. east bath 2nd floor, west bath 2nd floor, etc.) a network diagram was built based on the sequence of activities that was observed during the actual execution of the first phase of this project. A typical network diagram was shown in Figure 7.4. The logic shown is based on the technical dependencies that exist between the project activities and not on resource availability as discussed before.

In contrast with the contractor's plan where the time duration of the activities is based on the contractor's experience and judgement, the activity duration entered to the program as part of the observed process simulation data represents the actual execution time. The contractor's estimates implicitly consider productive and non-productive times. In other words, it considers activity execution time and times for breaks (e.g., coffee and lunch breaks). However, the level of detail shown in the contractor's plan does not show impacts of potential delays that could be provoked by unexpected situations. For instance, if an unexpected occurs, from the information given of the contractor's schedules, is not possible to determine what activities will have a higher priority of execution. These unexpected conditions could be modeled using computer simulation, allowing the contractor to have more accurate contingency plans.

Remember that the planning performed by project managers is very general and aggregates many factors including contingencies due to potential variations. The plan developed does not provide any details on resource flows. Basically, resources flow in an unexpected way at the site, causing interruptions to their tasks.

The researcher recorded starting dates and completion dates of each activity.

These interruptions were also recorded, however, only productive times were entered into the program. Making use of the resource module would have allowed the user to simulate these conditions more realistically, by means of priorities of execution and by relating activities to crews. This justifies differences in the duration of the output activities and the observed activities. In all cases, the simulated activities took considerable less time than the observed ones.

Not having the ability of introducing resource modeling into the program prevented the use of the type 3 tunnel concept recommended before for the modeling of renovation projects. All tunnels were then considered to be of type 1. This assumption implies that each tunnel would have independence from the others in terms of technical issues and resources availability. The ideal assumption is that resources will be available when needed.

The completion date obtained from the computer program was May 7, 1998. The observed completion date for all bathrooms demolition work was May 10, 1998.

7.5.3 MANUAL SIMULATION

In order to compare the observed times that were recorded on site with a SIMSUPER simulation that integrates resources allocation and a soft logic, the researcher built a manual simulation. This manual simulation replicates the latest SIMSUPER version modeling technique. To build this final simulation, the researcher considered two building areas, the east and west second floor bathrooms. The sequence of activities of the scope of work for these two building areas is shown in Figure 7.13. The scope of

work in the east and west second floor bathrooms is identical. For this reason, both bathrooms share the same activity network. These network diagram presents a total of 30 activities (refer to Table 7.3).

Column 3 in Table 7.3 represents the activity execution time. In column 4, all required crews are associated with the process activities. The fifth column in this table presents the preempting rules that were followed during the simulation of this process. In this case activity 9 preempts the execution of activity 33. Crew 3 performs both activities. So, if there is any conflicts between these two, activity 33 is interrupted, crew 3 is reassigned to the location where activity 9 has to be executed, and 33 is finished after the completion of activity 9. Finally, column 5 deals with activities that compete for the same resources. For example, crew 2 has the assignment of activity 2 and 32. If activity 2 starts before activity 32, the starting time of activity 32 is delayed until crew 2 completes activity 2.

Figure 7.14 presents the simulation of these activities. This figure presents a time line that keeps track of the starting and completion time of each single activity. Both building areas share the same resource center (RC 1). Resource flows are shown by means of dashed arrows and the activity execution by means of solid lines. When an activity is interrupted or delayed, a dashed line is shown. Each activity number is followed by its associated crews' number. For example, 1(1) refers to activity 1 executed by crew 1 and 4(2,3) refers to activity 4 executed by crews 2 and 3.

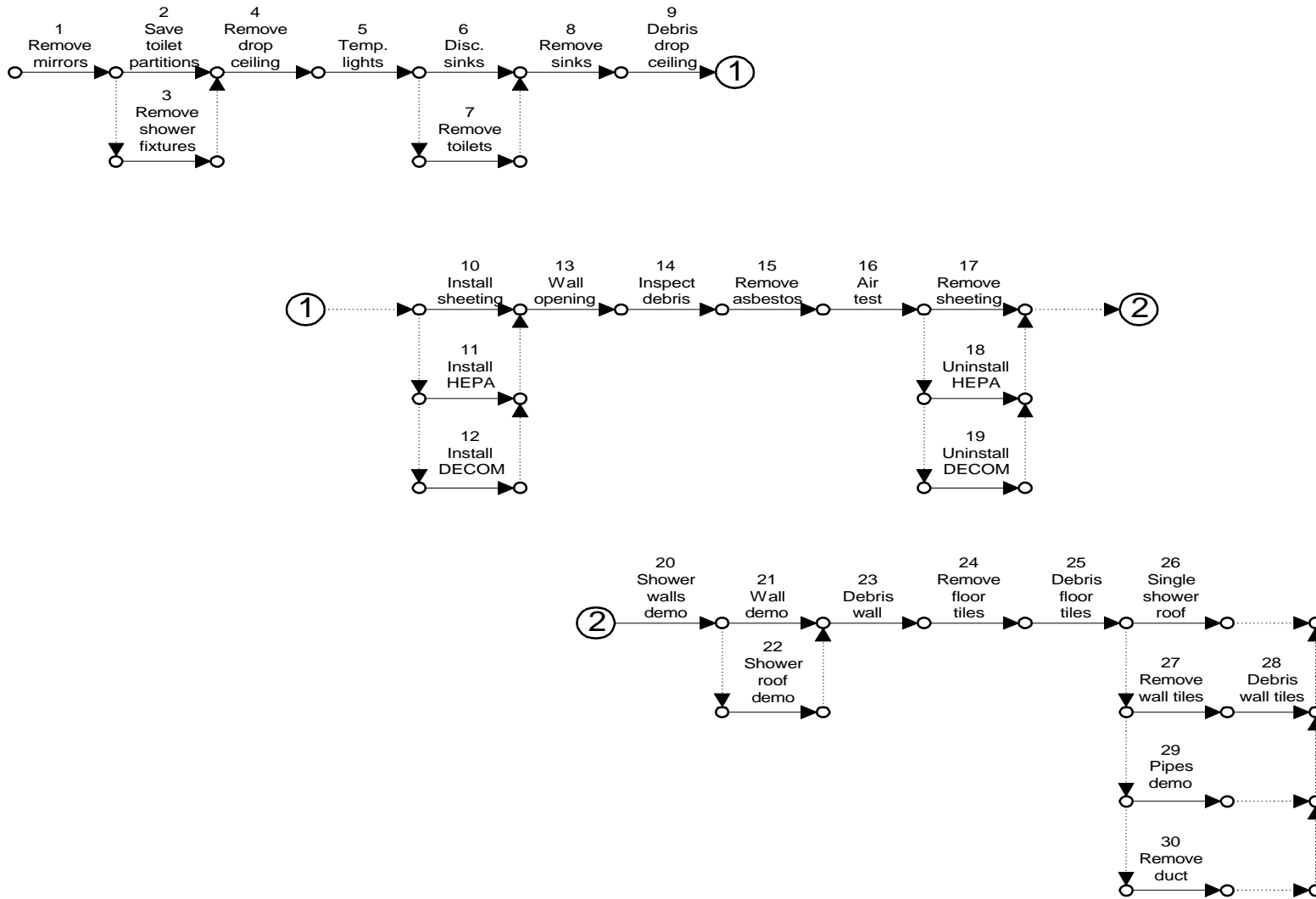


Figure 7.13. Demolition phase activity network for east and west second floor bathrooms

Table 7.3. Activity data for east and west second floor bathrooms

(1) Activity number	(2) Description	(3) Duration (min.)	(4) Assoc. Crew	(5) Preempt	(6) Conflict
1	Remove mirrors	15	1	-	-
2	Save toilet partitions	265	2	-	32
3	Remove shower fixtures	135	3	-	33
4	Remove drop ceiling	75	2 and 3	-	34
5	Temporary lights	20	5	-	-
6	Disconnect sinks	25	6	-	-
7	Remove toilets	20	7	-	-
8	Remove sinks	28	6 and 7	-	-
9	Debris drop ceiling	45	3	33	33
10	Install sheeting	120	9	-	-
11	Install HEPA	10	10	-	-
12	Install Decom	40	11	-	-
13	Wall opening	35	9	-	-
14	Inspect debris	15	9 and 12	-	-
15	Remove asbestos	45	9	-	-
16	Air testing	180	12	-	-
17	Remove sheeting	10	9	40	40
18	Uninstall HEPA	6	10	-	-
19	Uninstall Decom	8	11	-	-
20	Shower walls demolition	60	2	-	-
21	Partition wall demolition	265	3	-	-
22	Shower roof demolition	95	2	-	-
23	Debris partition wall	305	2 and 3	-	50
24	Remove floor tiles	90	2 and 3	-	50
25	Debris floor tiles	18	2 and 3	-	50
26	Single shower roof demolition	45	3	-	50
27	Remove wall tiles	55	2	-	50
28	Debris wall tiles	35	2 and 3	-	50
29	Plumbing pipes demolition	155	8	-	-
30	Remove ventilation ducts	62	13	-	-
31	Remove mirrors	15	1	-	-
32	Save toilet partitions	255	2	-	-
33	Remove shower fixtures	105	3	-	9
34	Remove drop ceiling	35	2 and 3	-	-
35	Temporary lights	20	5	-	-
36	Disconnect sinks	10	6	-	-
37	Remove toilets	35	7	-	-
38	Remove sinks	25	6 and 7	-	-
39	Debris drop ceiling	65	3	-	17
40	Install sheeting	145	9	-	-
41	Install HEPA	10	10	-	-
42	Install Decom	45	11	-	-

Table 7.3. Activity data for east and west second floor bathrooms (continued)

(1) Activity number	(2) Description	(3) Duration (min.)	(4) Assoc. Crew	(5) Preempt	(6) Conflict
43	Wall opening	65	9	-	-
44	Inspect debris	18	9 and 12	-	-
45	Remove asbestos	60	9	-	-
46	Air testing	180	12	-	-
47	Remove sheeting	15	9	-	-
48	Uninstall HEPA	6	10	-	-
49	Uninstall Decom	12	11	-	-
50	Shower walls demolition	95	2	-	-
51	Partition wall demolition	112	3	-	-
52	Shower roof demolition	125	2	-	-
53	Debris partition wall	220	2 and 3	-	-
54	Remove floor tiles	90	2 and 3	-	-
55	Debris floor tiles	18	2 and 3	-	-
56	Single shower roof demolition	36	3	-	-
57	Remove wall tiles	81	2	-	-
58	Debris wall tiles	28	2 and 3	-	-
59	Plumbing pipes demolition	85	8	-	-
60	Remove ventilation ducts	15	13	-	-

From Figure 7.14 below, starting at time zero, activity 1, executed in the west bath by crew 1, starts and is completed at time 15. At time 15, crew 1 is sent to the east bathroom to execute activity 31 while crews 2 and 3 are sent to the west bath to execute activities 2 and 3 respectively. Activity 31 is completed at time 30. Activities 32 and 33 follow the completion of activity 31, however, because activities 2 and 3 share the same resources as activities 2, 3 and 4, the starting time of activities 32 and 33 is delayed until activity 4 is completed, at time 355. Activity 33 is interrupted at time 428. At this time, activity 9 is ready to be executed. Activity 9 shares the same resources with activity 33, but activity 9 preempts activity 33, causing the completion of activity 33 to be delayed by 45 minutes. At time 473 activity 33 is reinitiated and gets completed at time 505.

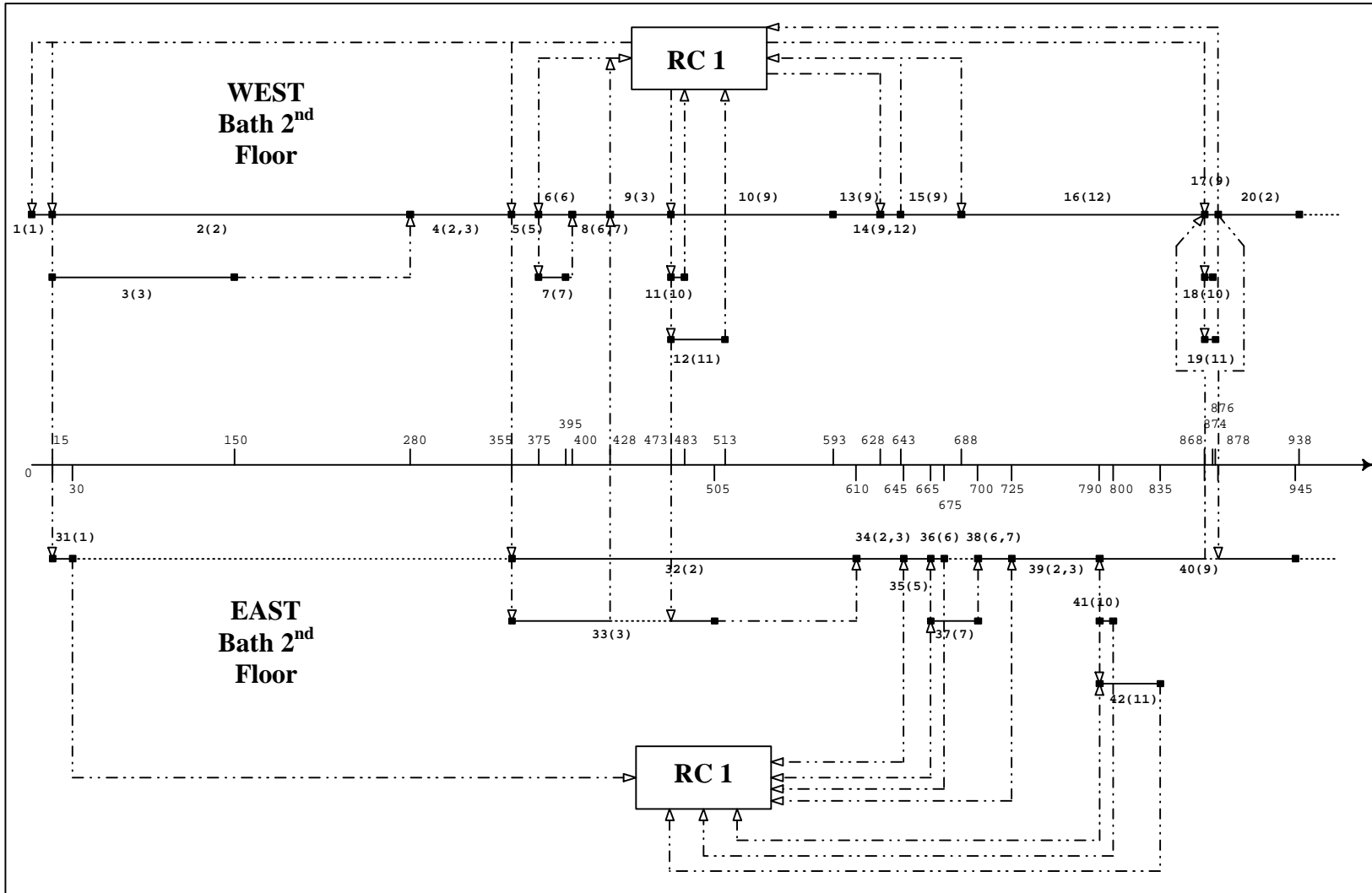


Figure 7.14. Manual simulation

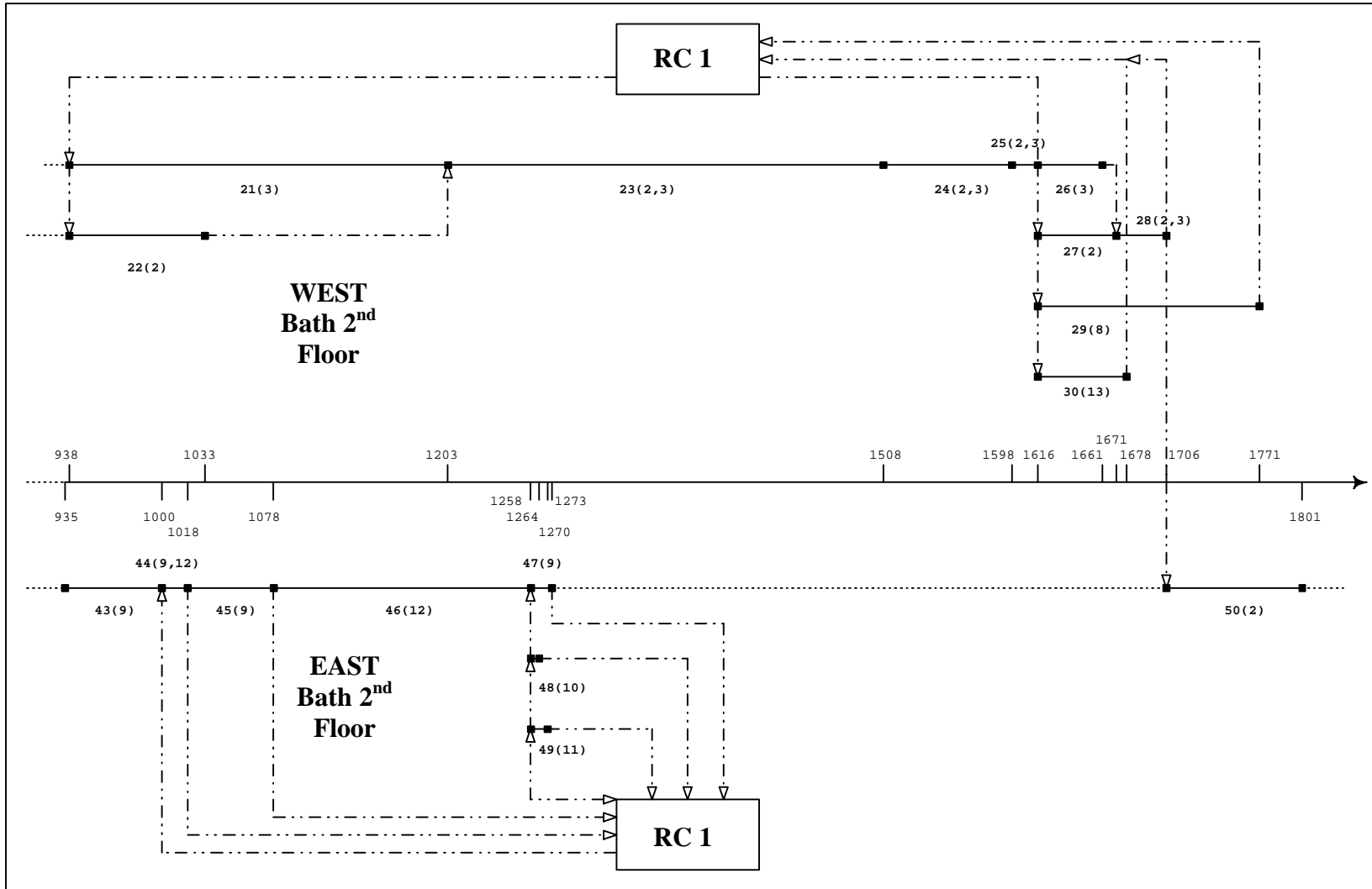


Figure 7.14. Manual simulation (continued)

