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**The Impact of Continuous Resource Utilization on Cost and
Duration of Projects with Repetitive Activities Using Simulation**

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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

وَيَسْأَلُونَكَ عَنِ الرُّوحِ قُلِ الرُّوحُ مِنْ أَمْرِ رَبِّي
وَمَا أُوتِيتُمْ مِنَ الْعِلْمِ إِلَّا قَلِيلًا

الإسراء (آية 85)

إلى جدِّي الغالي
السيد الحاج سلمان حسين الحلو ... أبو ناصر
بَارِك اللهُ فِي عُمُرِهِ وَصَالِحِ أَعْمَالِهِ

To my Dear Grandfather

Mr . Had j Salman Hussain Al Helou ... Abu Nasser

May Allah Bless his Life and Good

Deeds

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Abstract

Repetitive activities projects, such as infrastructure projects, multi story buildings, or house development, have a considerable economic standing in construction industry. The repetitive nature of these projects makes them more sensitive toward the utilization of resources, which has a direct influence on the project costs and duration. Many previous studies proved that conventional planning approaches that are commonly used, are not qualified to present the optimum resources plan for this type of projects.

This research adopts the simulation technique as a tool to enhance the resources planning process in the repetitive activities projects. Firstly, the application of simulation technique to plan a construction project was theoretically formulated in the "conceptual simulation model". Next, a typical simulation model was especially developed for infrastructure projects that includes the basic activities and their logical relationships. The model was designed to incorporate a great amount of production and cost data of the used resources, and to handle the input data particularly according such statistical approaches. The structure of this model allows a high level of overlapping between the executed activities through having eight possible scenarios for each project. In order to have a minimum user interpose during the activation of the simulation process, the model was formulated to be a general template for infrastructure projects, and have a flexible content of modules that is possible to be adjusted. The preliminary simulation process outputs are possible to be refined. The user can experiment a large number of execution scenarios, which could be automatically optimized when some related variables are specified. A case study was applied using both "Critical Path Method" as a commonly used planning approach, and the developed simulation model. The outputs quality, and the application methodology and environment, of that comparison indicated a considerable advantage for the simulation model. Besides remedying the planning deficiencies of the conventional planning approaches that applied for projects with repetitive activities, the simulation technique is able to empower the planner to be fully aware with the used resources and all of their related features during the project, just like the execution environment.

ملخص البحث

تمتلك المشاريع الإنشائية ذات الأنشطة المتكررة، كمشاريع البنية التحتية، المباني متعددة الطوابق، أو مشاريع التنمية الإسكانية، مكانة اقتصادية مهمة في صناعة الإنشاءات. الطبيعة التكرارية لتلك المشاريع تجعلها أكثر حساسية تجاه قضية استغلال الموارد، والتي تمتلك التأثير المباشر على تكاليف و زمن المشروع. العديد من الدراسات السابقة أثبت أن طرق التخطيط التقليدية الشائعة الاستخدام لم تكن مؤهلة كي تقدم الخطة النموذجية للموارد في هذا النوع من المشاريع. هذا البحث يتبنى تقنية المحاكاة كأداة لتحسين عملية تخطيط الموارد في المشاريع ذات الأنشطة المتكررة. في البداية، تم صياغة تطبيق تقنية المحاكاة نظريا على مشاريع الإنشاءات في "نموذج المحاكاة النظري". بعد ذلك تم تطوير نموذج محاكاة عملي خاص بمشاريع البنية التحتية، و يتضمن جميع الأنشطة الأساسية و روابطها المنطقية. و قد تم تصميم هذا النموذج لاستيعاب أكبر كم من المعلومات عن إنتاجية و تكاليف الموارد المستخدمة، حيث يتناول المعلومات المدخلة بشكل مفصل و تبعا لأساليب إحصائية. هيكلية هذا النموذج تسمح بمستوى عال من التداخل بين الأنشطة في حالة التنفيذ، و ذلك من خلال احتواء النموذج على ثماني سيناريوهات محتملة لتنفيذ المشروع. و من أجل الحصول على أقل تدخل للمستخدم في تفعيل عملية المحاكاة، تم هيكلة النموذج ليكون قابلا عاما لمشاريع البنية التحتية، بالإضافة إلى أن محتوى هذا النموذج يتمتع بالمرونة الكافية لتعديل أي من مركباته. كافة تفاصيل النتائج الأولية لعملية المحاكاة قابلة للتحسين، حيث يتاح للمستخدم تجريب عدد كبير من الاحتمالات التنفيذية، و التي يمكن الحصول على الحل النموذجي منها بشكل تلقائي بمجرد تعريف بعض المتغيرات. تم تطبيق حالة دراسة على كل من: طريقة المسار الحرج الشائعة الاستخدام، و نموذج المحاكاة. جودة النتائج، و طريقة و بيئة التطبيق المتعلقة بحالة الدراسة أعطت الأفضلية بشكل ملحوظ لنموذج المحاكاة. فإلى جانب معالجة الخلل التخطيطي لطرق التخطيط التقليدية المستخدمة في المشاريع ذات الأنشطة المتكررة، تعمل تقنية المحاكاة على جعل المستخدم واعيا بكل ما يتعلق بموضوع الموارد و كأنه في موقع التنفيذ.

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1 INTRODUCTION

It is an intuitive matter to consider resources in construction operations as a crucial element. This level of importance came from the essential contribution to determine the project cost and duration.

Construction industry stakeholders do their best to get the maximum value of the projects' manpower and equipment efficiencies. In addition of achieving the previous aim, they have to integrate it with the other contractual constraints, such as projects' schedule and budget.

Utilizing construction resources is dependent on the project schedule. Scheduler, a main responsible, has to eliminate time and space interruptions, and to minimize resources idleness as much as possible. Achieving this objective mainly depends on the scheduling environment, the planner skills and the project type.

1.1 Scheduling Repetitive Activities Projects

Repetitive activities are found commonly in the construction of multi-story buildings, pipelines, highways, and housing development projects. For such projects, similar activities are repetitively performed from unit to unit.

Projects with repetitive activities are very sensitive toward the resources issues. Its repetitive nature may complicate the time-space constraints, and the resources' idleness. Having resources work continuously has long been the goal for scheduling repetitive projects. Waste in repetitive projects is observed when labor and equipment is waiting, being idle, because the preceding resources have not finished their jobs, (Yang and Ioannou, 2001).