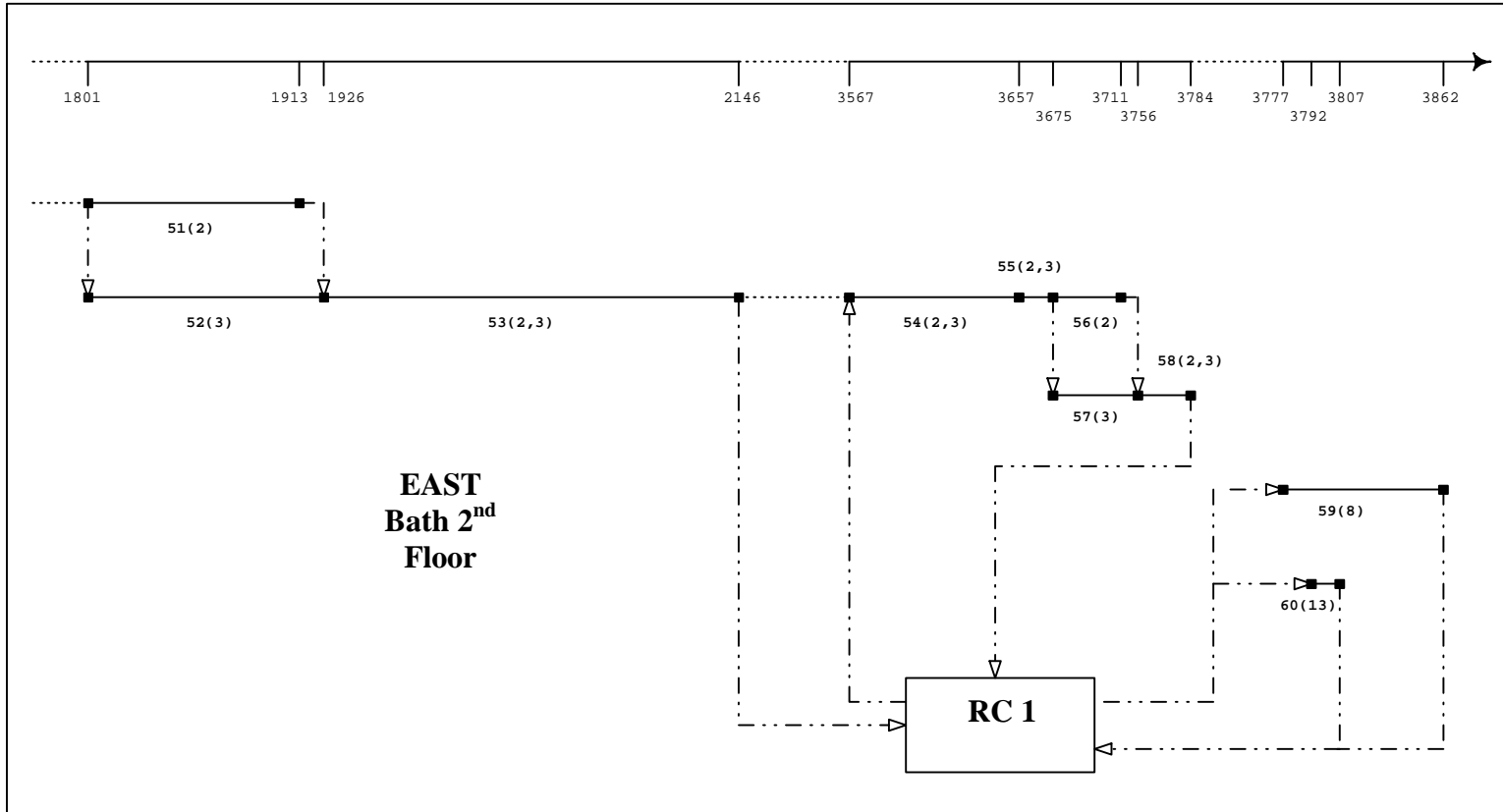


Figure 7.14. Manual simulation (continued)

This process was followed until all the bathroom activities corresponding to the demolition phase of the west and east second floor bathrooms were simulated. From this simulation, the total time for completion of the west bathroom equals 1771 minutes (473 minutes for the pre-asbestos demolition, 405 for the asbestos abatement, and 893 for the post-asbestos demolition). In contrast, the total time for completion for the east bathroom was 3862 minutes, including productive and non-productive times (790, 483, and 2589 for the pre-asbestos demolition, asbestos abatement, and post-asbestos demolition, respectively).

A comparison among the three simulations for the east and west second floor bathrooms is shown in Figure 7.15. In this figure, the black bars represent the contractor's estimates, the observed data is summarized in the gray bars, and the white bars represent the manual simulation results. Because the manual simulation integrates the resource modeling, as well as the preempting rules and conflict management capabilities of the latest SIMSUPER version, its estimates are able to replicate the observed process. The differences that exist between the observed process and the manual simulation against the contractor's estimate were expected. The contractor's plan, as discussed in section 7.4.1, is only an estimate of the conditions expected on site. Changes to the assumed conditions provoked by external factors like labor absenteeism, weather and other uncertain events will impact these estimates. The purpose of building computer simulations is to integrate these sources of uncertainty to most accurately predict the project completion date and total cost. Specially, in renovation projects where unexpected events play such a determinant role.

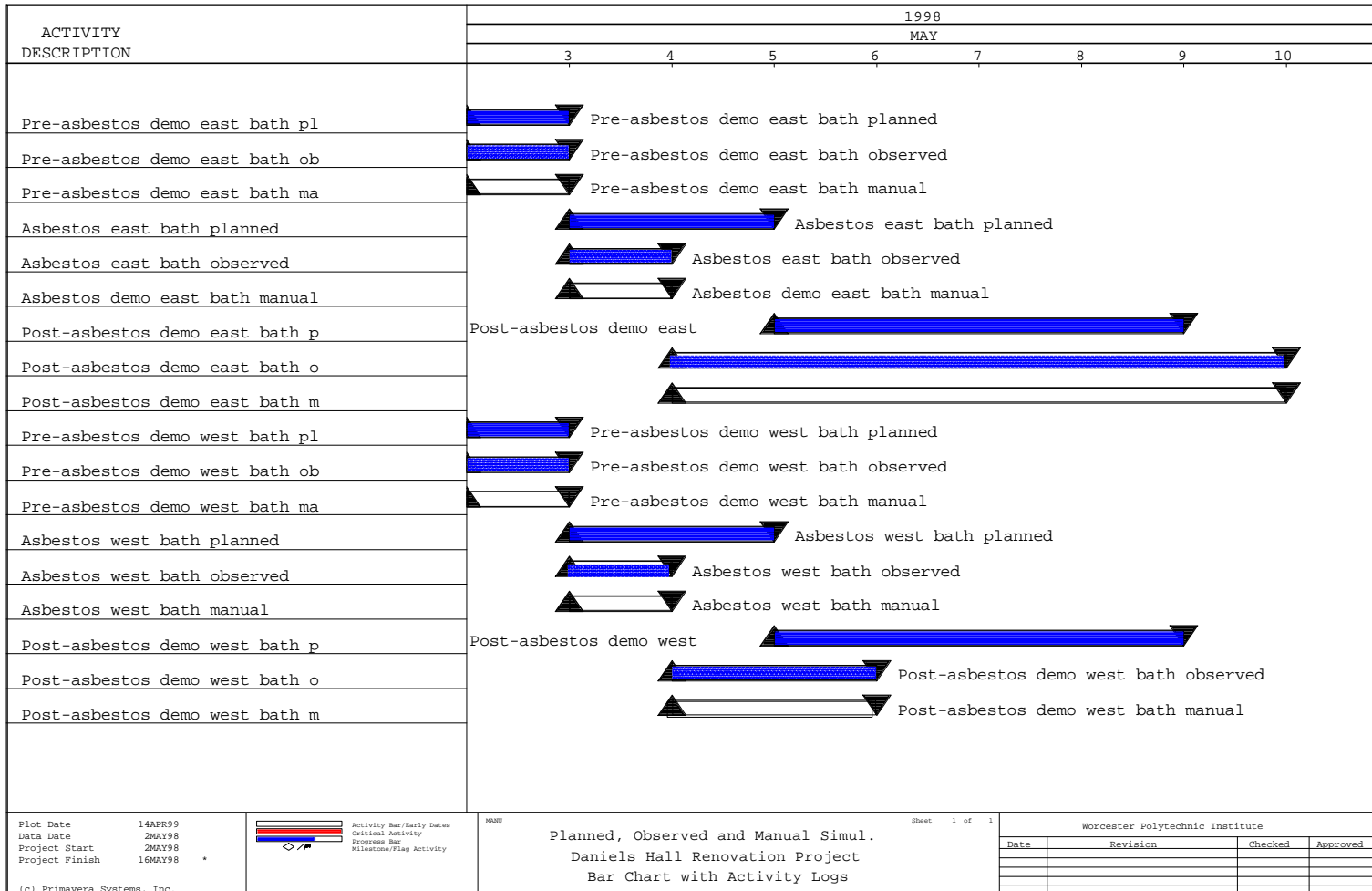


Figure 7.15. A comparison among the planned, observed process and simulated plan for the east and west baths 2nd floor

7.6 CONCLUSIONS

The scope of the work for the renovation of Daniels was translated into a series of network diagrams that allowed for the computer simulation of the activities executed on site by means of SIMSUPER. The existing SIMSUPER version at WPI did not have the ability for resource modeling. In building renovation projects this becomes a critical issue.

The nature of the spatial conditions in building projects allows activities to be performed in parallel in many locations. By contrast, in tunneling projects the critical activities for the excavation and initial support phase are pretty much concentrated in the tunnel face. For this reason, the resource modeling for renovation projects is more complex.

The author limited the computer analysis to the technical dependencies that establish the sequences in which project activities are executed. This prevented the simulation of activity interruptions resulting in a very optimistic estimate for project completion. In order to address the limitations encountered in the running version of the program, the researcher performed a manual simulation that captures resource flows and conflicts.

Chapter 8 will present in more details the conclusions at which the author arrived after testing the adaptability of SIMSUPER for the modeling of building renovation projects. Recommendations for future work are also addressed in the next chapter.

8 CONCLUSIONS AND FUTURE WORK

8.1 SUMMARY

The characteristics of renovation projects make project planning a very difficult task. Due to the numerous uncertainties and unforeseen conditions that characterize building renovation projects, traditional methods are not suitable for accurate planning purposes. As a result contractors tend to present very conservative bids relative to those presented for new building construction projects.

Reliable forecasts of the completion date and final cost of building renovation projects are major concerns for project management. This reliability is dependent upon the accuracy in representing the activities and sequence of operations that are necessary to complete the project. Considering the effect of conditions of uncertainty and the intermittent flow of resources is fundamental for the determination of the completion date.

Computer simulation is a tool that can be used to improve the reliability of these forecasts. Studies performed during the last two decades have demonstrated that computer simulation is a useful tool for analyzing construction processes and assessing the probabilities of meeting a stated completion date, under uncertainty conditions. The accuracy of simulation depends on the accuracy of the representation of the construction process, as well as on the data used in the study.

Computer simulation in construction has been used in the context of cyclic

operations. Simulators have been designed to optimize and analyze the construction process at the operation level. The CYCLONE model has been the basis for the development of numerous construction simulation systems. CYCLONE-based models are very efficient in simulating repetitive and cyclic stationary operations. However, their resource modeling techniques do not handle complex resource flows as those that are characteristic of building renovation projects. They are not able to replicate operations that are occurring simultaneously at different locations. None of these models provide spatial tracking and their fundamental structure is based on hard logic. For this reason, these systems do not dynamically respond to changes in the original conditions. This basic characteristic established that CYCLONE-based models are not suitable for the modeling of building renovation projects.

SIMSUPER is a discrete-event simulation model that has double-linked lists to control the occurrence of events within the network. The model structure uses a soft logic approach to modify the network logic as demanded by external factors, resource availability or varying job conditions.

It is the intent of this research to explore the use of SIMSUPER for building renovation projects. The approach followed by SIMSUPER demonstrated its potentials for the modeling of renovation projects. The model's ability for forecasting project completion time for building renovation projects has been tested. After such test, both at a conceptual and experimental level, certain issues need to be addressed in order to provide designers, engineers, contractors, and project owners with a reliable tool. These issues are discussed in the Conclusions and Future Work sections.

8.2 CONCLUSIONS

The major conclusion of this research establishes that the SIMSUPER conceptual approach is able to replicate the reality of the building renovation projects. SIMSUPER is suitable for the modeling of building renovation projects based on its adaptability to changing conditions, its ability to interconnect multiple network plans in a sequential and simultaneous fashion. Further exploration of this model is then worthwhile.

The major findings of this research can be summarized as follows:

- 1) The concept contained in the program proved to be efficient in providing the flexibility to adapt to changes in the original conditions, or to changes in the scope of the work that was required in the different building areas. By combining various network plans, SIMSUPER is able to relate specific building areas with feasible renovation methods.
- 2) The soft-logic rules that drive the simulation of the process replicate the observed plans. These rules are able to mirror the reality of the process. Depending on external factors, technical dependencies and resource conflicts, SIMSUPER is able to delay, interrupt and prioritize activity execution.
- 3) These soft-logic rules are also applied simultaneously at different locations, allowing for the modeling of construction operations that take place in various building areas at the same time. The multi-tunnel concept enhances much more the ability to accurately replicate the activities that take place on site. This allows for the modeling of the renovation process as a whole, in its entirety. The program is able to manage the execution of several activities at the same time.

- 4) The resource module and the construction module are able to track resources location during the execution of activities. The program has knowledge of the location of resources within the building areas and how fast are they moving and completing their tasks within the facility.
- 5) The resource module has the ability to integrate non-identical resources in the modeling of the construction operations. All resources are linked to specific activities. This allows making distinctions among them easing the resource allocation modeling. The fact that there may be idle resources does not necessarily mean that operations can take place. Not only resources must be available, but they have to be the ones that are capacitated to perform the work.
- 6) Even though SIMSUPER is a network-based model, it provides the user with the ability to simulate cyclic and non-cyclic operations. By means of round-by-round simulations the user could well simulate cyclic processes. On the other hand, processes that are not cyclic can be simulated by specifying a single round.
- 7) The use of the heading and bench provides for the simulation of various trades at the same building area. In other words, it allows for the entrance and exiting of resources after performing their work, without necessarily implying that the full operations at a specific location have been completed. It also allow to model the work perform by more than one trade in the same area at the same time.
- 8) Due to the flexibility of interpretation of the data entered, the user can easily defined a progress unit other than linear units. In other words, the user may easily

incorporate units of area or volume if he/she prefers to track project progress in such way.

During the modeling of the case study, the following limitations were encountered:

- 1) The Geologic Module, which is defined in terms of soil conditions, could not be used for the segmentation of the building system. For this reason, the researcher had to rely on direct segmentation. This implies that the user have enough information about the conditions that exist in the different building areas before performing any simulation.
- 2) In regard of spatial tracking, it was found that it would be very helpful to provide a tracking of resource flows within a building story and between stories (horizontal and vertical displacement).
- 3) For the simulation of building renovation projects using the existing versions of SIMSUPER, the program user will have to build a set of logical analogies between the process to be modeled and tunneling operations. This implies that the user must also command the operation of the computer simulation module to be able to perform the required simulations.
- 4) The major limitation was found in the use of the existing WPI's version of SIMSUPER. This tool is not a suitable one to evaluate the adaptability of the program to model building renovation projects. This version does not provide resource modeling.

8.3 FUTURE WORK

Certain modifications need to be made to continue enhancing the capabilities of SIMSUPER and its extension to non-tunneling projects. These have been sequenced in terms of their priorities:

- 1) The very first task must include the implementation of the latest tunneling version at MIT in terms of building renovation projects. The analysis performed in Chapter 7, the manual simulation, must be built into the program to test all the model features. Recent changes made to the program may have eliminated some of the concepts discussed in this report. In such case, it would be recommended to integrate them back into the Construction Module, evaluate the capabilities of the new program changes, or develop a whole new program code that would integrate all the features presented in this report.
- 2) The spatial tracking capabilities may have to be reviewed in more detail. In building projects resources displace in two basic directions: horizontally and vertically. The current versions do not provide for displacements between building stories.
- 3) Some software improvements are required in order to ease input construction and output interpretation. The existing user interface is defined in terms of tunneling projects. A new interface defined in terms of building renovation projects is needed. It is also recommended to link the program output with existing commercial software such as Primavera or MS Project Planner to enhance visualization. Three-dimensional animation may also prove to be very useful.

- 4) As discussed in Chapter 6, in order to be able to use probabilities to predict the different conditions that could be encountered in the job site, it is necessary to develop a Building Module analogous to the Geologic Module. This must be constructed in order to provide a building profile. This is a very complex task if the module is developed to the extent of the existing DAT Geologic Module. This task could become a complement of the site investigation that takes place during the early planning stages of the project. This task may not be as critical as it is in the tunneling case. In building renovation processes is much easier to identify the conditions that will be encountered relative to tunneling projects.