The scheduling problem posted by repetitive activities projects which is the minimization of the project duration subject to continuous resource utilization from unit to unit as well as the technical constraints between activities. The problem of achieving continuous resource utilization is not directly addressed by the traditional scheduling methods, (Yang, 2002).

Conventional network scheduling is advantageous when the project has discrete activities that do not repeat, but it is very difficult to understand if there are a large number of segments. It also has been criticized because it does not show enough technological and organizational connections between activities, (Ragolia, 1998).

Other scheduling methods, which are specialized in repetitive activities projects, succeeded in solving the problem of showing the technological and organizational constraints, and guaranteed an acceptable level of resources utilization, (Ragolia, 1998). However, it caused some problems for the scheduler due to its "pull driven concept". It increases the number of the critical activities, and decreases the floats of many activities.

1.2 Research Gap

Repetitive activities projects are the most common construction projects in any construction sector. From this perspective, their resources utilization or waste has a noticeable impact on the construction economy.

Traditional scheduling methods, that are widely used, mainly concentrates on getting the best schedule within time constraints and logical relationships, with a less priority for the resources utilization issue, and this could be considered as the main drawback of such methods when applying them to plan a project with repetitive activities. The sensitive nature of this type of projects towards resources interactions could make the traditional methods of scheduling non effective in the execution environment.

Although, some scheduling trends have more specialized and effective performance in repetitive activities projects that succeeded to remedy some of the traditional scheduling methods' deficiencies, they still suffer from some valuable risks regarding the duration of an activity, and even the entire project. Moreover, its demonstration of resources issues and interactions is very simple, while it is more complicated in the real life.

A real life construction project has a complex cycle of relationships and dependencies, so it has to be handled through a more detailed environment. For instance, being away from using the probabilistic approach for the input data is considered as a shared drawback for the used scheduling methods in handling the repetitive activities projects.

1.3 Simulation Technique

The research proposes the simulation technique as a tool to cover and remedy the mentioned gaps in handling the project's possible complexities. Simulation is expected to integrate the best outputs from the previous mentioned issues that relate to resources' utilization in repetitive activities projects.

The use of simulation utilities (such as probability and resource complexities options) in handling the resource utilization issue is expected to make the research output helpful for all parties in a construction project. Planners can get the optimum and cost effective schedule, contractors will have the maximum utilization value and the best allocation for resources.

Simulation is considered as one of the most new alternatives for project planning and scheduling. Besides its clear interface, it has several useful options for the planner.

Nowadays, simulation software are widely used in many purposes such as: military, manufacturing, traffic, ...etc. The complicated computation abilities of simulation technique has qualified it to develop specialized software for construction processes. It can schedule construction projects in more complicated environments regarding data, capacities and allocation of resources, and provides the probabilistic approach for the used data. Moreover, some modern packages has a helpful interface, accessories, simple and clear data input forms, and detailed reports and statistics.

1.4 Research Objectives

The research has two main objectives: First, to present the simulation technique as a tool to plan projects with repetitive activities, and to control the utilization of the used resources in the planning phase.

The second objective is to demonstrate the resource utilization effect on cost and duration of projects with repetitive activities through simulating a real life case, in order to get the optimum plan of such case.

LIST OF THE USED ABBREVIATIONS

RAP	Repetitive Activities Project.
CPM	Critical Path Method.
PERT	Program Evaluation and Review Technique.
PDM	Precedence Diagramming Method.
GERT	Generalized "Program Evaluation and Review Technique".
Q-GERT	The simulation package of "GERT" for large scale projects.
PNET	Probabilistic Network Evaluation Technique.
LSM	Linear Scheduling Method.
RSM	Repetitive Scheduling Method.
LOB	Line of Balance Scheduling Technique
TPN	Timed Petri Net.
DTPN	Deterministic Timed Petri Net.
STPN	Stochastic Timed Petri Net.
GSPN	Generalized Stochastic Petri Net.
DSM	Design Structure Matrix.
Stroboscope	STate and ResOurce Based Simulation of CONstruction ProcEsses.

2 LITERATURE REVIEW

2.1 Introduction

This chapter reviews the available literature that is related to Repetitive Activities Projects RAPs from several perspectives. First, it demonstrates the nature of repetitive activities projects. Afterward it will discuss the previous studies regarding scheduling methods and their limitations. Finally, this chapter presents the simulation technique as a tool to remedy the deficiencies of the conventional scheduling methods in handling RAPs.

2.2 Repetitive Activities Projects

2.2.1 RAP Categories

According to Yang and Ioannou (2001), repetitive activities projects were classified according to progress units into two categories: discrete RAPs and continuous RAPs. A discrete RAP has been described as discrete entities progress units, which may be floors for multi-story buildings, houses for housing development projects, etc. Despite the repetition of the project's units, the work quantities for an activity may not be the same in all units, besides, activities do not necessarily start at the same location or follow the same sequence. Project's technological constraints controls activities in terms of scheduling relationships; some activities have to start from lower level and proceed upwards, and some can start anywhere.

The Second category which was addressed by Yang and Ioannou, (2001) is called "continuous repetitive activities projects". Their progress is often plotted horizontally. They are found where progress is expressed in terms of meters, stations, or miles for highways, pipelines, tunnels, etc.

Planning decisions in continuous RAP are to determine when and where activities should start so as to minimize disturbance. Activities in continuous RAP are not necessarily present at all locations. Besides, they may not start and finish at the same location.

2.2.2 RAP Resource Utilization

Maintaining work continuity leads to maximize the learning curve effect and minimize the idle time of work crews. The application of traditional scheduling techniques to RAP has been criticized in the literature for their inability to achieve these aims. Despite the apparent advantages of maintaining crew work continuity, its strict application may increase the overall project duration. It has been suggested that work interruptions might solve the project duration problem. However, Some modern applications and techniques attempt to minimize the duration. These techniques require planners to specify, prior to scheduling, a set of interruption "vectors" for each crew formation in the project. Besides being a considerable challenge, specifying interruption vectors does not guarantee the optimum solution of the project schedule, (El-Rayes and Moselhi, 2001). The modern automation techniques, such as simulation, are expected to cover these planning gaps.

2.2.3 RAP Scheduling Requirements

Yang and Ioannou, (2001) evaluated the scheduling system for a RAP through its ability to eliminate idle time, provide the computational ability, and handle the real-life requirements. The following consideration should have been taken into account to schedule RAPs, (Figure 2.1):

- § Yang and Ioannou, (2001) stated that resources may have variable production rates, sizes and compositions at different work locations.
- § An activity may utilize multiple crews simultaneously, and one crew may perform multiple activities.
- § Activities may have multiple predecessors and successors.
- § The construction process (a set of activities and relationships) need not be the same at every work location.
- § One activity may link to another activity at non-contiguous locations.