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APPENDIX A - USING SIMSUPER

A.1 INTRODUCTION

This appendix presents a detailed description of the input and output files that are used and generated during the simulation runs. The purpose of this appendix is to provide a guide or manual for the use of the WPI's running version of SIMSUPER, specifically the Construction Module.

The first section of this chapter describes the steps that have to be followed to run the program. A second section presents the main input file or batch file, which defines the input and output files. A detailed description of each one of these input files is also included. The intent is to provide information on how to edit these files. Finally, a description of the program output is presented.

A.2 USING TELNET TO RUN SIMSUPER

The WPI's SIMSUPER running version is stored in a server called Hornfel. The following steps have to be followed to have access to the program files:

- 1) The user must run telnet "*hornfel.wpi.edu*." Once the "telnet *hornfel.wpi.edu*" window pops up, the user will be asked his/her username and password.
- 2) The files to be edited are stored in a folder called "*Simbuild*." In order to open this folder, please type "*cd //arkose/station/Simfire/Simbuild*." For editing purposes, the user must have access to the WPI network and must have received permission from the program's owner.

- 3) To run SIMSUPER, after completing all editing within Simbuild, the user would have to type "*../SIMSUPER.*" The simulation will then be executed and all output data will be stored in the selected output files.

The following sections present all SIMSUPER input and output files. Details for editing of each one of these are presented in these sections.

A.3 THE INPUT FILES

A.3.1 MONITOR.DAT

"*Monitor.dat*" is the main input file. This file defines all input and output files and provides general information about the tunnel system. The "*monitor.dat*" file is used by the executable command to run the program. A sample of this file is shown in Figure A.1 and a description of each one of its entries is presented below:

- 1) *Project name.* Defines the project under study.
- 2) *Number of simulations.* Defines the number of simulation runs to be executed. It is an integer other than zero.
- 3) *Number of tunnels or building areas.* Defines the number of tunnels or building areas in which a particular project has been divided (refer to sections 5.3 and 6.2.2.6 for more details). Again, this number must be an integer other than zero.
- 4) *Monitor output level.* This integer, from 1 to 3, specifies the frequency at which the simulation output will be presented by the real time output file:
 - a) For a single output per simulation, enter 1.
 - b) For a round-wise output, enter 2.

c) For an activity-wise output, enter 3.

Daniels Hall Renovation Simulations	; Project name
1 Maxsim	; Number of simulations
4	; Number of tunnels or building areas
3 Monitl	; Monitor output level
1 Rpoutl /var/tmp/simN.rep and /var/tmp/simN.stat	; Statistics level
1 Twoutl /var/tmp/simN.timw	; Time way output level
0 Coutl	; Cost output level
1 seed_flag	; Seed flag
0 Moutl 4 next lines only if Moutl != 0	; Input mode
plan.def	; Network and activity input file
ground	; Ground dependent variables input file
construction	; Ground independent variables input file
planequations.dat	; Equations input file
multinfoplan.dat	; Tunnel system input file
tunlocationplan.dat	; Tunnel location input file
93_interface_delay.dat	; Interface delay file
../Geology/seed	; Seed file
zonelengths.res	; Zone location data file
output.dat	; Real time output file
test.b	; Bug output file
plan.rep	; Round-wise output file
plan.stat	; Segment-wise output file
plantime.res	; Time way output file
plan.res	; Tunnel information output file

Figure A.1. A sample of the "monitor.dat" input file

- 5) *Statistics level.* This integer, 0 or 1, specifies whether or not a round-wise or segment-wise output data will be recorded in the "plan.rep" and "plan.stat" output files. A zero entry means that no output will be recorded and viceversa.
- 6) *Time way output level.* This integer specifies whether or not the time way output file will record output in the seed file. As in the statistics level, a zero means that no output will be recorded and viceversa.
- 7) *Cost output level.* As in the statistics and time way output levels, this integer specifies if any cost output will be stored in the cost output file.

- 8) *Seed flag*. Either 0 or 1, specifies if the random number generation seed will be updated in the seed file. If zero is entered, it will not be updated and viceversa.
- 9) *Input mode*. This entry must not be edited. It specifies that the input files to be used are defined in the next four lines of the file structure. Previous versions of SIMSUPER had an interactive data entry mode that has been eliminated.
- 10) *Network and activity input file*. It defines the name of the renovation activities input file. This file contains the process networks and a list of the activities that are part of these processes.
- 11) *Ground dependent variables input file*. Identifies the name of the ground dependent variables input file. This file presents the values of those variables that define the different ground or building conditions that could be encountered in the different ground classes or building areas.
- 12) *Ground independent variables input file*. It defines the construction variables input file name. This file contains values of those variables that are independent of the building or ground conditions.
- 13) *Equations input file*. This entry defines the construction equations input file name. This file contains all the equations that were developed to calculate the time duration of the activities listed in the network and activity input file.
- 14) *Tunnel system input file*. This entry specifies the name of the multi-tunnel input file. The "*multinoplan.dat*" file specifies the different types of tunnels or building areas that are used to represent the renovation operations that could take place in different location (refer to section 5.3).

- 15) *Tunnel location input file.* Defines the name of an input file, in this case "*tunlocationplan.dat*" which contains information pertaining to the building conditions of the different areas of the facility and links each area with a feasible construction method.
- 16) *Interface delay file.* This entry defines the name of a file that holds a matrix of values that represent time delays occurring at the interface between different ground classes. This file is only used for tunneling processes.
- 17) *Seed file.* Name of the seed file containing a number used for the random number generating function.
- 18) *Zone location data file.* This file contains information related to the zones or areas in which a tunnel has been divided. This file is an output from the Geologic Module, which was not used for the building renovation process.
- 19) *Real time output file.* The entry here could either be a file name or "screen." If text other than screen is specified (i.e., *output.dat*), a file with such a name will be generated containing a real time output of the simulation runs. On the other hand, if "screen" is specified, the simulation output will be presented in the computer monitor screen during the execution of the simulation.
- 20) *Bug output file.* Specifies the name of the bug file. In the event of a program run error, a description of the error will be presented in this file.
- 21) *Round-wise output file.* This entry defines the name of the output file that contains the results of the computer simulation in a round by round basis in the case of cyclic operation. In this example, this file has been named as "*plan.rep.*"

- 22) *Segment-wise output file*. Specifies the name of a file containing statistical results of the simulation by building segments or areas.
- 23) *Time way output file*. This entry defines the name of an output file that presents spatial information.
- 24) *Tunnel information output file*. This is the filename template for the tunnel or building information output file that contains information regarding the advance rate or productivity rate per tunnel or building area.

The files shown in bold letters in Figure A.1 are the ones that were edited for the purposes of simulating the building renovation project presented in Chapter 7. The rest are files generated by the Geologic Module simulations. As it was explained in Chapter 6, section 6.2.1, this module is defined in terms of tunneling operations reason for which was not used for the renovation case. A description of the files shown in bold letters is presented in the following sections.

A.3.2 NETWORK AND ACTIVITY INPUT FILE

The activity file contains a list of the activities that are part of the different construction methods. It also includes details on the sequence in which these activities are executed. This file links each activity with its associated construction time equation.

The file is divided into four major groups: "*l and m group*," "*n group*," "*t group*," and "*s group*" (refer to Figure A.2). The first group, ***l and m group***, lists the activities that are part of a particular construction method. For every process network, there will be an "*l and m group*." This group also defines the sequence in which the activities will be

executed. In other words, it defines the technical dependencies that exist between the process' activities (refer to Figure A.3).

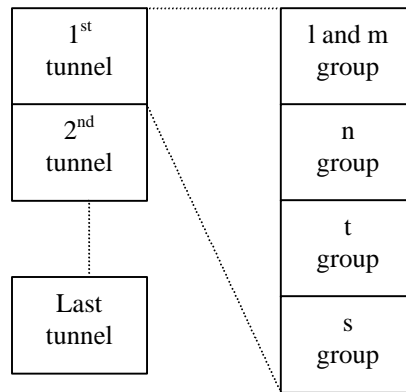


Figure A.2. Structure of the network and activity input file

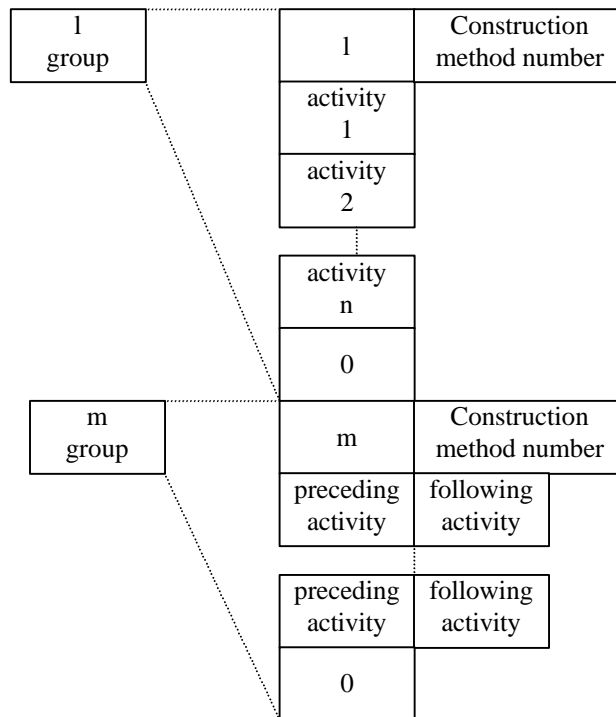


Figure A.3. The "l and m group"

The first number of each pair defines the preceding activity followed by its succeeding activity. In most cases, the data will be grouped in pairs, however it is possible to have one activity followed by several activities. On the other hand, one single activity can follow various activities. This activity will appear right after each of its preceding activities.

The second group, the "*n group*," has information related to the activities' transition between simulation rounds. Basically, when a round is over, the following activity could be part of the previous renovation method used or could be part of a different method. Each one of the building areas that represent the entire system has its own "*n group*." In other words, if one area is divided into two segments, with two different methods, four transitions will be considered (e.g., method 1 followed by method 1, method 1 followed by method 2, method 2 followed by method 1, and method 2 followed by method 2). Figure A.4 presents the group structure.

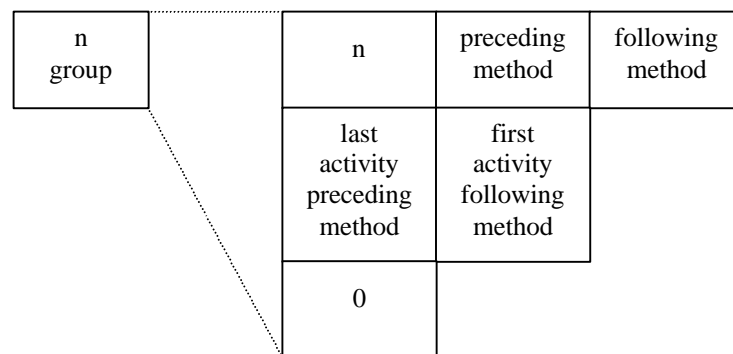


Figure A.4. The "n group" structure

All information associated to the renovation methods' activities entered in the previous groups is contained in the "*t group*." This group includes a list describing each activity in terms of the activity name, activity number, activity type, its associated construction time and cost equation, layer number, type of general and detailed section, and its assigned priority. Figure A.5 presents the "*t group*" structure.

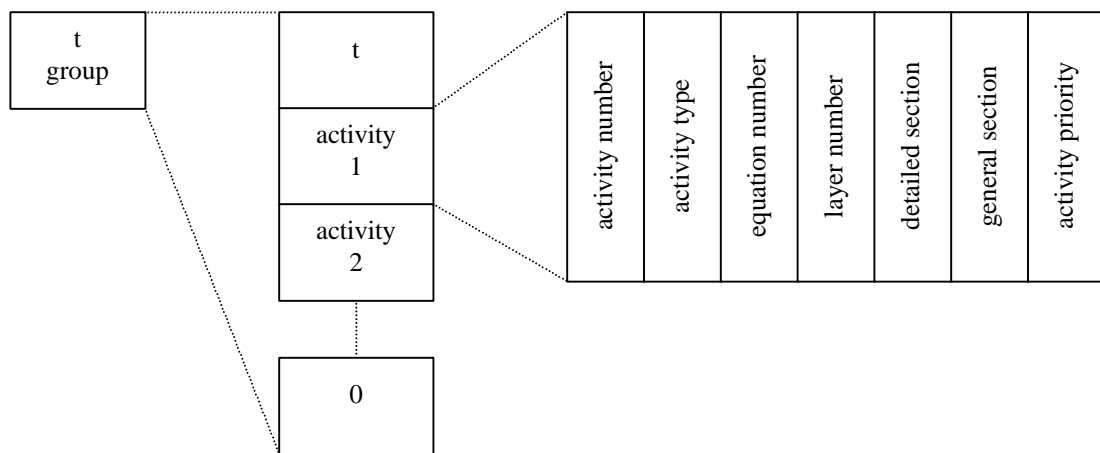


Figure A.5. The "*t group*" structure

The activity number corresponds to the number used to identify the activity in the "*l and m group*." The activity type, which is an integer equal to 1 or 3, defines if the activity is a decision activity or not. If the activity is a decision activity, then 3 is entered. The time equation number defines the equation that is used to calculate the duration and cost of that particular activity.

The layer number is strictly used for tunneling purposes. For this reason, no editing is required for renovation projects and should be equal to zero. The detailed section entry refers to the heading and bench drifts (refer to sections 5.4 and 6.2.2.5 for

more details). This number could be between 1 and 7 (i.e., full face = 1, head = 2, bench = 3, right head = 4, left head = 5, right bench = 6, and left bench = 7). On the other hand, the general section entry distinguishes among face, head and bench operations (e.g., 0 for face, 1 for head, and 2 for bench).

Finally, the activity priority number, which indicates the priority of execution of an activity, related to other activities that are part of the construction method. This indicator could be an integer between 0 and 5. Zero corresponds to the highest priority and 5 to the lowest.

The fourth and last group, the "s *group*," defines the tunnel or building segmentation. Every line in this group corresponds to one building segment, area or group. A building segment is a subdivision of a building area in which only one method is feasible. Figure A.6 presents the "s group" structure.

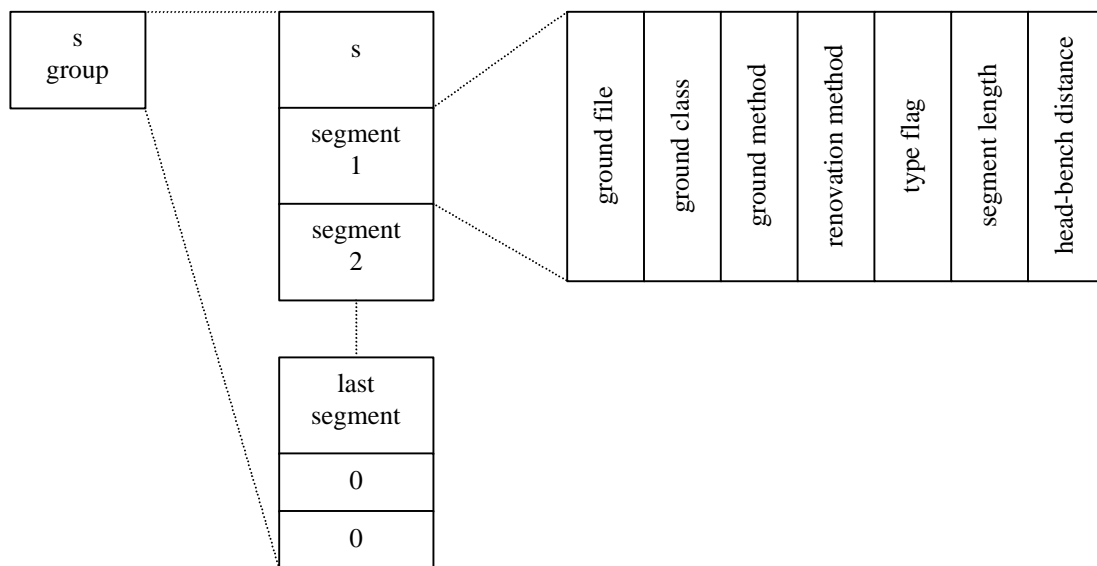


Figure A.6. The "s group" structure

The ground file presented in the main input file (i.e., ground) is the one that establishes the values of the variables included in the construction time equations. Its name, "ground" is hardwire into the program. However, depending on the different working environments that could be governing the methods to be used in different building areas, there could be various ground files (e.g., ground1.var, ground2.var, etc.). This entry contains the number of the file to be used. For example, if a segment has a particular environment for which its impact on the construction parameters is presented in the ground2.var file, this entry will be equal to 2.

Each ground file contains various ground classes and methods. A node number identifies each ground class. These two entries represent the node number from which all the values of the environment parameters will be taken. The fourth entry of this segment, links one of the renovation methods of the "m group" with a single building segment. In other words, this number indicates which method will be applied for the renovation of a building area.

The segment length entry is equal to the actual length of the building area or segment. On the other hand, the heading and bench distance defines the distance between the face of the head and the face of the bench (refer to sections 5.4 and sections 6.2.2.5). If the head-bench distance is zero, the type flag has a value of 1.

At the end of one tunnel or building area data, the "e flag" appears. This specifies the end of a tunnel input. In the event that more than one tunnel is considered, the input groups associated with the next tunnel will follow right below the "e flag". For samples of the network and activity input file please refer to Appendix B.

A.3.3 THE GROUND FILE

As it was mentioned before, the ground file contains the values for the construction time equations' variables that are used to determine the duration and cost of the renovation operations. Each one of these variables could be defined in terms of three point estimates (i.e., most optimistic value, most likely value, and most pessimistic value). On the other hand, single values could also be used. Figure A.7 presents the structure of this input file.

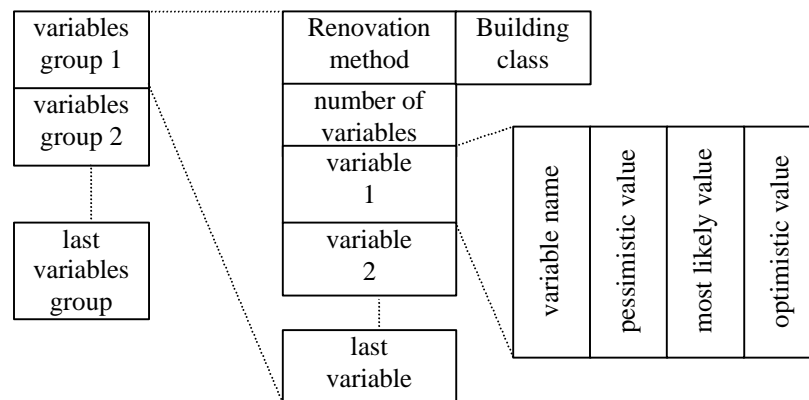


Figure A.7. The ground file structure

The first pair of entries, the renovation method and the building class, is used to identify the ground class associated to a certain building area. This pair is known as the node number. The number of variables is the total number of variables defined in a variable group. Below the number of variables, a list of variables' names follows, with their associated values. In the case of single-value estimates, only one entry will follow the variable name. For a sample of this file, please refer to Appendix B.

A.3.4 THE CONSTRUCTION FILE

The construction input file stores values for those variables that are independent of the building conditions. In the building renovation case, this file holds two basic variables only: "*l_face_holes*" and "*adv_round*." The first of these two is the average length of the simulation rounds. For a non-cyclic process, this number equals the segment length. However, if a cyclic process merits, this number will be equal to the segment length divided by the number of cycles required to complete the work task. The second variable, advance round, should not be edited for the building renovations case and must be equal to 1. This variable is hardwired into the file and it is used for tunneling purposes.

The structure of the construction file is similar to the structure of the ground file (see Figure A.8). Although, the two variables contained on it are defined by single-value estimates. These values are constant. For a sample of the construction file please refer to Appendix B.

<i>l_face_holes</i>	30.00
<i>adv_round</i>	1.00

Figure A.8. *The construction file structure*

A.3.5 THE EQUATIONS FILE

The time taken to complete an activity can be calculated by means of a mathematical equation or a constant value. The user defines the time equations. The equation developed to determine the time duration and cost of an activity is defined in terms of the

variables stored in the ground file. Each activity is associated with an equation (refer to section A.3.2). Figure A.9 shows the structure of the equations file. A sample of this file is shown in Appendix B.

first equation		equation number	equation
second equation		equation number	equation
⋮			
last equation		equation number	equation

Figure A.9. The equations file structure

A.3.6 THE TUNNEL SYSTEM FILE

The tunnel system file, the "*multinfo*.dat*," in this case "*multinfoplan.dat*," stores information that relates individual building areas (tunnels) of a building facility (tunnel system) to each other. The structure of the multi-tunnel system file is shown in Figure A.10.

Each building area (tunnel) is identified with an identification number (tunnel number). Depending on the tunnel type that the user would like to define a particular building area (refer to section 5.3), a tunnel could be associated with other tunnels and could also become a new tunnel type once it reaches a convergence point and meets its associated tunnels. The first pair of entries defines these two tunnel aspects, the tunnel type and the next type. Following the tunnel type, a list of associated tunnels could be included as well as a list of tunnels that are associated to the next tunnel type. The first

list defines those tunnels that are associated to the original tunnel type. The second list defines the tunnels that are associated to the next tunnel type. Both lists are followed by a -1 indicating the end of the list.

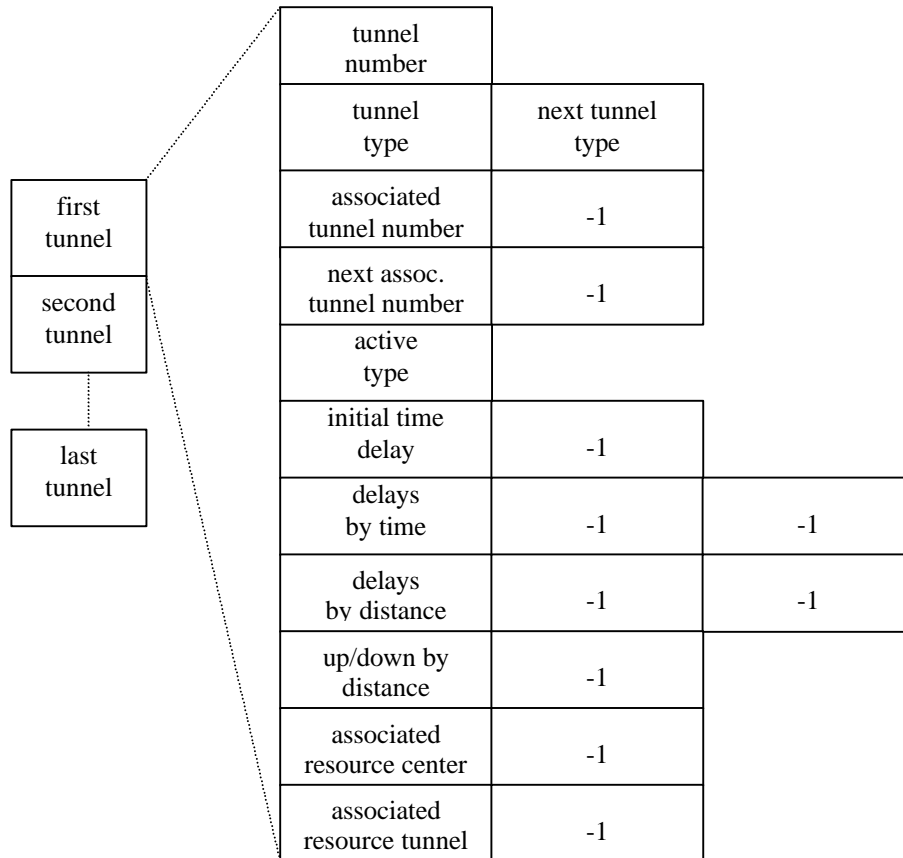


Figure A.10. The multi-tunnel system file structure

The active type defines the status of the construction operations that will take place in a particular tunnel. For example, five possible statuses could be declared:

- 1) Tunnel construction begins after a delay, enter a -2.
- 2) Tunnel is pausing for a delay, enter a -1.

- 3) Tunnel construction is finished completely, enter a 0.
- 4) Tunnel is under construction, enter a 1.
- 5) Tunnel construction begins immediately, enter a 2.

The user could specify initial delays for the starting time of the operations in specific building areas (tunnels). For instance, the user has the ability to specify delays that will occur at a certain time after construction started or at a certain length of tunnel. Delays by time are useful to specify breaks such as lunch or coffee breaks. Delays by distance are more useful for the tunneling cases. These two types of delays, by time and by distance are entered in pairs: the time at which the delay starts and ends, and the distance at which the delay starts and ends.

The up/down distance entry is strictly defined for tunneling operations. It basically specifies the slope of the tunnel, whether it is upward or downward at each point in the tunnel length. The last two entries are related to resource allocation issues. As it was mentioned in Chapter 7, the resource module is not in function in the WPI's SIMSUPER version. For this reason, those entries that are not applicable for the case under study are not filled and a -1 will only be shown. For a sample of the multi-tunnel file please refer to Appendix B.

This concludes the input files that need to be edited in order to perform the simulation runs of a particular project. The only files which name is hardwired into the program are the ground and construction files. The others could be named as desired by the user. The files that have not been discussed here are those that are either an output from the

Geologic Module and do not have any direct impact over the simulation runs performed by the Construction Module.

A.4 THE OUTPUT FILES

From the input entered to the Construction Module a set of output files is generated per simulation run. These files contain the results of the time duration and cost of executing all the activities that are part of the process as well as the productivity rate and total completion time. The level of detail presented by each one of these files is different.

The report file, "*plan.rep*" in Figure A.1, includes the time duration of performing each activity in the different tunnels or building areas per cycle or round. The statistical data report, "*plan.stat*" as in Figure A.1, is very similar to the report file but it presents statistical data such as average duration, standard deviation, and highest and lowest duration. Finally, the "*plan.res*" output file, presents a summary of the operations that took place on each building area (tunnel) in terms of location, starting construction time, completion time, total duration, idle time, advance rate, and total project cost. For a sample of these files, please refer to Appendix C.

APPENDIX B - INPUT FILES

B.1 INTRODUCTION

This appendix present the actual input files that were constructed for the simulation of the renovation operations that took place in Daniels Hall (refer to Chapter 7). There are two sets of input files, the contractor's plan simulation and the observed process simulation. The files included here are the ones that were discussed in Appendix A.

B.2 THE CONTRACTOR'S PLAN

B.2.1 THE NETWORK AND ACTIVITY FILE

Four building areas are considered in this example. These are the 1st floor bathrooms (tunnel 1), 2nd floor bathrooms (tunnel 2), 3rd floor bathrooms (tunnel 3) and 4th floor bathrooms (tunnel 4). The length of the 1st floor bathroom or tunnel 1 is equal to 24 feet, while the length of the remaining areas is equal to 36 feet. Twenty-seven activities and twenty-seven equations have been defined. Each building area has been associated with only one renovation method, for a total of four renovation networks. The variables used to defining the time equations are contained in the ground files 3 and 4 (i.e., *ground3.var* and *ground4.var*). The excavation method considered was a full-face, for that reason the head and bench distance equals zero. A sample of the "*plan.def*" or network and activity file is presented below.

```
l 1
  1
  2
  3
  4
  5
  6
  7
  8
  9
 10
 11
 12
 13
 14
 15
 16
 17
 18
 19
 20
 21
  0
m 1
  1 2 3
  2 4 5 6 7 8
  3 4 5 6 7 8
  4 9
  5 9
  6 9
  7 9
  8 9
  9 10
 10 11
 11 12 13
 12 14
 13 15 16
 14 20
 15 20
 16 17
 17 18 19
 18 20
 19 20
 20 21
  0
n 1 1
 21 1
  0
t
  1 1 1 0 1 0 0
Initial_demo
  2 1 2 0 1 0 0
Final_demo
  3 1 3 0 1 0 0
```

```
Asbestos_ceiling
 4 1 4 0 1 0 0
Plumbing_rough
 5 1 5 0 1 0 0
Electrical_rough
 6 1 6 0 1 0 0
Sprinkler_rough
 7 1 7 0 1 0 0
HVAC_rough
 8 1 8 0 1 0 0
Floor_studs
 9 1 9 0 1 0 0
GWB
10 1 10 0 1 0 0
Delay_1920
11 1 11 0 1 0 0
Paint_1st
12 1 12 0 1 0 0
Paint_2nd
13 1 13 0 1 0 0
Ceramic
14 1 14 0 1 0 0
Paint_3rd
15 1 15 0 1 0 0
Glazed_block
16 1 16 0 1 0 0
HM_frames
17 1 17 0 1 0 0
Delay_7680
18 1 18 0 1 0 0
Fixtures
19 1 19 0 1 0 0
RGD_&_heads
20 3 20 0 1 0 0
Decision
21 1 21 0 1 0 0
Advance_round
22 1 22 0 1 0 0
Asbestos_pipes
23 1 23 0 1 0 0
Steel_framing
24 1 24 0 1 0 0
Delay_1440
25 1 25 0 1 0 0
Toilet_parts
26 1 26 0 1 0 0
Delay_3360
27 1 27 0 1 0 0
Delay_960
0
s
3 1 1 1 0 24 0
0
0
```



```
e
1 1
  1
  2
  4
  5
  6
  7
  8
  9
11
12
13
15
16
18
19
20
21
22
23
24
25
26
0
m 1
  1 2 22
  2 4 5 6 7 8 23
22 4 5 6 7 8 23
  4 9
  5 9
  6 9
  7 9
  8 26
23 9
26 9
  9 24
24 11
11 13 15 16
13 12
15 12
16 12
12 25
25 18 19
18 20
19 20
20 21
  0
n 1 1
  21 1
  0
s
  4 1 1 1 0 36 0
  0
```

```
0
e
l 1 1
  1
  2
  4
  5
  6
  7
  8
  9
10
11
12
13
15
16
18
19
20
21
22
23
25
0
m 1
  1 22
 22 2
  2 23 8
23 4 5 6 7
  8 9
  4 9
  5 9
  6 9
  7 9
  9 10
10 11
11 13
13 12
12 15 16
15 25
16 25
25 18 19
18 20
19 20
20 21
  0
n 1 1
 21 1
  0
s
  4 1 2 1 0 36 0
  0
  0
```

```
e
1 1
  2
  4
  5
  6
  7
  8
  9
11
12
13
15
16
18
19
20
21
22
23
25
  0
m 1
  22 2
    2 8 23
    8 4 5 6 7
  23 4 5 6 7
    4 9
    5 9
    6 9
    7 9
    9 11
  11 13 15 16
  13 12
  15 12
  16 12
  12 25
  25 18 19
  18 20
  19 20
  20 21
    0
n 1 1
  21 22
    0
s
  4 1 3 1 0 36 0
  0
  0
e
```

B.2.2. THE GROUND FILE

A sample of the "ground3.var" and "ground4.var" files used to store the variables for the time equations of the contractor's plan, respectively is shown below. These only present the nodes that contain the variables needed for the building areas included in the network and activity file.

Ground3.var:

```

1 1
 19
initial_demo      480.00
final_demo        2880.00
asbestos_ceiling  2880.00
plumbing_rough    3360.00
electrical_rough  3360.00
sprinkler_rough   3360.00
HVAC_rough        3360.00
floor_studs       3360.00
GWB               3360.00
delay_1920        1920.00
paint_1st         1440.00
paint_2nd         960.00
ceramic           3360.00
paint_3rd         2400.00
glazed_block      3360.00
HM_frames         1440.00
delay_7680        7680.00
fixtures          840.00
RGD_&_heads       840.00

```

Ground4.var:

```

1 1
 20
initial_demo      480.00
final_demo        2880.00
plumbing_rough    3360.00
electrical_rough  3360.00
sprinkler_rough   3360.00
HVAC_rough        3360.00
floor_studs       3360.00
GWB               3360.00
paint_1st         1440.00
paint_2nd         960.00
ceramic           3360.00
glazed_block      3360.00

```

```
HM_frames      1440.00
fixtures       840.00
RGD_&_heads    840.00
asbestos_pipes 960.00
steel_framing  3360.00
delay_1440     1440.00
toilet_parts   3360.00
delay_3360     3360.00
1 2
20
initial_demo   0.00
final_demo     3360.00
plumbing_rough 3360.00
electrical_rough 3360.00
sprinkler_rough 3360.00
HVAC_rough     3360.00
floor_studs    3360.00
GWB            3360.00
delay_1920     1920.00
paint_1st      1440.00
paint_2nd      2400.00
ceramic        3360.00
glazed_block   3360.00
HM_frames      1440.00
fixtures       840.00
RGD_&_heads    840.00
asbestos_pipes 1440.00
steel_framing  3360.00
toilet_parts   3360.00
delay_960      960.00
1 3
17
final_demo     6720.00
plumbing_rough 3360.00
electrical_rough 3360.00
sprinkler_rough 3360.00
HVAC_rough     3360.00
floor_studs    3360.00
GWB            3360.00
paint_1st      1440.00
paint_2nd      2400.00
ceramic        3360.00
glazed_block   3360.00
HM_frames      1440.00
fixtures       840.00
RGD_&_heads    840.00
asbestos_pipes 1440.00
steel_framing  3360.00
toilet_parts   3360.00
```

B.2.3 THE CONSTRUCTION FILE

A sample of the "*construction3.var*" and "*construction4.var*" files is shown below. These contain the variable values that are independent of the building conditions that could be encountered.