§ Ragolia, (1998) referred to "lag" as a useful criteria for an activity and even for whole project. Some activities, depending on their nature, may need a minimum lag time between other activities to successfully and safely complete the construction process. Yang and Ioannou, (2001) indicated that activities may require time-buffer (lead-time) in addition to space-buffer (lead-distance).

§ Not all construction activities have to move continuously through the project. Many activities have certain advantages if they are split over the life of the project, (Ragolia, 1998). It means that work interruption should be allowed if desired, (Yang and Ioannou, 2001).

§ Ragolia, (1998) believed that activity overlap is an important criteria due to its contribution to shorten the overall project duration. Such criterion handle the ability of more than one activity to occupy the same unit at the same time. These criterion are function of the construction process, available work space and safety issues.

§ The non-repetitive portion of project work should be incorporated into the framework of repetitive scheduling, (Yang and Ioannou, 2001).

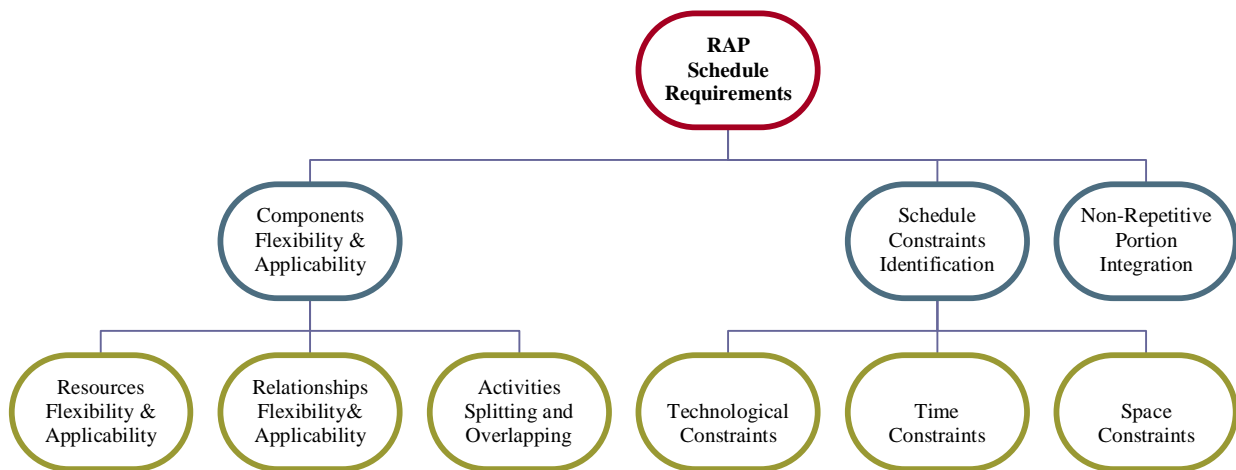


Figure 2.1: RAP Schedule Requirements Summary

2.3 Scheduling Methods

A schedule consists of a series of work tasks that are linked to each other in a logical manner. Schedule development requires a project network to be constructed showing the technological and managerial constraints amongst work tasks, (Sawhney, 1997). Harris et al, (1998) have defined the main challenge of scheduling RAPs as: getting the optimum project duration subject to resource continuity constraints as well as technical precedence constraints. The following sections numerates the common used methodologies of scheduling RAPs, and demonstrates their advantages and drawbacks.

2.3.1 Push-Driven Approach

In order to avoid delaying successors, activities are expected to start at their earliest possible date. Tommelein, (1997) stated that "Push Driven Approach" is based on the assumption that all required resources to perform an activity will be available at its early start time. While it may be possible to start work with an incomplete set of resources, this will negatively affect productivity. Because of the sudden appearance of the uncertainties during process execution, remedial actions must be decided on in real time. At that point, rigorously adhering to the initial schedule may not be the best approach for successful project completion. Yang and Ioannou, (2001) criticized the push-system approach due to its inability to ensure the continuous utilization of resources. To remedy this issue, work continuity must also pull preceding activities or segments to eliminate gaps.

2.3.2 Network Scheduling

A very common form of representation used by the construction industry is the network based methods such as Critical Path Method CPM, Program Evaluation and Review Technique PERT, and Precedence Diagramming Method PDM. These tools provide a means of obtaining a time schedule for the various work tasks associated with a construction project, (Sawhney, 1997)

Cho, (2001) has introduced the GERT network as a generalized PERT network, a CPM approach, that allows probabilistic routing and feedback loops, and Q-GERT is its simulation package for large-scale projects.

While Sawhney, (1997) talked about a developed technique called: Probabilistic Network Evaluation Technique PNET; this technique applies probability theory to reduce the number of possible critical paths and evaluates the expected project duration based on representative paths in the network.

Yi et al, (2002) implied that the project activities can be generated by dividing the continuous process of construction into a set of discrete elements. Among the elements of a construction project, several resources can be regarded as discrete. In a RAP, the units or sections, can also be considered to be discrete. Even after the activities have been defined, it is possible to draw a different logic for the same set of activities. The project completion time can be changed, not only by crashing activities on the critical path, but also by changing the logical relationships of the activities.

The critique of Sawhney, (1997) started from network techniques origin. It has been inherited from the aerospace and manufacturing industry with disregard to the nature of the construction projects. Such techniques have limited modeling adaptability and ineffective to model a system that has a dynamic and stochastic environment such as a construction project.

2.3.3 Critical Path Method CPM

The Critical Path Method CPM approach has been widely acknowledged as industry standard technique for project management for the past fifty years. In the network-based models such as the CPM, a project network is usually built by identifying precedence relationships among the tasks that are close to one another in a sequence from experience, (Cho, 2001). In construction projects, the process of planning, scheduling, and control is typically accomplished using the CPM. One of the reasons why CPM is still the most popular and practical scheduling method is because it permits both manual practice and computerized applications. A number of versions of this technique have been developed and were used as the basis for many of the popular project management software packages, (Mendes and Heineck, 1998). CPM uses a network diagram, which shows the sequence of work, interdependencies, and interrelationships among project activities.