Construction3.var:

```
l_face_holes  24.00
adv_round     1.00
```

Construction4.var:

```
l_face_holes  36.00
adv_round     1.00
```

B.2.4 THE EQUATIONS FILE

A sample of the equations file, "*planequations.dat*" is shown below.

```
1  initial_demo = initial_demo
2  final_demo = final_demo
3  asbestos_ceiling = asbestos_ceiling
4  plumbing_rough = plumbing_rough
5  electrical_rough = electrical_rough
6  sprinkler_rough = sprinkler_rough
7  HVAC_rough = HVAC_rough
8  floor_studs = floor_studs
9  GWB = GWB
10 delay_1920 = delay_1920
11 paint_1st = paint_1st
12 paint_2nd = paint_2nd
13 ceramic = ceramic
14 paint_3rd = paint_3rd
15 glazed_block = glazed_block
16 HM_frames = HM_frames
17 delay_7680 = delay_7680
18 fixtures = fixtures
19 RGD_&_heads = RGD_&_heads
20 decision = 0
21 advance_round = 0
22 asbestos_pipes = asbestos_pipes
23 steel_framing = steel_framing
24 delay_1440 = delay_1440
25 toilet_parts = toilet_parts
26 delay_3360 = delay_3360
```

```
27 delay_960 = delay_960
0
```

B.2.5 THE TUNNEL SYSTEM FILE

A sample of the "*multinfoplan.dat*" file is shown below. As it can be observed from the sample, construction for tunnels 1 and 2 starts immediately while 3 and 4 have initial delays of 16 and 32 hours respectively.

```
1
1 0
-1
-1
2
-1
-1 -1
-1
-1.000000
-1.000000
-1 -1.000000
-1
-1.000000

2
1 0
-1
-1
2
-1
-1 -1
-1
-1.000000
-1.000000
-1 -1.000000
-1
-1.000000

3
1 0
-1
-1
-2
16 -1
-1 -1
-1
-1.000000
-1.000000
```

```

-1 -1.000000
-1
-1.000000

4
1 0
-1
-1
-2
32 -1
-1 -1
-1
-1.000000
-1.000000
-1 -1.000000
-1
-1.000000

```

B.3 THE OBSERVED PROCESS

B.3.1 THE NETWORK AND ACTIVITY FILE

Six building areas are considered in this example. These are the 2nd floor east and west bathrooms (tunnels 1 and 2), 3rd floor east and west bathrooms (tunnel 3 and 4) and 4th floor east and west bathrooms (tunnel 5 and 6). The length of all bathrooms is equal to 36 feet. Thirty-eight activities and thirty-eight equations have been defined. Each building area has been associated with only one renovation method, for a total of six renovation networks. The variables used to defining the time equations are contained in the ground file 1 (i.e., *ground1.var*). The excavation method considered was a full-face, for that reason the head and bench distance equals zero. A sample of the "*daniels.def*" or network and activity file is presented below.


```
/* Tunnel 1:
 * East bath 2 */
1 1
  1
  2
  3
  4
  5
  6
  7
  8
  9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
37
38
  0
m 1
  1 2 3
  2 4
  3 4
  4 5
  5 6 7
  6 8
  7 8
  8 9
  9 10 11 12
10 13
11 13
12 13
13 14
14 15
15 16
16 17 18 19
17 20
```

```
18 20
19 20
20 21 22
21 23
22 23
23 24
24 25
25 26 27 29 30
26 38
27 28
28 38
29 38
30 38
38 37
0
n 1 1
37 1
0
t
1 1 1 0 1 0 0
Remo_mirrors
2 1 2 0 1 0 0
Save_toilet_partitions
3 1 3 0 1 0 0
Remo_shwr_fixtures
4 1 4 0 1 0 0
Remo_drop_ceiling
5 1 5 0 1 0 0
Temp_lights
6 1 6 0 1 0 0
Disc_sink_pipes
7 1 7 0 1 0 0
Remo_toilets
8 1 8 0 1 0 0
Remo_sinks
9 1 9 0 1 0 0
Debris_drop_ceiling
10 1 10 0 1 0 0
Install_sheet
11 1 11 0 1 0 0
Install_HEPA
12 1 12 0 1 0 0
Install_DECOM
13 1 13 0 1 0 0
Wall_opening
14 1 14 0 1 0 0
Inspect_debris
15 1 15 0 1 0 0
Remo_asbestos
16 1 16 0 1 0 0
Air_test
17 1 17 0 1 0 0
Remo_sheet
18 1 18 0 1 0 0
```

```
Uninst_HEPA
 19 1 19 0 1 0 0
Uninst_DECOM
 20 1 20 0 1 0 0
Shwr_walls_demo
 21 1 21 0 1 0 0
Wall_demo
 22 1 22 0 1 0 0
Shwr_roof_demo
 23 1 23 0 1 0 0
Debris_wall
 24 1 24 0 1 0 0
Remo_floor_tiles
 25 1 25 0 1 0 0
Debris_floor_tiles
 26 1 26 0 1 0 0
Single_shwr_roof
 27 1 27 0 1 0 0
Remo_wall_tiles
 28 1 28 0 1 0 0
Debris_wall_tiles
 29 1 29 0 1 0 0
Pipes_demo
 30 1 30 0 1 0 0
Remo_duct
 31 1 31 0 1 0 0
Remo_toilet_partitions
 32 1 32 0 1 0 0
Debris_shwr_roof
 33 1 33 0 1 0 0
Debris_wall_opening
 34 1 34 0 1 0 0
Debris_shwr_roof_wall
 35 1 35 0 1 0 0
Remo_duct_roof
 36 1 36 0 1 0 0
Debris_wall_roof_tiles
 37 3 37 0 1 0 0
Decision
 38 1 38 0 1 0 0
Advance_round
 0
s
 1 1 1 1 0 36 0
 0
 0
e
/* Tunnel 2:
 * West bath 2 */
l 1
 1
 2
 3
 4
```

5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
37
38
0
m 1
1 2 3
2 4
3 4
4 5
5 6 7
6 8
7 8
8 9
9 10 11 12
10 13
11 13
12 13
13 14
14 15
15 16
16 17 18 19
17 20
18 20
19 20
20 21 22
21 23
22 23
23 24
24 25

```
25 26 27 29 30
26 38
27 28
28 38
29 38
30 38
38 37
0
n 1 1
37 1
0
s
1 1 2 1 0 36 0
0
0
e
/* Tunnel 3:
 * East bath 3 */
l 1
1
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
37
38
0
```

```
m 1
  1 6 7
  6 8
  7 3
  3 31
  8 31
31 4
  4 9 5
  9 20
  5 20
20 22
22 32
32 10 11 12
10 13
11 13
12 13
13 14
14 15
15 16
16 17 18 19
17 33
18 33
19 33
33 24
24 25
25 30
30 21 26
21 23
26 23
23 27 29
27 28
29 28
28 38
38 37
  0
n 1 1
  37 1
  0
s
  1 1 3 1 0 36 0
  0
  0
e
/* Tunnel 4:
 * West bath 3 */
l 1
  1
  3
  4
  5
  6
  7
  8
  9
```

10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
34
37
38
0
m 1
1 31
31 5 6 7
5 4
6 8
7 3
8 4
3 4
4 9
9 22
22 20
20 34
34 10 11 12
10 13
11 13
12 13
13 14
14 15
15 16
16 17 18 19
17 21
18 21
19 21
21 23
23 24
24 25
25 26 29 30
26 27

```
29 27
30 27
27 28
28 38
38 37
0
n 1 1
37 1
0
s
1 1 4 1 0 36 0
0
0
e
/* Tunnel 5:
 * East bath 4 */
l 1
1
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
29
30
31
35
36
37
38
0
m 1
1 6
6 3
```



```
3 4
4 9 5
9 31 8
5 31 8
31 7
8 7
7 10 11 12
10 13
11 13
12 13
13 14
14 15
15 16
16 17 18 19
17 30
18 30
19 30
30 24
24 25
25 20
20 22
22 21
21 23
23 29 35
29 27 26
27 36
26 36
35 38
36 38
38 37
0
n 1 1
37 1
0
s
1 1 5 1 0 36 0
0
0
e
/* Tunnel 6:
* West bath 4 */
l 1
1
3
4
5
6
7
8
9
10
11
12
13
```

14
15
16
17
18
19
20
21
22
23
24
25
26
27
29
30
31
35
36
37
38
0
m 1
1 4
4 9 5
9 31
31 7
5 6
6 3
3 8
8 7
7 10 11 12
10 13
11 13
12 13
13 14
14 15
15 16
16 17 18 19
17 20
18 20
19 20
20 22
22 21
21 23 29 30
23 24
29 24
30 24
24 25
25 35
35 27 26
27 36
26 36
36 38

```

38 37
0
n 1 1
37 1
0
s
1 1 6 1 0 36 0
0
0
e

```

B.3.2. THE GROUND FILE

A sample of the "ground1.var" file used to store the variables for the time equations of the observed process is shown below. The values stored in this file were obtained from a time study performed on-site by the researcher.

```

1 1
30
remove_mirrors      15.00
save_toilet_partitions  265.00
remove_shower_fixtures 135.00
remove_drop_ceiling   75.00
temporary_lights     20.00
disconnect_sinks_pipes 25.00
remove_toilets       20.00
remove_sinks         28.00
debris_drop_ceiling  45.00
install_sheet        120.00
install_HEPA         10.00
install_DECOM        40.00
wall_opening         35.00
inspect_debris       15.00
remove_asbestos      45.00
air_test             180.00
remove_sheet         10.00
uninstall_HEPA       6.00
uninstall_DECOM      8.00
shower_walls_demo    60.00
wall_demo            265.00
shower_roof_demo     95.00
debris_wall          305.00
remove_floor_tiles   90.00
debris_floor_tiles   18.00
single_shower_roof  45.00

```

```
remove_wall_tiles    55.00
debris_wall_tiles    35.00
pipes_demo           155.00
remove_duct           62.00
1 2
30
remove_mirrors        15.00
save_toilet_partitions 255.00
remove_shower_fixtures 105.00
remove_drop_ceiling   35.00
temporary_lights      20.00
disconnect_sinks_pipes 10.00
remove_toilets        35.00
remove_sinks          25.00
debris_drop_ceiling   65.00
install_sheet         135.00
install_HEPA          10.00
install_DECOM         45.00
wall_opening          65.00
inspect_debris        18.00
remove_asbestos       60.00
air_test              180.00
remove_sheet          15.00
uninstall_HEPA        6.00
uninstall_DECOM       12.00
shower_walls_demo     95.00
wall_demo             112.00
shower_roof_demo      125.00
debris_wall           220.00
remove_floor_tiles    90.00
debris_floor_tiles    18.00
single_shower_roof    36.00
remove_wall_tiles     45.00
debris_wall_tiles     28.00
pipes_demo            85.00
remove_duct           15.00
1 3
32
remove_mirrors        11.00
disconnect_sinks_pipes 20.00
remove_toilets        25.00
remove_sinks          45.00
remove_shower_fixtures 115.00
remove_drop_ceiling   65.00
debris_drop_ceiling   25.00
remove_toilet_partitions 10.00
temporary_lights      35.00
shower_walls_demo     90.00
shower_roof_demo      105.00
debris_shower_roof    120.00
install_sheet         80.00
install_HEPA          10.00
install_DECOM         40.00
wall_opening          60.00
```

```

inspect_debris      12.00
remove_asbestos    110.00
air_test           180.00
remove_sheet       10.00
uninstall_HEPA     6.00
uninstall_DECOM    8.00
debris_wall_opening 170.00
remove_floor_tiles 80.00
debris_floor_tiles 30.00
remove_duct        115.00
wall_demo          60.00
single_shower_roof 36.00
debris_wall        235.00
remove_wall_tiles  100.00
debris_wall_tiles  45.00
pipes_demo         60.00
1 4
31
remove_mirrors     12.00
remove_toilet_partitions 15.00
temporary_lights  30.00
disconnect_sink_pipes 22.00
remove_toilets    10.00
remove_sinks      25.00
remove_shower_fixtures 90.00
remove_drop_ceiling 45.00
debris_drop_ceiling 20.00
shower_roof_demo  80.00
shower_walls_demo 150.00
debris_shower_roof_&_wall 35.00
install_sheet     110.00
install_HEPA      15.00
install_DECOM     90.00
wall_opening      60.00
inspect_debris    8.00
remove_asbestos   175.00
air_test          180.00
remove_sheet      10.00
uninstall_HEPA    6.00
uninstall_DECOM   9.00
wall_demo         45.00
debris_wall       450.00
remove_floor_tiles 150.00
debris_floor_tiles 45.00
single_shower_roof 55.00
pipes_demo        100.00
remove_duct       40.00
remove_wall_tiles 65.00
debris_wall_tiles 50.00
1 5
31
remove_mirrors     10.00
disconnect_sink_pipes 15.00
remove_shower_fixtures 95.00

```

```

remove_drop_ceiling    40.00
debris_drop_ceiling    25.00
temporary_lights      95.00
remove_toilet_partitions 45.00
remove_sinks          20.00
remove_toilets        15.00
install_sheet         155.00
install_HEPA          15.00
install_DECOM         40.00
wall_opening          115.00
inspect_debris        12.00
remove_asbestos       110.00
air_test              180.00
remove_sheet          18.00
uninstall_HEPA        8.00
uninstall_DECOM       14.00
remove_duct           25.00
remove_floor_tiles    70.00
debris_floor_tiles    25.00
shower_walls_demo     70.00
shower_roof_demo     75.00
wall_demo             420.00
debris_wall           450.00
pipes_demo            110.00
remove_duct_from_roof 235.00
remove_wall_tiles     95.00
single_shower_roof    35.00
debris_wall_tiles_&_shower_roof 55.00
1 6
31
remove_mirrors        10.00
remove_drop_ceiling   90.00
debris_drop_ceiling   25.00
temporary_lights      35.00
remove_toilet_partitions 10.00
disconnect_sink_pipes 10.00
remove_shower_fixtures 85.00
remove_sinks          16.00
remove_toilets        8.00
install_sheet         110.00
install_HEPA          15.00
install_DECOM         90.00
wall_opening          25.00
inspect_debris        7.00
remove_asbestos       85.00
air_test              180.00
remove_sheet          20.00
uninstall_HEPA        6.00
uninstall_DECOM       14.00
shower_walls_demo     140.00
shower_roof_demo     85.00
wall_demo             80.00
debris_wall           355.00
pipes_demo            135.00

```

```

remove_duct      40.00
remove_floor_tiles  120.00
debris_floor_tiles  45.00
remove_duct_from_roof  225.00
remove_wall_tiles  55.00
single_shower_roof  30.00
debris_wall_tiles_&_shower_roof  28.00

```

B.3.3 THE CONSTRUCTION FILE

A sample of the "*construction1.var*" file is shown below. This file contains the variable values that are independent of the building conditions that could be encountered.

```

l_face_holes  36.00
adv_round     1.00

```

B.3.4 THE EQUATIONS FILE

A sample of the equations file, "*equations.dat*" is shown below.

```

1  remove_mirrors = remove_mirrors
2  save_toilet_partitions = save_toilet_partitions
3  remove_shower_fixtures = remove_shower_fixtures
4  remove_drop_ceiling = remove_drop_ceiling
5  temporary_lights = temporary_lights
6  disconnect_sinks_pipes = disconnect_sinks_pipes
7  remove_toilets = remove_toilets
8  remove_sinks = remove_sinks
9  debris_drop_ceiling = debris_drop_ceiling
10 install_sheet = install_sheet
11 install_HEPA = install_HEPA
12 install_DECOM = install_DECOM
13 wall_opening = wall_opening
14 inspect_debris = inspect_debris
15 remove_asbestos = remove_asbestos
16 air_test = air_test
17 remove_sheet = remove_sheet
18 uninstall_HEPA = uninstall_HEPA
19 uninstall_DECOM = uninstall_DECOM
20 shower_walls_demo = shower_walls_demo
21 wall_demo = wall_demo
22 shower_roof_demo = shower_roof_demo
23 debris_wall = debris_wall
24 remove_floor_tiles = remove_floor_tiles

```

```

25 debris_floor_tiles = debris_floor_tiles
26 single_shower_roof = single_shower_roof
27 remove_wall_tiles = remove_wall_tiles
28 debris_wall_tiles = debris_wall_tiles
29 pipes_demo = pipes_demo
30 remove_duct = remove_duct
31 remove_toilet_partitions = remove_toilet_partitions
32 debris_shower_roof = debris_shower_roof
33 debris_wall_opening = debris_wall_opening
34 debris_shower_roof_&_wall = debris_shower_roof_&_wall
35 remove_duct_from_roof = remove_duct_from_roof
36 debris_wall_tiles_&_shower_roof = debris_wall_tiles_&_shower_roof
37 decision = 0
38 advance_round = 0
0

```

B.3.5 THE TUNNEL SYSTEM FILE

A sample of the "*multinfo.dat*" file is shown below. As it can be observed from the sample, construction for tunnels 1, and 2 starts immediately while 3, 4, 5, and 6 have initial delays of 8, 8, 16 and 16 hours respectively.

```

1
1 0
-1
-1
2
-1
-1 -1
-1
-1.000000
-1.000000
-1 -1.000000
-1
-1.000000

2
1 0
-1
-1
2
-1
-1 -1
-1
-1.000000
-1.000000
-1 -1.000000

```


-1
-1.000000

3
1 0
-1
-1
-2
8 -1
-1
-1
-1.000000
-1.000000
-1 -1.000000
-1
-1.000000

4
1 0
-1
-1
-2
8 -1
-1 -1
-1
-1.000000
-1.000000
-1 -1.000000
-1
-1.000000

5
1 0
-1
-1
-2
16 -1
-1 -1
-1
-1.000000
-1.000000
-1 -1.000000
-1
-1.000000

6
1 0
-1
-1
-2
16 -1
-1 -1
-1
-1.000000

```
-1.000000  
-1 -1.000000  
-1  
-1.000000
```

APPENDIX C - OUTPUT FILES

C.1 INTRODUCTION

This appendix present the actual output files that were generated from the simulation of the renovation operations that took place in Daniels Hall (refer to Chapter 7). There are two sets of output files, the contractor's plan simulation and the observed process simulation. The files included here are the ones that were discussed in Appendix A. For an interpretation of the results shown here, please refer to Chapter 7, sections 7.5.1 to 7.5.3.