CPM employs a network analysis method, involving forward and backward pass computation, which logically defines the critical path and performs scheduling to define the scheduled dates of a project and its activities. In order to successfully construct a network diagram, a construction project, which is a continuous process, must be converted to a set of discrete events, (Yi et al, 2002) .

Yang and Ioannou, (2001) clarified that CPM negative aspects came from the perspective of lean production philosophy, which aims to avoid waste. CPM has been attacked for its inability to model non-value adding activities (idleness), such as waiting, inspecting, and moving. When CPM is applied to schedule repetitive projects, the early start schedule may not be optimal because floats attached to repeating activities represent significant amount of waste. CPM possesses various deficiencies in scheduling repetitive projects such as cumbersome repetition of similar activities and relationships, and the negligence of important production information, such as production rate and work location.

Harris and Ioannou, (1998) mentioned that the use of typical CPM scheduling techniques cannot ensure this continuity in resource utilization because it cannot deal with the resource continuity constraint. Harris et al, (1998) agreed that the problem of uninterrupted deployment of resources was not addressed by the critical path method CPM, nor by its resource-oriented extensions, such as time-cost trade-off, limited resource allocation, and resource leveling.

Mendes and Heineck, (1998) stated that the more complex becomes the project the more complex it will be this CPM network approach. Other important disadvantage relies on the main idea of the CPM which is the concentration on finding the path which is critical. The emphasis is on project duration shortage and resource leveling.

The fact of having a "critical path" implies having non critical ones, which have float time. It means that the planning construction incorporates wastes what significantly diverts from a modern construction philosophy. Cho, (2001) added to the previous drawbacks that these basic techniques are not suitable for managing complex engineering projects due to their limited analytical capabilities.

2.3.4 Pull-Driven Approach

The pull-system approach is pulling activities and/or activity segments to later start times so that unforced idleness can be eliminated, (Yang and Ioannou, 2001). To implement a pull technique, selective control is needed to draw resources for any given activity. This selection is driven by information not only about resources in the queues immediately preceding such activity, but also about work-in-progress and successor activities' resources. Resources get priority over others if they are known to match up with resources already available in queues further downstream in the process. As a result, those available resources will not improperly wait their match, but they can be in process for any time not longer than needed, (Tommelein, 1997).

2.3.5 Linear Scheduling Method LSM

Mendes and Heineck, (1998) defined the family of linear scheduling techniques as techniques that have been developed to schedule RAPs. Ericsson, (2001) mentioned that linear scheduling methods LSM, have been widely used as analytical techniques for planning, scheduling, and optimizing construction operations.

Ragolia, (1998) proposed the linear scheduling, a pull-driven methodology, as the clearest way to show the construction process on projects that have a repetitive nature. A time-space scheduling or linear schedule is useful because it clearly shows the connections of activities, their duration, and the space where they take place at a given time. Harmelink and Bernal, (1998) concentrated on the visual aspect advantage of the linear scheduling techniques as a useful tool to facilitate schedule control.

The major critique that implied by Ericsson, (2001) to LSM method was the lack of its capability to cope with random and dynamic factors.

2.3.6 Repetitive Scheduling Method RSM

Harris et al, (1998) posed the Repetitive Scheduling Method RSM as one of the linear scheduling techniques that ensures continuous resource utilization and is applicable to both vertical and horizontal RAPs. Two new concepts emerge from the development of RSM: control points and the controlling sequence.

RSM is not a complicated technique, it is easily applied scheduling methodology that follows naturally from the concepts and relationships found in CPM precedence networks. Harris and Ioannou, (1998) described the Repetitive Scheduling Method RSM graphically as an X-Y plot of unit production, One axis of the plot represents units and the other time. Ragolia, (1998) distinguished RSM with having technical constraints as well as resource constraints. A technical constraint basically means that the logic must be the same in each unit and the activities flow through the units in the same pattern. A resource constraint states that the same resource be assigned to the same activity. Figure 2.2 demonstrates a typical RSM schedule.

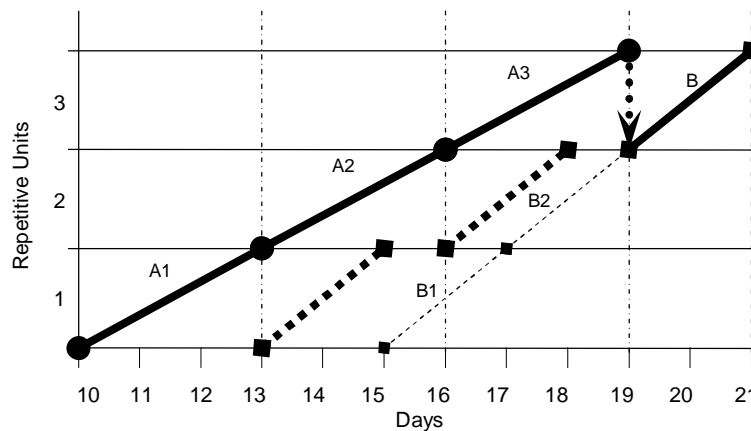


Figure 2.2: RSM schedule for a repetitive activities project, (Harris and Ioannou, 1998)

2.3.7 Line of Balance LOB

Ragolia, (1998) stated that the line of balance technique can be used for planning, scheduling and controlling repetitive construction projects. Such technique is considered important because it has similar inputs (unit network and progress completion chart) which are usually represented graphically.

Mendes and Heineck, (1998) considered the Line of Balance LOB technique, which was developed in the early 40's, and adapted for using on construction industry in the 70's, as a production scheduling and control technique which tries to surpass the CPM difficulties for RAP scheduling.

The main concept on the line of balance is the work continuity of the labor teams over the construction units. The labor teams work with "Rhythmic Production", and no wastes are willingly planned or introduced into the schedule. In order to find the optimum use of resources, crews and equipment are designed to yield the same production rate "Rhythmic Production", in terms of construction units. If activities are planned to be built in this way, all activities could become critical. Thus, an "all activities critical" planning might not be applicable for the whole project. Figure 2.3 summarizes the main characteristics of LOB.