C.2 THE CONTRACTOR'S PLAN

C.2.1 THE REAL TIME OUTPUT FILE

Note: The time units represent minutes instead of seconds as shown below.

```

Begin simulation 1

Tunnel 1 Round # 1 specified as method # 1
Tunnel 2 Round # 1 specified as method # 1
TIME: 0
START Initial_demo , round 1, tunnel 1, duration 480 seconds
Tunnel 1 Round 1 Starts at Time 0
START Initial_demo , round 1, tunnel 2, duration 480 seconds
Tunnel 2 Round 1 Starts at Time 0
TIME: 480
END Initial_demo , round # 1 tunnel 1
END Initial_demo , round # 1 tunnel 2
START Final_demo , round 1, tunnel 1, duration 2880 seconds
START Asbestos_ceiling , round 1, tunnel 1, duration 2880 seconds
START Final_demo , round 1, tunnel 2, duration 2880 seconds
START Asbestos_pipes, round 1, tunnel 2, duration 960 seconds
Tunnel 3 Round # 1 specified as method # 1
TIME: 960
START Initial_demo , round 1, tunnel 3, duration 0 seconds
Tunnel 3 Round 1 Starts at Time 960

```

```

END          Initial_demo , round # 1 tunnel 3
START       Asbestos_pipes, round 1, tunnel 3, duration 1440 seconds
TIME: 1440
END          Asbestos_pipes, round # 1 tunnel 2
Tunnel 4 Round # 1 specified as method # 1
TIME: 1920
START       Asbestos_pipes, round 1, tunnel 4, duration 1440 seconds
Tunnel 4 Round 1 Starts at Time 1920
TIME: 2400
END          Asbestos_pipes, round # 1 tunnel 3
START       Final_demo , round 1, tunnel 3, duration 3360 seconds
TIME: 3360
END          Final_demo , round # 1 tunnel 1
END          Asbestos_ceiling , round # 1 tunnel 1
END          Final_demo , round # 1 tunnel 2
END          Asbestos_pipes, round # 1 tunnel 4
START       Plumbing_rough, round 1, tunnel 1, duration 3360 seconds
START       Electrical_rough, round 1, tunnel 1, duration 3360 seconds
START       Sprinkler_rough, round 1, tunnel 1, duration 3360 seconds
START       HVAC_rough, round 1, tunnel 1, duration 3360 seconds
START       Floor_studs, round 1, tunnel 1, duration 3360 seconds
START       Plumbing_rough, round 1, tunnel 2, duration 3360 seconds
START       Electrical_rough, round 1, tunnel 2, duration 3360 seconds
START       Sprinkler_rough, round 1, tunnel 2, duration 3360 seconds
START       HVAC_rough, round 1, tunnel 2, duration 3360 seconds
START       Floor_studs, round 1, tunnel 2, duration 3360 seconds
START       Steel_framing, round 1, tunnel 2, duration 3360 seconds
START       Final_demo , round 1, tunnel 4, duration 6720 seconds
TIME: 5760
END          Final_demo , round # 1 tunnel 3
START       Steel_framing, round 1, tunnel 3, duration 3360 seconds
START       Floor_studs, round 1, tunnel 3, duration 3360 seconds
TIME: 6720
END          Plumbing_rough, round # 1 tunnel 1
END          Electrical_rough, round # 1 tunnel 1
END          Sprinkler_rough, round # 1 tunnel 1
END          HVAC_rough, round # 1 tunnel 1
END          Floor_studs, round # 1 tunnel 1
END          Plumbing_rough, round # 1 tunnel 2
END          Electrical_rough, round # 1 tunnel 2
END          Sprinkler_rough, round # 1 tunnel 2
END          HVAC_rough, round # 1 tunnel 2
END          Floor_studs, round # 1 tunnel 2
END          Steel_framing, round # 1 tunnel 2
START       GWB , round 1, tunnel 1, duration 3360 seconds
START       Delay_3360, round 1, tunnel 2, duration 3360 seconds
TIME: 9120
END          Steel_framing, round # 1 tunnel 3
END          Floor_studs, round # 1 tunnel 3
START       Plumbing_rough, round 1, tunnel 3, duration 3360 seconds
START       Electrical_rough, round 1, tunnel 3, duration 3360 seconds
START       Sprinkler_rough, round 1, tunnel 3, duration 3360 seconds
START       HVAC_rough, round 1, tunnel 3, duration 3360 seconds
TIME:10080

```

```

END          Final_demo , round # 1 tunnel 4
END          GWB , round # 1 tunnel 1
END          Delay_3360, round # 1 tunnel 2
START       Floor_studs, round 1, tunnel 4, duration 3360 seconds
START       Steel_framing, round 1, tunnel 4, duration 3360 seconds
START       Delay_1920, round 1, tunnel 1, duration 1920 seconds
START       GWB , round 1, tunnel 2, duration 3360 seconds
TIME:12000
END          Delay_1920, round # 1 tunnel 1
START       Paint_1st, round 1, tunnel 1, duration 1440 seconds
TIME:12480
END          Plumbing_rough, round # 1 tunnel 3
END          Electrical_rough, round # 1 tunnel 3
END          Sprinkler_rough, round # 1 tunnel 3
END          HVAC_rough, round # 1 tunnel 3
START       GWB , round 1, tunnel 3, duration 3360 seconds
TIME:13440
END          Floor_studs, round # 1 tunnel 4
END          Steel_framing, round # 1 tunnel 4
END          GWB , round # 1 tunnel 2
END          Paint_1st, round # 1 tunnel 1
START       Plumbing_rough, round 1, tunnel 4, duration 3360 seconds
START       Electrical_rough, round 1, tunnel 4, duration 3360 seconds
START       Sprinkler_rough, round 1, tunnel 4, duration 3360 seconds
START       HVAC_rough, round 1, tunnel 4, duration 3360 seconds
START       Delay_1440, round 1, tunnel 2, duration 1440 seconds
START       Paint_2nd, round 1, tunnel 1, duration 960 seconds
START       Ceramic, round 1, tunnel 1, duration 3360 seconds
TIME:14400
END          Paint_2nd, round # 1 tunnel 1
START       Paint_3rd, round 1, tunnel 1, duration 2400 seconds
TIME:14880
END          Delay_1440, round # 1 tunnel 2
START       Paint_1st, round 1, tunnel 2, duration 1440 seconds
TIME:15840
END          GWB , round # 1 tunnel 3
START       Delay_1920, round 1, tunnel 3, duration 1920 seconds
TIME:16320
END          Paint_1st, round # 1 tunnel 2
START       Ceramic, round 1, tunnel 2, duration 3360 seconds
START       Glazed_block, round 1, tunnel 2, duration 3360 seconds
START       HM_frames, round 1, tunnel 2, duration 1440 seconds
TIME:16800
END          Plumbing_rough, round # 1 tunnel 4
END          Electrical_rough, round # 1 tunnel 4
END          Sprinkler_rough, round # 1 tunnel 4
END          HVAC_rough, round # 1 tunnel 4
END          Ceramic, round # 1 tunnel 1
END          Paint_3rd, round # 1 tunnel 1
START       GWB , round 1, tunnel 4, duration 3360 seconds
START       Glazed_block, round 1, tunnel 1, duration 3360 seconds
START       HM_frames, round 1, tunnel 1, duration 1440 seconds
TIME:17760
END          Delay_1920, round # 1 tunnel 3

```

```

END          HM_frames, round # 1 tunnel 2
START       Paint_1st, round  1, tunnel 3, duration 1440 seconds
TIME:18240
END          HM_frames, round # 1 tunnel 1
START       Delay_7680, round  1, tunnel 1, duration 7680 seconds
TIME:19200
END          Paint_1st, round # 1 tunnel 3
START       Ceramic, round  1, tunnel 3, duration 3360 seconds
TIME:19680
END          Ceramic, round # 1 tunnel 2
END          Glazed_block, round # 1 tunnel 2
START       Paint_2nd, round  1, tunnel 2, duration 960 seconds
TIME:20160
END          GWB , round # 1 tunnel 4
END          Glazed_block, round # 1 tunnel 1
START       Paint_1st, round  1, tunnel 4, duration 1440 seconds
TIME:20640
END          Paint_2nd, round # 1 tunnel 2
START       Toilet_parts, round  1, tunnel 2, duration 3360 seconds
TIME:21600
END          Paint_1st, round # 1 tunnel 4
START       Ceramic, round  1, tunnel 4, duration 3360 seconds
START       Glazed_block, round  1, tunnel 4, duration 3360 seconds
START       HM_frames, round  1, tunnel 4, duration 1440 seconds
TIME:22560
END          Ceramic, round # 1 tunnel 3
START       Paint_2nd, round  1, tunnel 3, duration 2400 seconds
TIME:23040
END          HM_frames, round # 1 tunnel 4
TIME:24000
END          Toilet_parts, round # 1 tunnel 2
START       Fixtures, round  1, tunnel 2, duration 840 seconds
START       RGD_&_heads, round  1, tunnel 2, duration 840 seconds
TIME:24840
END          Fixtures, round # 1 tunnel 2
END          RGD_&_heads, round # 1 tunnel 2
Tunnel  2 Round #  2 specified as method # 0
START       Decision, round  1, tunnel 2, duration  0 seconds
END          Decision, round # 1 tunnel 2
START       Advance_round, round  1, tunnel 2, duration  0 seconds
END          Advance_round, round # 1 tunnel 2
Tunnel  2 Round  1 Complete at Time  24840
TIME:24960
END          Ceramic, round # 1 tunnel 4
END          Glazed_block, round # 1 tunnel 4
END          Paint_2nd, round # 1 tunnel 3
START       Paint_2nd, round  1, tunnel 4, duration 2400 seconds
START       Glazed_block, round  1, tunnel 3, duration 3360 seconds
START       HM_frames, round  1, tunnel 3, duration 1440 seconds
TIME:25920
END          Delay_7680, round # 1 tunnel 1
START       Fixtures, round  1, tunnel 1, duration 840 seconds
START       RGD_&_heads, round  1, tunnel 1, duration 840 seconds
TIME:26400

```

```

END          HM_frames, round # 1 tunnel 3
TIME:26760
END          Fixtures, round # 1 tunnel 1
END          RGD_&_heads, round # 1 tunnel 1
Tunnel 1 Round # 2 specified as method # 0
START       Decision, round 1, tunnel 1, duration 0 seconds
END         Decision, round # 1 tunnel 1
START       Advance_round, round 1, tunnel 1, duration 0 seconds
END         Advance_round, round # 1 tunnel 1
Tunnel 1 Round 1 Complete at Time 26760
TIME:27360
END          Paint_2nd, round # 1 tunnel 4
START       Toilet_parts, round 1, tunnel 4, duration 3360 seconds
TIME:28320
END          Glazed_block, round # 1 tunnel 3
START       Toilet_parts, round 1, tunnel 3, duration 3360 seconds
TIME:30720
END          Toilet_parts, round # 1 tunnel 4
START       Fixtures, round 1, tunnel 4, duration 840 seconds
START       RGD_&_heads, round 1, tunnel 4, duration 840 seconds
TIME:31560
END          Fixtures, round # 1 tunnel 4
END          RGD_&_heads, round # 1 tunnel 4
Tunnel 4 Round # 2 specified as method # 0
START       Decision, round 1, tunnel 4, duration 0 seconds
END         Decision, round # 1 tunnel 4
START       Advance_round, round 1, tunnel 4, duration 0 seconds
END         Advance_round, round # 1 tunnel 4
Tunnel 4 Round 1 Complete at Time 31560
TIME:31680
END          Toilet_parts, round # 1 tunnel 3
START       Fixtures, round 1, tunnel 3, duration 840 seconds
START       RGD_&_heads, round 1, tunnel 3, duration 840 seconds
TIME:32520
END          Fixtures, round # 1 tunnel 3
END          RGD_&_heads, round # 1 tunnel 3
Tunnel 3 Round # 2 specified as method # 0
START       Decision, round 1, tunnel 3, duration 0 seconds
END         Decision, round # 1 tunnel 3
START       Advance_round, round 1, tunnel 3, duration 0 seconds
END         Advance_round, round # 1 tunnel 3
Tunnel 3 Round 1 Complete at Time 32520

```

C.2.2 THE ROUND-WISE OUTPUT FILE

SIMULATION STATISTICS

*****TUNNEL 1 *****

Segment 1 Ground Class 1 Method Type 1

```

Method                1
Round                 1
Round Length(ft|m)   24.0
Round Loc. (End)-ft|m 24.0
Elapsed Time(minutes) 26760
Net Elapsed Time     26760
Waiting for Blasting NA
Head / Bench Deferred NA
    
```

ACTIVITY DURATIONS (minutes):

```

Initial_demo         480
Final_demo           2880
Asbestos_ceiling    2880
Plumbing_rough      3360
Electrical_rough    3360
Sprinkler_rough     3360
HVAC_rough          3360
Floor_studs         3360
GWB                 3360
Delay_1920          1920
Paint_1st           1440
Paint_2nd            960
Ceramic             3360
Paint_3rd           2400
Glazed_block        3360
HM_frames           1440
Delay_7680          7680
Fixtures            840
RGD_&_heads         840
Decision            0
Advance_round       0
    
```

*****TUNNEL 4*****

```

Segment 1 Ground Class 1 Method Type 3
    
```

```

Method                1
Round                 1
Round Length(ft|m)   36.0
Round Loc. (End)-ft|m 36.0
Elapsed Time(minutes) 29640
Net Elapsed Time     29640
Waiting for Blasting NA
Head / Bench Deferred NA
    
```

ACTIVITY DURATIONS (minutes):

```

Final_demo           6720
Plumbing_rough      3360
    
```


Electrical_rough	3360
Sprinkler_rough	3360
HVAC_rough	3360
Floor_studs	3360
GWB	3360
Paint_1st	1440
Paint_2nd	2400
Ceramic	3360
Glazed_block	3360
HM_frames	1440
Fixtures	840
RGD_&_heads	840
Decision	0
Advance_round	0
Asbestos_pipes	1440
Steel_framing	3360
Toilet_parts	3360

*****TUNNEL 3 *****

Segment 1 Ground Class 1 Method Type 2

Method	1
Round	1
Round Length(ft m)	36.0
Round Loc. (End)-ft m	36.0
Elapsed Time(minutes)	31560
Net Elapsed Time	31560
Waiting for Blasting	NA
Head / Bench Deferred	NA

ACTIVITY DURATIONS (minutes):

Initial_demo	0
Final_demo	3360
Plumbing_rough	3360
Electrical_rough	3360
Sprinkler_rough	3360
HVAC_rough	3360
Floor_studs	3360
GWB	3360
Delay_1920	1920
Paint_1st	1440
Paint_2nd	2400
Ceramic	3360
Glazed_block	3360
HM_frames	1440
Fixtures	840
RGD_&_heads	840
Decision	0
Advance_round	0
Asbestos_pipes	1440

Steel_framing 3360
 Toilet_parts 3360

*****TUNNEL 2*****

Segment 1 Ground Class 1 Method Type 1

Method 1
 Round 1
 Round Length(ft|m) 36.0
 Round Loc. (End)-ft|m 36.0
 Elapsed Time(minutes) 24840
 Net Elapsed Time 24840
 Waiting for Blasting NA
 Head / Bench Deferred NA

ACTIVITY DURATIONS (minutes):

Initial_demo 480
 Final_demo 2880
 Plumbing_rough 3360
 Electrical_rough 3360
 Sprinkler_rough 3360
 HVAC_rough 3360
 Floor_studs 3360
 GWB 3360
 Paint_1st 1440
 Paint_2nd 960
 Ceramic 3360
 Glazed_block 3360
 HM_frames 1440
 Fixtures 840
 RGD_&_heads 840
 Decision 0
 Advance_round 0
 Asbestos_pipes 960
 Steel_framing 3360
 Delay_1440 1440
 Toilet_parts 3360
 Delay_3360 3360

C.2.3 THE TUNNEL INFORMATION OUTPUT FILE

Run No. 1052 Simulation No. 1 14-01-1999 13:21:55

Tu Nr	Ar Nr	Gm Tp	Beg-X [ft]	End-X [ft]	Length [ft]	Beg-T [hr]	End-T [hr]	Duratn. [hr]	Idle-T [hr]	Ad.Rt [m/hr]	Cost [MF]	cost/m [KFr/m]
1	1	1	0	24	24	0.0	446.0	446.0	0.0	0.05	0	0.0

2	1	1	0	36	36	0.0	828.0	828.0	0.0	0.04	0	0.0
3	1	1	0	36	36	16.0	542.0	526.0	0.0	0.07	0	0.0
4	1	1	0	36	36	32.0	526.0	494.0	0.0	0.07	0	0.0

Total Time : 828.00 hrs.
Total Cost : 0.00 M.

C.3 THE OBSERVED PROCESS

C.3.1 THE REAL TIME OUTPUT FILE

Note: The time units represent minutes instead of seconds as shown below.

```

Begin simulation 1

Tunnel 1 Round # 1 specified as method # 1
Tunnel 2 Round # 1 specified as method # 1
TIME: 0
START Remo_mirrors , round 1, tunnel 1, duration 15 seconds
Tunnel 1 Round 1 Starts at Time 0
START Remo_mirrors , round 1, tunnel 2, duration 15 seconds
Tunnel 2 Round 1 Starts at Time 0
TIME: 15
END Remo_mirrors , round # 1 tunnel 1
END Remo_mirrors , round # 1 tunnel 2
START Save_toilet_partit, round 1, tunnel 1, duration 265 seconds
START Remo_shwr_fixtures, round 1, tunnel 1, duration 135 seconds
START Save_toilet_partit, round 1, tunnel 2, duration 255 seconds
START Remo_shwr_fixtures, round 1, tunnel 2, duration 105 seconds
TIME: 120
END Remo_shwr_fixtures, round # 1 tunnel 2
TIME: 150
END Remo_shwr_fixtures, round # 1 tunnel 1
TIME: 270
END Save_toilet_partit, round # 1 tunnel 2
START Remo_drop_ceiling, round 1, tunnel 2, duration 35 seconds
TIME: 280
END Save_toilet_partit, round # 1 tunnel 1
START Remo_drop_ceiling, round 1, tunnel 1, duration 75 seconds
TIME: 305
END Remo_drop_ceiling, round # 1 tunnel 2
START Temp_lights, round 1, tunnel 2, duration 20 seconds
TIME: 325
END Temp_lights, round # 1 tunnel 2
START Disc_sink_pipes, round 1, tunnel 2, duration 10 seconds
START Remo_toilets, round 1, tunnel 2, duration 35 seconds
TIME: 335
END Disc_sink_pipes, round # 1 tunnel 2

```

```

TIME: 355
END      Remo_drop_ceiling, round # 1 tunnel 1
START    Temp_lights, round 1, tunnel 1, duration 20 seconds
TIME: 360
END      Remo_toilets, round # 1 tunnel 2
START    Remo_sinks, round 1, tunnel 2, duration 25 seconds
TIME: 375
END      Temp_lights, round # 1 tunnel 1
START    Disc_sink_pipes, round 1, tunnel 1, duration 25 seconds
START    Remo_toilets, round 1, tunnel 1, duration 20 seconds
TIME: 385
END      Remo_sinks, round # 1 tunnel 2
START    Debris_drop_ceilin, round 1, tunnel 2, duration 65 seconds
TIME: 395
END      Remo_toilets, round # 1 tunnel 1
TIME: 400
END      Disc_sink_pipes, round # 1 tunnel 1
START    Remo_sinks, round 1, tunnel 1, duration 28 seconds
TIME: 428
END      Remo_sinks, round # 1 tunnel 1
START    Debris_drop_ceilin, round 1, tunnel 1, duration 45 seconds
TIME: 450
END      Debris_drop_ceilin, round # 1 tunnel 2
START    Install_sheet, round 1, tunnel 2, duration 135 seconds
START    Install_HEPA, round 1, tunnel 2, duration 10 seconds
START    Install_DECOM, round 1, tunnel 2, duration 45 seconds
TIME: 460
END      Install_HEPA, round # 1 tunnel 2
TIME: 473
END      Debris_drop_ceilin, round # 1 tunnel 1
START    Install_sheet, round 1, tunnel 1, duration 120 seconds
START    Install_HEPA, round 1, tunnel 1, duration 10 seconds
START    Install_DECOM, round 1, tunnel 1, duration 40 seconds
Tunnel 3 Round # 1 specified as method # 1
Tunnel 4 Round # 1 specified as method # 1
TIME: 480
START    Remo_mirrors , round 1, tunnel 3, duration 11 seconds
Tunnel 3 Round 1 Starts at Time 480
START    Remo_mirrors , round 1, tunnel 4, duration 12 seconds
Tunnel 4 Round 1 Starts at Time 480
TIME: 483
END      Install_HEPA, round # 1 tunnel 1
TIME: 491
END      Remo_mirrors , round # 1 tunnel 3
START    Disc_sink_pipes, round 1, tunnel 3, duration 20 seconds
START    Remo_toilets, round 1, tunnel 3, duration 25 seconds
TIME: 492
END      Remo_mirrors , round # 1 tunnel 4
START    Remo_toilet_partit, round 1, tunnel 4, duration 15 seconds
TIME: 495
END      Install_DECOM, round # 1 tunnel 2
TIME: 507
END      Remo_toilet_partit, round # 1 tunnel 4
START    Temp_lights, round 1, tunnel 4, duration 30 seconds