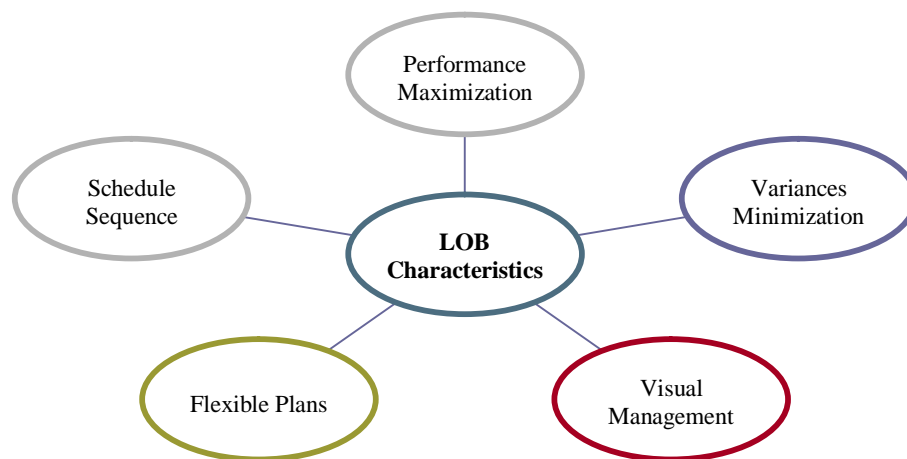


Figure 2.3: LOB Scheduling Characteristics

2.3.8 Petri Nets

Sawhney, (1997) developed the Petri Nets as a hybrid scheduling system, consisted of graphical and mathematical modeling tools that can be used to perform static and dynamic analysis. A Petri Nets system has inserted the following concepts during the scheduling phase:

- § Hierarchical decomposition of the project.
- § Incorporation of risk and uncertainty in the activity time and cost estimates.
- § Modeling of dynamically allocated resources.

A Petri Net is illustrated as: weighted, bipartite graph consisting of the elements shown in Table 2.1. A typical CPM network and its equivalent Petri net based network are also shown by Figure 2.4a and 2.4b respectively.

Table 2.1 Modeling Elements of Petri Nets.

Element	Symbol	Function
Place	○	Represents a condition such as input data, input signal, resource, condition, or buffer.
Transition	■	Represents an event such as a computation step, task, or activity.
Token	●	Provide necessary dynamic links between the places (conditions) and transitions (tasks or events).
Arc	\xrightarrow{k}	Utilized to connect places and transitions in a Petri Net. Multiplicity of an input arc, represented by an integer (k) dictates the number of tokens required to fire or enable a transition.

Source: (Sawhney, 1997)

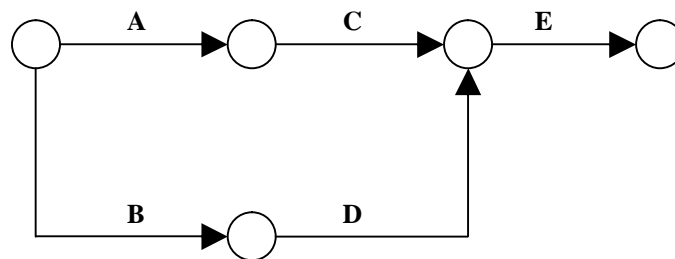


Figure 2.4a: CPM Based Project Network

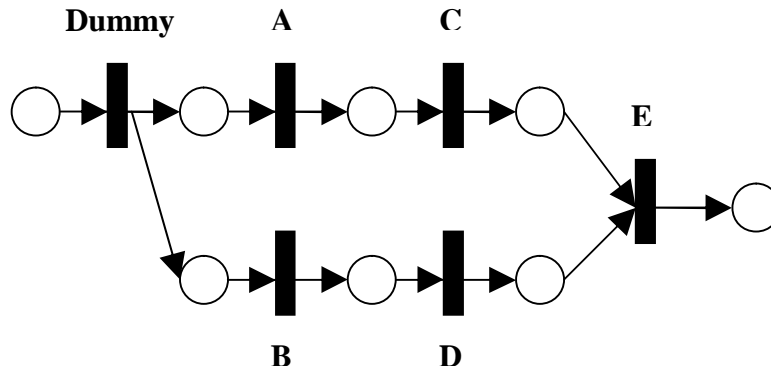


Figure 2.4b: Petri Net Based Project Network, (Sawhney, 1997)

Sawhney, (1997) has defined the Timed Petri Net TPN as: incorporating time by introducing a delay after a transition is enabled. If the transition times are deterministic, the Petri Net is called a Deterministic Timed Petri Net DTPN, and if the transition times are allowed to be random variables, then it is called a Stochastic Timed Petri Net STPN. A Petri Net that contains immediate transitions, deterministic transitions, and stochastic transitions is called a Generalized Stochastic Petri Net GSPN.

2.3.9 Dynamic Programming

El-Rayes and Moselhi, (2001) developed an automated scheduling model for optimizing resource utilization for RAPs. The model is based on a dynamic programming formulation, designed to identify an optimum crew formation and interruption option for each activity in the project that leads to minimum project duration. Such model consists of a scheduling algorithm and an interruption algorithm. Figure 2.5 illustrates the functions of both scheduling and interruption algorithms. However, the current method has proposed a valuable tool to handle resources planning, it could be considered as a discrete technique, due to be consisted of two separate algorithms. Besides, such trend is so hard to be a common application because of the learning challenge of the used programming languages. The simulation technique is expected to be credible to be learned, in addition of the automated plans that it could produce.

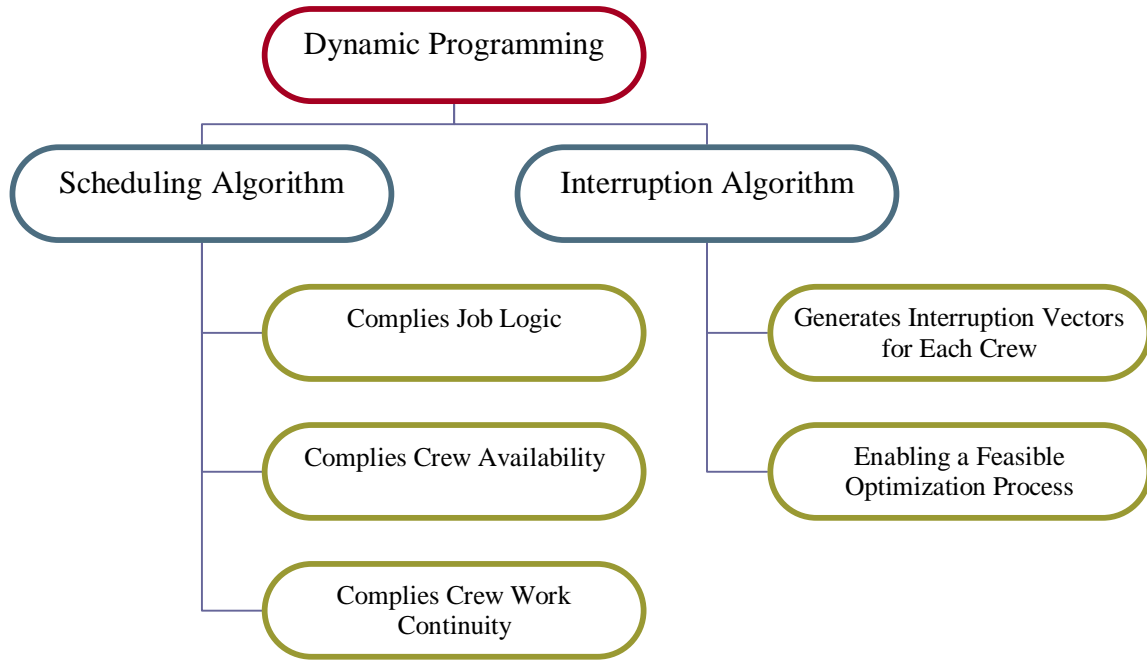


Figure 2.5: Functions of Scheduling and Interruption Algorithms

2.3.10 Design Structure Matrix DSM

Cho, (2001) mentioned that design structure matrix technique DSM has been widely applied to various manufacturing industries as a planning tool. It models the information flow of tasks, and identifies their iterative loops. It matches the traditional scheduling methods by presenting a structural view of a project in a compact square matrix. However, such method has criticized by:

- § Limited capability to develop a useful time scale (Poor time aspects).
- § Limited compatibility with the network-based scheduling methods and tools.

The basic sequence of a project planning process, (structuring, modeling, and scheduling), is shown in Table 2.2.

Table 2.2 DSM Planning Process Sequence.

	Inputs	Outputs
Structuring	<ul style="list-style-type: none"> § A list of tasks § Information flows among tasks § Information flow patterns 	<ul style="list-style-type: none"> § Design Structure Matrix § A critical dependency sequence and slack of tasks
Modeling	<ul style="list-style-type: none"> § Duration estimates of tasks § Resource requirements of tasks § Overlapping and sequential iterations § Rework risk tolerance 	<ul style="list-style-type: none"> § Probability distributions of the project durations § Resource-constrained slack § Critical Paths § Simulated Gantt charts
Scheduling	<ul style="list-style-type: none"> § Scheduled durations of tasks , chosen from the probability distribution § Due date buffer size 	<ul style="list-style-type: none"> § PERT or Gantt chart § Schedule risk that the project fails to meet the due date

Source: (Cho, 2001)

2.4 Construction Simulation

Construction process which transforms the project's resources into a utilized facility is not predictable due to its random nature. A real life construction process is always dynamic (i.e. containing time factor). However, it is sometimes simplified into a static model such as CPM representation.

While a project cannot be fully known until it has been executed, it will be considered as a stochastic model, which force planners to treat an activity duration as a random variable defined by a random distribution function.

Although a construction operation is a continuous process, the concerns are mostly when it starts and ends. The intermediate process between the two events is not the interest. Therefore, discrete models are widely used for construction simulation, (Ericsson, 2001). Figure 2.4 summarizes a real life project characteristics that the need of simulation has been resulted in.

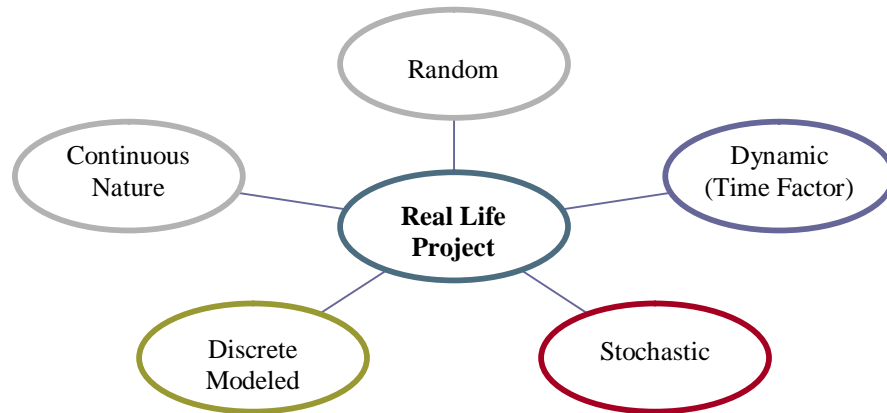


Figure 2.6: Characteristics of a Real Life Construction Project

As mentioned before, many of the scheduling packages now in use assume that construction projects are static and deterministic systems. Edward and Ahitov, (1996) talked about the use of simulation as a precursor to scheduling that covers the previous mentioned gaps in scheduling, and permits consideration of probabilistic events. Nassar et al, (2003) confirmed such concept by mentioning the ability of simulation to handle the uncertain nature of the construction project as well as the dynamic assessment of resources, movement, and allocation.

2.4.1 Simulation Technique: Concept and Advantages

As a modern technique, simulation concept was not facing any definitions' discrepancies in the literature. Shi, (2001) has generally defined simulation as a: "description or enactment of a real-life process". Lueke et al, (1999) have a more complicated definition that says simulation is "a computer-based environment built to enable a practitioner who is knowledgeable in a given domain to model a project within that domain in a manner where symbolic representations, navigation schemes within the environment, creation of model specifications and reporting are completed in a format native to the domain itself".

According to Shi, (2001), a simulation process consisting three phases: modeling the project, applying such model on the computer, and optimizing the system by improving the model performance.

As mentioned before, simulation is considered as a leading technique that has the ability and flexibility to remedy the scheduling problems and drawbacks that addressed by the traditional scheduling method. The focus adopted in the simulation, as addressed by Vargas et al, (1998), is to bring to classroom situations that we often find on field, such as: equipment and labor unproductive times, material wastes, production lack of sequence, inadequate stocks, etc.

As a stochastic tool, Oloufa et al, (1998) found that simulation modeling can provide a powerful tool for the study and analysis of construction projects, and offers a fast and inexpensive means for the study of different alternatives and approaches to a project problem. (Sawhney, 1997) pointed that simulation can provide an excellent solution to the problem of construction scheduling.

McCabe, (1998) added that simulation model is used to represent the operation and to determine the effect that changes in resource configuration have on the model performance. Similarly, Vern and Gunal, (1998) reported that simulation provides a tool to measure the benefits of implementing a productivity solution before investing in it.