```

```

START      Disc_sink_pipes, round  1, tunnel  4, duration  0 seconds
END        Disc_sink_pipes, round # 1 tunnel  4
START      Remo_toilets, round  1, tunnel  4, duration 10 seconds
START      Remo_sinks, round  1, tunnel  4, duration 25 seconds
TIME:     511
END        Disc_sink_pipes, round # 1 tunnel  3
START      Remo_sinks, round  1, tunnel  3, duration 45 seconds
TIME:     513
END        Install_DECOM, round #  1 tunnel  1
TIME:     516
END        Remo_toilets, round #  1 tunnel  3
START      Remo_shwr_fixtures, round  1, tunnel  3, duration 115 seconds
TIME:     517
END        Remo_toilets, round #  1 tunnel  4
START      Remo_shwr_fixtures, round  1, tunnel  4, duration  90 seconds
TIME:     532
END        Remo_sinks, round #  1 tunnel  4
TIME:     537
END        Temp_lights, round #  1 tunnel  4
TIME:     556
END        Remo_sinks, round #  1 tunnel  3
TIME:     585
END        Install_sheet, round #  1 tunnel  2
START      Wall_opening, round  1, tunnel  2, duration  65 seconds
TIME:     593
END        Install_sheet, round #  1 tunnel  1
START      Wall_opening, round  1, tunnel  1, duration  35 seconds
TIME:     607
END        Remo_shwr_fixtures, round #  1 tunnel  4
START      Remo_drop_ceiling, round  1, tunnel  4, duration  45 seconds
TIME:     628
END        Wall_opening, round #  1 tunnel  1
START      Inspect_debris, round  1, tunnel  1, duration  15 seconds
TIME:     631
END        Remo_shwr_fixtures, round #  1 tunnel  3
START      Remo_toilet_partit, round  1, tunnel  3, duration  10 seconds
TIME:     641
END        Remo_toilet_partit, round #  1 tunnel  3
START      Remo_drop_ceiling, round  1, tunnel  3, duration  65 seconds
TIME:     643
END        Inspect_debris, round #  1 tunnel  1
START      Remo_asbestos, round  1, tunnel  1, duration  45 seconds
TIME:     650
END        Wall_opening, round #  1 tunnel  2
START      Inspect_debris, round  1, tunnel  2, duration  18 seconds
TIME:     652
END        Remo_drop_ceiling, round #  1 tunnel  4
START      Debris_drop_ceilin, round  1, tunnel  4, duration  20 seconds
TIME:     668
END        Inspect_debris, round #  1 tunnel  2
START      Remo_asbestos, round  1, tunnel  2, duration  60 seconds
TIME:     672
END        Debris_drop_ceilin, round #  1 tunnel  4
START      Shwr_roof_demo, round  1, tunnel  4, duration  80 seconds

```

```

TIME: 688
END      Remo_asbestos, round # 1 tunnel 1
START    Air_test, round 1, tunnel 1, duration 180 seconds
TIME: 706
END      Remo_drop_ceiling, round # 1 tunnel 3
START    Debris_drop_ceilin, round 1, tunnel 3, duration 25 seconds
START    Temp_lights, round 1, tunnel 3, duration 35 seconds
TIME: 728
END      Remo_asbestos, round # 1 tunnel 2
START    Air_test, round 1, tunnel 2, duration 180 seconds
TIME: 731
END      Debris_drop_ceilin, round # 1 tunnel 3
TIME: 741
END      Temp_lights, round # 1 tunnel 3
START    Shwr_walls_demo, round 1, tunnel 3, duration 90 seconds
TIME: 752
END      Shwr_roof_demo, round # 1 tunnel 4
START    Shwr_walls_demo, round 1, tunnel 4, duration 150 seconds
TIME: 831
END      Shwr_walls_demo, round # 1 tunnel 3
START    Shwr_roof_demo, round 1, tunnel 3, duration 105 seconds
TIME: 868
END      Air_test, round # 1 tunnel 1
START    Remo_sheet, round 1, tunnel 1, duration 10 seconds
START    Uninst_HEPA, round 1, tunnel 1, duration 6 seconds
START    Uninst_DECOM, round 1, tunnel 1, duration 8 seconds
TIME: 874
END      Uninst_HEPA, round # 1 tunnel 1
TIME: 876
END      Uninst_DECOM, round # 1 tunnel 1
TIME: 878
END      Remo_sheet, round # 1 tunnel 1
START    Shwr_walls_demo, round 1, tunnel 1, duration 60 seconds
TIME: 902
END      Shwr_walls_demo, round # 1 tunnel 4
START    Debris_shwr_roof_w, round 1, tunnel 4, duration 35 seconds
TIME: 908
END      Air_test, round # 1 tunnel 2
START    Remo_sheet, round 1, tunnel 2, duration 15 seconds
START    Uninst_HEPA, round 1, tunnel 2, duration 6 seconds
START    Uninst_DECOM, round 1, tunnel 2, duration 12 seconds
TIME: 914
END      Uninst_HEPA, round # 1 tunnel 2
TIME: 920
END      Uninst_DECOM, round # 1 tunnel 2
TIME: 923
END      Remo_sheet, round # 1 tunnel 2
START    Shwr_walls_demo, round 1, tunnel 2, duration 95 seconds
TIME: 936
END      Shwr_roof_demo, round # 1 tunnel 3
START    Debris_shwr_roof, round 1, tunnel 3, duration 120 seconds
TIME: 937
END      Debris_shwr_roof_w, round # 1 tunnel 4
START    Install_sheet, round 1, tunnel 4, duration 110 seconds

```

```

START          Install_HEPA, round  1, tunnel  4, duration  15 seconds
START          Install_DECOM, round  1, tunnel  4, duration  90 seconds
  TIME:  938
  END          Shwr_walls_demo, round # 1 tunnel  1
START          Wall_demo, round  1, tunnel  1, duration 265 seconds
START          Shwr_roof_demo, round  1, tunnel  1, duration  95 seconds
  TIME:  952
  END          Install_HEPA, round # 1 tunnel  4
  Tunnel  5 Round #  1 specified as method # 1
  Tunnel  6 Round #  1 specified as method # 1
  TIME:  960
START          Remo_mirrors  , round  1, tunnel  5, duration  10 seconds
  Tunnel  5 Round  1 Starts at Time  960
START          Remo_mirrors  , round  1, tunnel  6, duration  10 seconds
  Tunnel  6 Round  1 Starts at Time  960
  TIME:  970
  END          Remo_mirrors  , round # 1 tunnel  5
  END          Remo_mirrors  , round # 1 tunnel  6
START          Disc_sink_pipes, round  1, tunnel  5, duration  0 seconds
  END          Disc_sink_pipes, round # 1 tunnel  5
START          Remo_drop_ceiling, round  1, tunnel  6, duration  90 seconds
START          Remo_shwr_fixtures, round  1, tunnel  5, duration  95 seconds
  TIME: 1018
  END          Shwr_walls_demo, round # 1 tunnel  2
START          Wall_demo, round  1, tunnel  2, duration 112 seconds
START          Shwr_roof_demo, round  1, tunnel  2, duration 125 seconds
  TIME: 1027
  END          Install_DECOM, round # 1 tunnel  4
  TIME: 1033
  END          Shwr_roof_demo, round # 1 tunnel  1
  TIME: 1047
  END          Install_sheet, round # 1 tunnel  4
START          Wall_opening, round  1, tunnel  4, duration  60 seconds
  TIME: 1056
  END          Debris_shwr_roof, round # 1 tunnel  3
START          Install_sheet, round  1, tunnel  3, duration  80 seconds
START          Install_HEPA, round  1, tunnel  3, duration  10 seconds
START          Install_DECOM, round  1, tunnel  3, duration  40 seconds
  TIME: 1060
  END          Remo_drop_ceiling, round # 1 tunnel  6
START          Debris_drop_ceilin, round  1, tunnel  6, duration  25 seconds
START          Temp_lights, round  1, tunnel  6, duration  35 seconds
  TIME: 1065
  END          Remo_shwr_fixtures, round # 1 tunnel  5
START          Remo_drop_ceiling, round  1, tunnel  5, duration  40 seconds
  TIME: 1066
  END          Install_HEPA, round # 1 tunnel  3
  TIME: 1085
  END          Debris_drop_ceilin, round # 1 tunnel  6
START          Remo_toilet_partit, round  1, tunnel  6, duration  10 seconds
  TIME: 1095
  END          Temp_lights, round # 1 tunnel  6
  END          Remo_toilet_partit, round # 1 tunnel  6
START          Disc_sink_pipes, round  1, tunnel  6, duration  0 seconds

```

```

END          Disc_sink_pipes, round # 1 tunnel 6
START      Remo_shwr_fixtures, round 1, tunnel 6, duration 85 seconds
TIME: 1096
END          Install_DECOM, round # 1 tunnel 3
TIME: 1105
END          Remo_drop_ceiling, round # 1 tunnel 5
START      Debris_drop_ceilin, round 1, tunnel 5, duration 25 seconds
START      Temp_lights, round 1, tunnel 5, duration 95 seconds
TIME: 1107
END          Wall_opening, round # 1 tunnel 4
START      Inspect_debris, round 1, tunnel 4, duration 8 seconds
TIME: 1115
END          Inspect_debris, round # 1 tunnel 4
START      Remo_asbestos, round 1, tunnel 4, duration 175 seconds
TIME: 1130
END          Wall_demo, round # 1 tunnel 2
END          Debris_drop_ceilin, round # 1 tunnel 5
TIME: 1136
END          Install_sheet, round # 1 tunnel 3
START      Wall_opening, round 1, tunnel 3, duration 60 seconds
TIME: 1143
END          Shwr_roof_demo, round # 1 tunnel 2
START      Debris_wall, round 1, tunnel 2, duration 220 seconds
TIME: 1180
END          Remo_shwr_fixtures, round # 1 tunnel 6
START      Remo_sinks, round 1, tunnel 6, duration 16 seconds
TIME: 1196
END          Wall_opening, round # 1 tunnel 3
END          Remo_sinks, round # 1 tunnel 6
START      Inspect_debris, round 1, tunnel 3, duration 12 seconds
START      Remo_toilets, round 1, tunnel 6, duration 8 seconds
TIME: 1200
END          Temp_lights, round # 1 tunnel 5
START      Remo_toilet_partit, round 1, tunnel 5, duration 45 seconds
START      Remo_sinks, round 1, tunnel 5, duration 20 seconds
TIME: 1203
END          Wall_demo, round # 1 tunnel 1
START      Debris_wall, round 1, tunnel 1, duration 305 seconds
TIME: 1204
END          Remo_toilets, round # 1 tunnel 6
START      Install_sheet, round 1, tunnel 6, duration 110 seconds
START      Install_HEPA, round 1, tunnel 6, duration 15 seconds
START      Install_DECOM, round 1, tunnel 6, duration 90 seconds
TIME: 1208
END          Inspect_debris, round # 1 tunnel 3
START      Remo_asbestos, round 1, tunnel 3, duration 110 seconds
TIME: 1219
END          Install_HEPA, round # 1 tunnel 6
TIME: 1220
END          Remo_sinks, round # 1 tunnel 5
TIME: 1245
END          Remo_toilet_partit, round # 1 tunnel 5
START      Remo_toilets, round 1, tunnel 5, duration 15 seconds
TIME: 1260

```



```

END          Remo_toilets, round # 1 tunnel 5
START       Install_sheet, round 1, tunnel 5, duration 155 seconds
START       Install_HEPA, round 1, tunnel 5, duration 15 seconds
START       Install_DECOM, round 1, tunnel 5, duration 40 seconds
TIME: 1275
END          Install_HEPA, round # 1 tunnel 5
TIME: 1290
END          Remo_asbestos, round # 1 tunnel 4
START       Air_test, round 1, tunnel 4, duration 180 seconds
TIME: 1294
END          Install_DECOM, round # 1 tunnel 6
TIME: 1300
END          Install_DECOM, round # 1 tunnel 5
TIME: 1314
END          Install_sheet, round # 1 tunnel 6
START       Wall_opening, round 1, tunnel 6, duration 25 seconds
TIME: 1318
END          Remo_asbestos, round # 1 tunnel 3
START       Air_test, round 1, tunnel 3, duration 180 seconds
TIME: 1339
END          Wall_opening, round # 1 tunnel 6
START       Inspect_debris, round 1, tunnel 6, duration 7 seconds
TIME: 1346
END          Inspect_debris, round # 1 tunnel 6
START       Remo_asbestos, round 1, tunnel 6, duration 85 seconds
TIME: 1363
END          Debris_wall, round # 1 tunnel 2
START       Remo_floor_tiles, round 1, tunnel 2, duration 90 seconds
TIME: 1415
END          Install_sheet, round # 1 tunnel 5
START       Wall_opening, round 1, tunnel 5, duration 115 seconds
TIME: 1431
END          Remo_asbestos, round # 1 tunnel 6
START       Air_test, round 1, tunnel 6, duration 180 seconds
TIME: 1453
END          Remo_floor_tiles, round # 1 tunnel 2
START       Debris_floor_tiles, round 1, tunnel 2, duration 18 seconds
TIME: 1470
END          Air_test, round # 1 tunnel 4
START       Remo_sheet, round 1, tunnel 4, duration 10 seconds
START       Uninst_HEPA, round 1, tunnel 4, duration 6 seconds
START       Uninst_DECOM, round 1, tunnel 4, duration 9 seconds
TIME: 1471
END          Debris_floor_tiles, round # 1 tunnel 2
START       Single_shwr_roof, round 1, tunnel 2, duration 36 seconds
START       Remo_wall_tiles, round 1, tunnel 2, duration 45 seconds
START       Pipes_demo, round 1, tunnel 2, duration 85 seconds
START       Remo_duct, round 1, tunnel 2, duration 15 seconds
TIME: 1476
END          Uninst_HEPA, round # 1 tunnel 4
TIME: 1479
END          Uninst_DECOM, round # 1 tunnel 4
TIME: 1480
END          Remo_sheet, round # 1 tunnel 4

```

```

START          Wall_demo, round  1, tunnel  4, duration  45 seconds
TIME: 1486
END            Remo_duct, round #  1 tunnel  2
TIME: 1498
END            Air_test, round #  1 tunnel  3
START          Remo_sheet, round  1, tunnel  3, duration  10 seconds
START          Uninst_HEPA, round  1, tunnel  3, duration   6 seconds
START          Uninst_DECOM, round  1, tunnel  3, duration   8 seconds
TIME: 1504
END            Uninst_HEPA, round #  1 tunnel  3
TIME: 1506
END            Uninst_DECOM, round #  1 tunnel  3
TIME: 1507
END            Single_shwr_roof, round #  1 tunnel  2
TIME: 1508
END            Debris_wall, round #  1 tunnel  1
END            Remo_sheet, round #  1 tunnel  3
START          Remo_floor_tiles, round  1, tunnel  1, duration  90 seconds
START          Debris_wall_openin, round  1, tunnel  3, duration 170 seconds
TIME: 1516
END            Remo_wall_tiles, round #  1 tunnel  2
START          Debris_wall_tiles, round  1, tunnel  2, duration  28 seconds
TIME: 1525
END            Wall_demo, round #  1 tunnel  4
START          Debris_wall, round  1, tunnel  4, duration 450 seconds
TIME: 1530
END            Wall_opening, round #  1 tunnel  5
START          Inspect_debris, round  1, tunnel  5, duration  12 seconds
TIME: 1542
END            Inspect_debris, round #  1 tunnel  5
START          Remo_asbestos, round  1, tunnel  5, duration 110 seconds
TIME: 1544
END            Debris_wall_tiles, round #  1 tunnel  2
TIME: 1556
END            Pipes_demo, round #  1 tunnel  2
START          Advance_round , round  1, tunnel  2, duration   0 seconds
END            Advance_round , round #  1 tunnel  2
Tunnel  2 Round #   2 specified as method # 0
START          Decision , round  1, tunnel  2, duration   0 seconds
END            Decision , round #  1 tunnel  2
Tunnel  2 Round   1 Complete at Time  1556
TIME: 1598
END            Remo_floor_tiles, round #  1 tunnel  1
START          Debris_floor_tiles, round  1, tunnel  1, duration  18 seconds
TIME: 1611
END            Air_test, round #  1 tunnel  6
START          Remo_sheet, round  1, tunnel  6, duration  20 seconds
START          Uninst_HEPA, round  1, tunnel  6, duration   6 seconds
START          Uninst_DECOM, round  1, tunnel  6, duration  14 seconds
TIME: 1616
END            Debris_floor_tiles, round #  1 tunnel  1
START          Single_shwr_roof, round  1, tunnel  1, duration  45 seconds
START          Remo_wall_tiles, round  1, tunnel  1, duration  55 seconds
START          Pipes_demo, round  1, tunnel  1, duration 155 seconds