Shi, (2001) handled simulation usefulness from the perspective of describing complicated processes, where the relations are difficult to define causally, or an analytic model would be too difficult to solve. And added, "simulation method can be recommended for firms engaged in construction of repetitive projects, especially large projects where sufficient funds for planning are available".

Smith and Peters, (1996) implied that simulation can be used in the main phases of a project. It is as an analysis and decision-making tool for design problems, planning problems, and operational problems.

Further, simulation has the advantage to cope with random and dynamic features essential for construction operations (Ericsson, 2001). Moreover, by synthesizing input data based on the probability distributions of actual operations, each step of an operation can be recreated. A computer can recreate each step very quickly thus allowing the simulation of lengthy and real operations, Dunlop (2000).

2.4.2 Simulation Software

The first application of simulation in construction was reported in 1963 actual applications reported significant improvement in construction productivity, (Shi, 2001). The growing number and quality of simulation software, the cost of the package, the set-up cost and the running cost and the fact that the complexity of simulation packages requires expertise for their evaluation make the selection of an appropriate simulation package a vital issue to simulation practitioners, (Nikoukaran et al, 1999).

CYCLONE is the oldest and most used general-purpose simulation tool designed specifically for construction. Its logic depends on GERT networks. There have been at least four different implementations of CYCLONE: Mainframe CYCLONE, INSIGHT, UM-CYCLONE, and Micro-CYCLONE.

RESQUE incorporates CYCLONE's conceptual and functional extensions, but the model is not limited to the information conveyed by the network. A RESQUE model also includes an overlay that defines resource distinctions and increases simulation control. The overlay provides it with significant flexibility.

COOPS is an object-oriented system that enhances CYCLONE's conceptual and functional extensions with some relaxed node precedence rules. COOPS models are defined via a graphical user interface where all resources are treated as individually identifiable objects to provide statistics from the point of view of each individual resource. In addition, COOPS allows for the generation and consolidation of resources at links and uses calendars that can be used to preempt activities during work breaks.

CIPROS is both a process level and project level planning tool. It contains an expandable knowledge base of construction techniques and methods. The resource characterization capabilities in CIPROS go beyond those in RESQUE to allow multiple real properties for resources as well as more complex resource selection schemes. CIPROS also integrates process-level and project-level planning by representing activities through process networks, all of which can use a common resource pool, (Martinez and Loannou, 1999).

Harmelink and Bernal, (1998) have defined Stroboscope as: S**T**ate and R**E**s**O**ur**C**e B**A**sed S**I**mulation of C**O**nstruction P**R**oc**E**sses, which is a general purpose simulation programming language designed to model construction operations.

Martinez et al, (1994) presented Stroboscope as a programming language for construction process simulation that provides access to the state simulation and resources properties, and allows creation of realistic models that can make utilization, consumption, and production of resources, and perform dynamic resource allocation and can make dynamic decision regarding the sequence of operations. Stroboscope is based on a network of interconnected elements and on a series of programming statements that give the elements unique behavior and control the simulation. Modeling elements of stroboscope allow simulation models to consider uncertainty for time and resources quantities.

There are two basic modeling elements used in any Stroboscope model, Nassar et al, (2003). The COMBI resembles activities that are performed during the construction operation. QUEUEs, the second element, are used to represent holding places for resources. Each COMBI must be preceded by a QUEUE and each QUEUE must be followed by a COMBI. Another modeling element used in Stroboscope models is the NORMAL which is similar to COMBIs except for the fact that they do not have to be preceded by a QUEUE. DURATION is the attribute that defines the duration of each activity they represent. These durations can be stochastic and have a wide array of probability distributions. Using this stochastic nature of the activity durations, Stroboscope is able to compute the total time required to perform a specific construction operation. In addition, a large number of programming statements offer a detailed control of the simulation.

Sadowski et al, (1998) has presented Arena as a simulation software that support a breadth of applications, scaled to fit different needs through a project life cycle, and integrated with corporate modeling and database systems. First released in 1993, Arena employs an object-oriented design for entirely graphical model development. Simulation models are built using graphical objects called modules to define system logic and physical components such as machines, operators, clerks, etc. The design of the core product engine makes Arena easy to learn and use.

New users find an inviting, familiar interface through Arena's compatibility with Microsoft Windows 95/NT, and Microsoft Office 97. The power afforded by Arena extends to its ability to integrate with other technologies, such as databases, drawing/modeling products, or spreadsheets. In order to cover the simulation learning difficulties, Arena utilize a core software engine that is designed with the following objectives: ease-of-use and rapid mastery, power for complex system modeling, modeling objects that closely fit the target systems, and built-in integration with leading applications.

With SIMAN inside, Arena develops a heritage of power simulation software in a natural, graphical interface. At the heart of Arena is the SIMAN simulation language, which provides a powerful foundation for modeling complex systems and a fast simulation engine for efficient analysis of design alternatives.

Nassar et al, (2003) added that Arena is a generic discrete event simulation language with a powerful 3D animation interface, in contrast to Stroboscope, which is a construction-oriented discrete event simulation language.

2.4.3 Simulation Limitations

Although, simulation has covered most of the traditional scheduling methods' gaps and deficiencies, literature has numerous critiques regarding it, each critique depends upon the type of the used software. Shi, (2001) reported that simulation suffers some serious drawbacks. First of all, it is difficult to use so that simulation is still treated as the last resort among various planning tools. Moreover, process-based simulation results should be integrated to a higher project level. It requires technical training to get the desired knowledge for conducting simulation. The learning process can be months or even years long. One of the major difficulties in using computer simulation involves in modeling because modeling elements are foreign to construction practitioners.

Kim and Gibson (2003) referred to the amount of time and cost that consumed to develop a simulation model, and the less user-friendly environment regarding the simulation software itself.

McCabe, (1998) has located the obstacle to the acceptance of simulation by the construction industry. It is the effort required for experimentation with the model in order to optimize it. In the same context, Arsham, (2002) criticized simulation in the design phase by the gap between simulation and optimization techniques to be effectively used. Shi, (2001) added that a simulation model can not optimize, but by performing a number of trial runs and comparing the results, an estimate of the optimum may be reached. Zhang et al, (2002) found that construction-oriented discrete-event simulation often faces the problem of defining uncertain information input, such as subjectivity in selecting probability distributions that result from insufficient or lack of site productivity data. Finally, Zhang et al, (2002) criticized the existing simulation tools by not having a dynamic resource allocation policy. Simulation set only the predefined allocation priorities or entity management strategies without considering the limitation of resources.