```

```

START          Remo_duct, round  1, tunnel  1, duration  62 seconds
TIME: 1617
END            Uninst_HEPA, round #  1 tunnel  6
TIME: 1625
END            Uninst_DECOM, round #  1 tunnel  6
TIME: 1631
END            Remo_sheet, round #  1 tunnel  6
START          Shwr_walls_demo, round  1, tunnel  6, duration 140 seconds
TIME: 1652
END            Remo_asbestos, round #  1 tunnel  5
START          Air_test, round  1, tunnel  5, duration 180 seconds
TIME: 1661
END            Single_shwr_roof, round #  1 tunnel  1
TIME: 1671
END            Remo_wall_tiles, round #  1 tunnel  1
START          Debris_wall_tiles, round  1, tunnel  1, duration  35 seconds
TIME: 1678
END            Debris_wall_openin, round #  1 tunnel  3
END            Remo_duct, round #  1 tunnel  1
START          Remo_floor_tiles, round  1, tunnel  3, duration  80 seconds
TIME: 1706
END            Debris_wall_tiles, round #  1 tunnel  1
TIME: 1758
END            Remo_floor_tiles, round #  1 tunnel  3
START          Debris_floor_tiles, round  1, tunnel  3, duration  30 seconds
TIME: 1771
END            Pipes_demo, round #  1 tunnel  1
END            Shwr_walls_demo, round #  1 tunnel  6
START          Advance_round , round  1, tunnel  1, duration   0 seconds
END            Advance_round , round #  1 tunnel  1
START          Shwr_roof_demo, round  1, tunnel  6, duration  85 seconds
Tunnel  1 Round #   2 specified as method # 0
START          Decision , round  1, tunnel  1, duration   0 seconds
END            Decision , round #  1 tunnel  1
Tunnel  1 Round   1 Complete at Time  1771
TIME: 1788
END            Debris_floor_tiles, round #  1 tunnel  3
START          Remo_duct, round  1, tunnel  3, duration 115 seconds
TIME: 1832
END            Air_test, round #  1 tunnel  5
START          Remo_sheet, round  1, tunnel  5, duration  18 seconds
START          Uninst_HEPA, round  1, tunnel  5, duration   8 seconds
START          Uninst_DECOM, round  1, tunnel  5, duration  14 seconds
TIME: 1840
END            Uninst_HEPA, round #  1 tunnel  5
TIME: 1846
END            Uninst_DECOM, round #  1 tunnel  5
TIME: 1850
END            Remo_sheet, round #  1 tunnel  5
START          Remo_duct, round  1, tunnel  5, duration  25 seconds
TIME: 1856
END            Shwr_roof_demo, round #  1 tunnel  6
START          Wall_demo, round  1, tunnel  6, duration  80 seconds
TIME: 1875

```

```

END          Remo_duct, round # 1 tunnel 5
START       Remo_floor_tiles, round 1, tunnel 5, duration 70 seconds
TIME: 1903
END          Remo_duct, round # 1 tunnel 3
START       Wall_demo, round 1, tunnel 3, duration 60 seconds
START       Single_shwr_roof, round 1, tunnel 3, duration 36 seconds
TIME: 1936
END          Wall_demo, round # 1 tunnel 6
START       Debris_wall, round 1, tunnel 6, duration 355 seconds
START       Pipes_demo, round 1, tunnel 6, duration 135 seconds
START       Remo_duct, round 1, tunnel 6, duration 40 seconds
TIME: 1939
END          Single_shwr_roof, round # 1 tunnel 3
TIME: 1945
END          Remo_floor_tiles, round # 1 tunnel 5
START       Debris_floor_tiles, round 1, tunnel 5, duration 25 seconds
TIME: 1963
END          Wall_demo, round # 1 tunnel 3
START       Debris_wall, round 1, tunnel 3, duration 235 seconds
TIME: 1970
END          Debris_floor_tiles, round # 1 tunnel 5
START       Shwr_walls_demo, round 1, tunnel 5, duration 70 seconds
TIME: 1975
END          Debris_wall, round # 1 tunnel 4
START       Remo_floor_tiles, round 1, tunnel 4, duration 150 seconds
TIME: 1976
END          Remo_duct, round # 1 tunnel 6
TIME: 2040
END          Shwr_walls_demo, round # 1 tunnel 5
START       Shwr_roof_demo, round 1, tunnel 5, duration 75 seconds
TIME: 2071
END          Pipes_demo, round # 1 tunnel 6
TIME: 2115
END          Shwr_roof_demo, round # 1 tunnel 5
START       Wall_demo, round 1, tunnel 5, duration 420 seconds
TIME: 2125
END          Remo_floor_tiles, round # 1 tunnel 4
START       Debris_floor_tiles, round 1, tunnel 4, duration 45 seconds
TIME: 2170
END          Debris_floor_tiles, round # 1 tunnel 4
START       Single_shwr_roof, round 1, tunnel 4, duration 55 seconds
START       Pipes_demo, round 1, tunnel 4, duration 100 seconds
START       Remo_duct, round 1, tunnel 4, duration 40 seconds
TIME: 2198
END          Debris_wall, round # 1 tunnel 3
START       Remo_wall_tiles, round 1, tunnel 3, duration 100 seconds
START       Pipes_demo, round 1, tunnel 3, duration 60 seconds
TIME: 2210
END          Remo_duct, round # 1 tunnel 4
TIME: 2225
END          Single_shwr_roof, round # 1 tunnel 4
TIME: 2258
END          Pipes_demo, round # 1 tunnel 3
TIME: 2270

```

```

END          Pipes_demo, round # 1 tunnel 4
START       Remo_wall_tiles, round 1, tunnel 4, duration 65 seconds
TIME: 2291
END          Debris_wall, round # 1 tunnel 6
START       Remo_floor_tiles, round 1, tunnel 6, duration 120 seconds
TIME: 2298
END          Remo_wall_tiles, round # 1 tunnel 3
START       Debris_wall_tiles, round 1, tunnel 3, duration 45 seconds
TIME: 2335
END          Remo_wall_tiles, round # 1 tunnel 4
START       Debris_wall_tiles, round 1, tunnel 4, duration 50 seconds
TIME: 2343
END          Debris_wall_tiles, round # 1 tunnel 3
START       Advance_round , round 1, tunnel 3, duration 0 seconds
END          Advance_round , round # 1 tunnel 3
Tunnel 3 Round # 2 specified as method # 0
START       Decision , round 1, tunnel 3, duration 0 seconds
END          Decision , round # 1 tunnel 3
Tunnel 3 Round 1 Complete at Time 2343
TIME: 2385
END          Debris_wall_tiles, round # 1 tunnel 4
START       Advance_round , round 1, tunnel 4, duration 0 seconds
END          Advance_round , round # 1 tunnel 4
Tunnel 4 Round # 2 specified as method # 0
START       Decision , round 1, tunnel 4, duration 0 seconds
END          Decision , round # 1 tunnel 4
Tunnel 4 Round 1 Complete at Time 2385
TIME: 2411
END          Remo_floor_tiles, round # 1 tunnel 6
START       Debris_floor_tiles, round 1, tunnel 6, duration 45 seconds
TIME: 2456
END          Debris_floor_tiles, round # 1 tunnel 6
START       Remo_duct_roof, round 1, tunnel 6, duration 225 seconds
TIME: 2535
END          Wall_demo, round # 1 tunnel 5
START       Debris_wall, round 1, tunnel 5, duration 450 seconds
TIME: 2681
END          Remo_duct_roof, round # 1 tunnel 6
START       Remo_wall_tiles, round 1, tunnel 6, duration 55 seconds
START       Single_shwr_roof, round 1, tunnel 6, duration 30 seconds
TIME: 2711
END          Single_shwr_roof, round # 1 tunnel 6
TIME: 2736
END          Remo_wall_tiles, round # 1 tunnel 6
START       Debris_wall_roof_t, round 1, tunnel 6, duration 28 seconds
TIME: 2764
END          Debris_wall_roof_t, round # 1 tunnel 6
START       Advance_round , round 1, tunnel 6, duration 0 seconds
END          Advance_round , round # 1 tunnel 6
Tunnel 6 Round # 2 specified as method # 0
START       Decision , round 1, tunnel 6, duration 0 seconds
END          Decision , round # 1 tunnel 6
Tunnel 6 Round 1 Complete at Time 2764
TIME: 2985

```

```

END          Debris_wall, round # 1 tunnel 5
START       Pipes_demo, round 1, tunnel 5, duration 110 seconds
START       Remo_duct_roof, round 1, tunnel 5, duration 235 seconds
TIME: 3095
END          Pipes_demo, round # 1 tunnel 5
START       Remo_wall_tiles, round 1, tunnel 5, duration 95 seconds
START       Single_shwr_roof, round 1, tunnel 5, duration 35 seconds
TIME: 3130
END          Single_shwr_roof, round # 1 tunnel 5
TIME: 3190
END          Remo_wall_tiles, round # 1 tunnel 5
START       Debris_wall_roof_t, round 1, tunnel 5, duration 55 seconds
TIME: 3220
END          Remo_duct_roof, round # 1 tunnel 5
TIME: 3245
END          Debris_wall_roof_t, round # 1 tunnel 5
START       Advance_round , round 1, tunnel 5, duration 0 seconds
END          Advance_round , round # 1 tunnel 5
Tunnel 5 Round # 2 specified as method # 0
START       Decision , round 1, tunnel 5, duration 0 seconds
END          Decision , round # 1 tunnel 5
Tunnel 5 Round 1 Complete at Time 3245
    
```

C.3.2 THE ROUND-WISE OUTPUT FILE

SIMULATION STATISTICS

*****TUNNEL 1 *****

Segment 1 Ground Class 1 Method Type 1

```

Method                1
Round                  1
Round Length(ft|m)    36.0
Round Loc. (End)-ft|m 36.0
Elapsed Time(minutes) 1771
Net Elapsed Time      1771
Waiting for Blasting  NA
Head / Bench Deferred NA
    
```

ACTIVITY DURATIONS (minutes):

```

Remo_mirrors          15
Save_toilet_partit    265
Remo_shwr_fixtures    135
Remo_drop_ceiling     75
Temp_lights           20
    
```

Disc_sink_pipes	25
Remo_toilets	20
Remo_sinks	28
Debris_drop_ceilin	45
Install_sheet	120
Install_HEPA	10
Install_DECOM	40
Wall_opening	35
Inspect_debris	15
Remo_asbestos	45
Air_test	180
Remo_sheet	10
Uninst_HEPA	6
Uninst_DECOM	8
Shwr_walls_demo	60
Wall_demo	265
Shwr_roof_demo	95
Debris_wall	305
Remo_floor_tiles	90
Debris_floor_tiles	18
Single_shwr_roof	45
Remo_wall_tiles	55
Debris_wall_tiles	35
Pipes_demo	155
Remo_duct	62
Decision	0
Advance_round	0

*****TUNNEL 3 *****

Segment 1 Ground Class 1 Method Type 3

Method	1
Round	1
Round Length(ft m)	36.0
Round Loc. (End)-ft m	0.0
Elapsed Time(minutes)	1863
Net Elapsed Time	1863
Waiting for Blasting	NA
Head / Bench Deferred	NA

ACTIVITY DURATIONS (minutes):

Remo_mirrors	11
Remo_shwr_fixtures	115
Remo_drop_ceiling	65
Temp_lights	35
Disc_sink_pipes	20
Remo_toilets	25
Remo_sinks	45
Debris_drop_ceilin	25
Install_sheet	80

Install_HEPA	10
Install_DECOM	40
Wall_opening	60
Inspect_debris	12
Remo_asbestos	110
Air_test	180
Remo_sheet	10
Uninst_HEPA	6
Uninst_DECOM	8
Shwr_walls_demo	90
Wall_demo	60
Shwr_roof_demo	105
Debris_wall	235
Remo_floor_tiles	80
Debris_floor_tiles	30
Single_shwr_roof	36
Remo_wall_tiles	100
Debris_wall_tiles	45
Pipes_demo	60
Remo_duct	115
Remo_toilet_partit	10
Debris_shwr_roof	120
Debris_wall_openin	170
Decision	0
Advance_round	0

*****TUNNEL 4 *****

Segment 1 Ground Class 1 Method Type 4

Method	1
Round	1
Round Length(ft m)	36.0
Round Loc. (End)-ft m	36.0
Elapsed Time(minutes)	1905
Net Elapsed Time	1905
Waiting for Blasting	NA
Head / Bench Deferred	NA

ACTIVITY DURATIONS (minutes):

Remo_mirrors	12
Remo_shwr_fixtures	90
Remo_drop_ceiling	45
Temp_lights	30
Disc_sink_pipes	0
Remo_toilets	10
Remo_sinks	25
Debris_drop_ceilin	20
Install_sheet	110
Install_HEPA	15
Install_DECOM	90

Wall_opening	60
Inspect_debris	8
Remo_asbestos	175
Air_test	180
Remo_sheet	10
Uninst_HEPA	6
Uninst_DECOM	9
Shwr_walls_demo	150
Wall_demo	45
Shwr_roof_demo	80
Debris_wall	450
Remo_floor_tiles	150
Debris_floor_tiles	45
Single_shwr_roof	55
Remo_wall_tiles	65
Debris_wall_tiles	50
Pipes_demo	100
Remo_duct	40
Remo_toilet_partit	15
Debris_shwr_roof_w	35
Decision	0
Advance_round	0

*****TUNNEL 6*****

Segment 1 Ground Class 1 Method Type 6

Method	1
Round	1
Round Length(ft m)	36.0
Round Loc. (End)-ft m	36.0
Elapsed Time(minutes)	1804
Net Elapsed Time	1804
Waiting for Blasting	NA
Head / Bench Deferred	NA

ACTIVITY DURATIONS (minutes):

Remo_mirrors	10
Remo_shwr_fixtures	85
Remo_drop_ceiling	90
Temp_lights	35
Disc_sink_pipes	0
Remo_toilets	8
Remo_sinks	16
Debris_drop_ceilin	25
Install_sheet	110
Install_HEPA	15
Install_DECOM	90
Wall_opening	25
Inspect_debris	7
Remo_asbestos	85

Air_test	180
Remo_sheet	20
Uninst_HEPA	6
Uninst_DECOM	14
Shwr_walls_demo	140
Wall_demo	80
Shwr_roof_demo	85
Debris_wall	355
Remo_floor_tiles	120
Debris_floor_tiles	45
Single_shwr_roof	30
Remo_wall_tiles	55
Pipes_demo	135
Remo_duct	40
Remo_toilet_partit	10
Remo_duct_roof	225
Debris_wall_roof_t	28
Decision	0
Advance_round	0

*****TUNNEL 2 *****

Segment 1 Ground Class 1 Method Type 2

Method	1
Round	1
Round Length(ft m)	36.0
Round Loc. (End)-ft m	36.0
Elapsed Time(minutes)	1556
Net Elapsed Time	1556
Waiting for Blasting	NA
Head / Bench Deferred	NA

ACTIVITY DURATIONS (minutes):

Remo_mirrors	15
Save_toilet_partit	255
Remo_shwr_fixtures	105
Remo_drop_ceiling	35
Temp_lights	20
Disc_sink_pipes	10
Remo_toilets	35
Remo_sinks	25
Debris_drop_ceilin	65
Install_sheet	135
Install_HEPA	10
Install_DECOM	45
Wall_opening	65
Inspect_debris	18
Remo_asbestos	60
Air_test	180
Remo_sheet	15

Uninst_HEPA	6
Uninst_DECOM	12
Shwr_walls_demo	95
Wall_demo	112
Shwr_roof_demo	125
Debris_wall	220
Remo_floor_tiles	90
Debris_floor_tiles	18
Single_shwr_roof	36
Remo_wall_tiles	45
Debris_wall_tiles	28
Pipes_demo	85
Remo_duct	15
Decision	0
Advance_round	0

*****TUNNEL 5*****

Segment 1 Ground Class 1 Method Type 5

Method	1
Round	1
Round Length(ft m)	36.0
Round Loc. (End)-ft m	0.0
Elapsed Time(minutes)	2285
Net Elapsed Time	2285
Waiting for Blasting	NA
Head / Bench Deferred	NA

ACTIVITY DURATIONS (minutes):

Remo_mirrors	10
Remo_shwr_fixtures	95
Remo_drop_ceiling	40
Temp_lights	95
Disc_sink_pipes	0
Remo_toilets	15
Remo_sinks	20
Debris_drop_ceilin	25
Install_sheet	155
Install_HEPA	15
Install_DECOM	40
Wall_opening	115
Inspect_debris	12
Remo_asbestos	110
Air_test	180
Remo_sheet	18
Uninst_HEPA	8
Uninst_DECOM	14
Shwr_walls_demo	70
Wall_demo	420
Shwr_roof_demo	75

Debris_wall	450
Remo_floor_tiles	70
Debris_floor_tiles	25
Single_shwr_roof	35
Remo_wall_tiles	95
Pipes_demo	110
Remo_duct	25
Remo_toilet_partit	45
Remo_duct_roof	235
Debris_wall_roof_t	55
Decision	0
Advance_round	0

C.3.3 THE TUNNEL INFORMATION OUTPUT FILE

Run No. 1049 Simulation No. 1 14-01-1999 13:15:38

Tu Nr	Ar Nr	Gm Tp	Beg-X [ft]	End-X [ft]	Length [ft]	Beg-T [hr]	End-T [hr]	Duratn. [hr]	Idle-T [hr]	Ad.Rt [m/d]	Cost [MF]	cost/m [KFr/m]
1	1	1	0	36	36	0.0	29.5	29.5	0.0	1.22	0	0.0
2	1	1	0	36	36	0.0	51.9	51.9	0.0	0.69	0	0.0
3	1	1	0	36	36	8.0	39.0	31.1	0.0	1.16	0	0.0
4	1	1	0	36	36	8.0	39.8	31.8	0.0	1.13	0	0.0
5	1	1	0	36	36	16.0	54.1	38.1	0.0	0.95	0	0.0
6	1	1	0	36	36	16.0	46.1	30.1	0.0	1.20	0	0.0
Total Time :			54.08 hrs.									
Total Cost :			0.00 M.									