2.4.4 Simulation Errors

As a programming language, there has to be an area of computer errors during handling a model. Shi, (2001) numerated the types of errors of a simulation process as follows:

- § Type zero errors: occurs when the modeler asks the wrong questions. The results are that the model does totally the wrong thing, or the model does not operate in the fashion as it is intended to.
- § Type I errors: correspond to the classical statistical hypothesis testing while a valid model is wrongly rejected because there is a certain probability that an error may occur.
- § Type II errors: occur while a false model is accepted as valid because of the accuracy of the statistics.

Type zero errors are very severe and must be avoided. Type I and II errors cannot be avoided but can be limited by a given confidence level.

3 RESEARCH METHODOLOGY

3.1 Introduction

This chapter establishes the main frame of the research. It is distributed into three main sections: model formulation, model development, and model validation. Mainly, the first section handles the conceptual part. A generalized model for RAPs is to be generated from the gathered related information to cope the desired requirements. The second section is considered as the simulation model building phase. It firstly starts with the selection of a RAP case study, then model it via simulation software and according the conceptual model. Finally analyzing the last section illustrates the application features and results to develop conclusions. By tracing such steps, the study is expected to be directed in the orientation of the research objectives. Figure 3.1 particularly clarifies the research methodology's steps, and their links and interdependencies.

3.2 The Desired Objectives

There are two main objectives of this research. The first one is to utilize the simulation technique as a tool to plan and control the used resources of a RAP. Such objective will be achieved through the following steps:

- § Formulating a conceptual model that satisfies the RAP scheduling requirements, the simulation principles and conditions, and remedies the deficiencies of the conventional methods in scheduling RAPs.

- § Selecting an appropriate and representative case study for a RAP, and choosing a suitable simulation software that adaptable with the formulated conceptual model.

- § Developing a typical simulation model for the selected case study using the chosen software. Such model will be used as a template for the selected RAP category in order to facilitate the use of the simulation tool for planners. And in the same time, this model satisfies the conditions of the conceptual model.

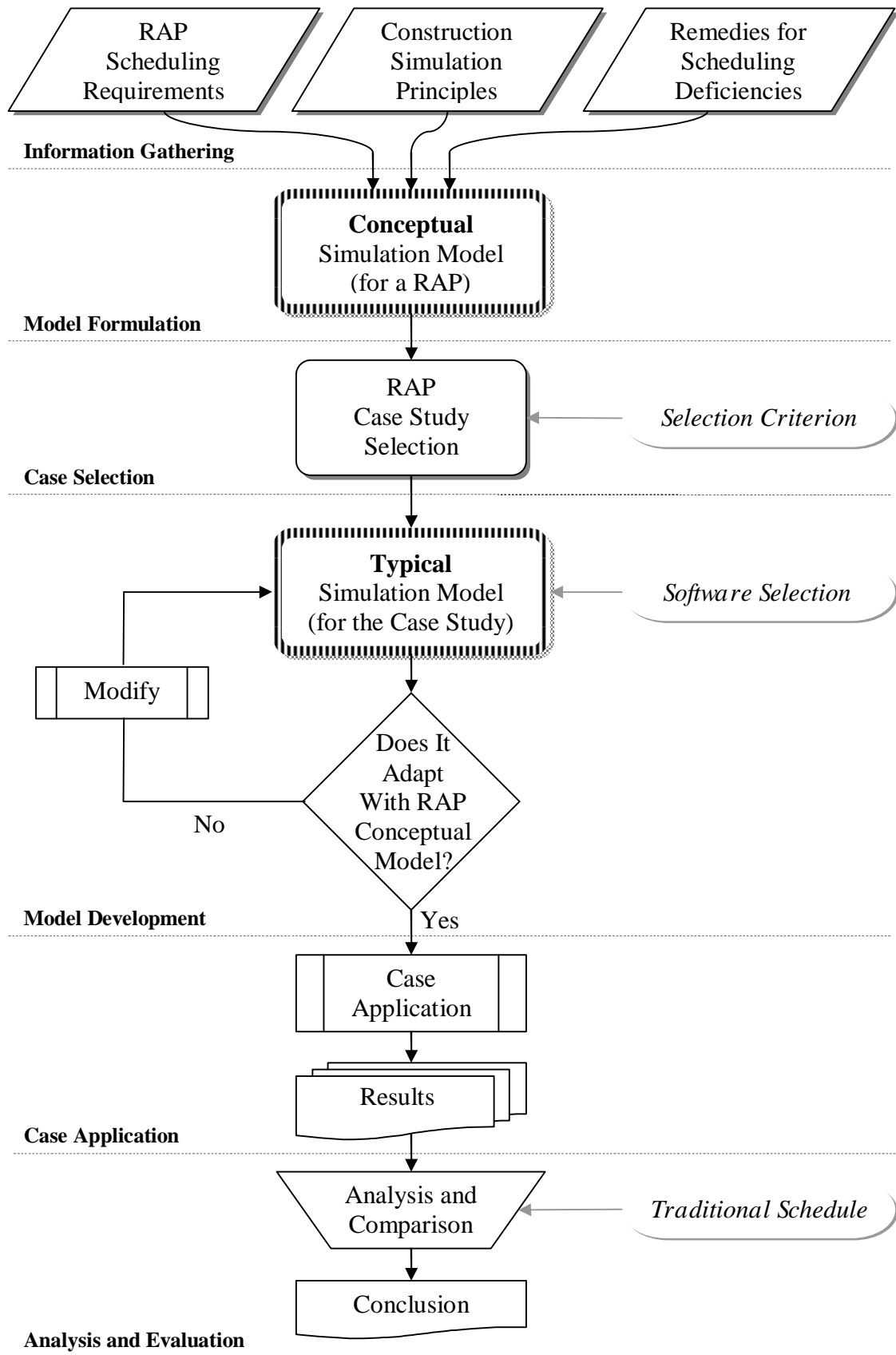


Figure 3.1: The Research Methodology Flowchart

The second objective, which is to clarify the effect of the resources utilization on the cost and duration of a RAP, will be carried out through the following steps:

- § Gathering such detailed data and records about the used resources in the selected case study.
- § Applying the case study within the typical simulation model.
- § Comparing the resulted facts of the simulated plan with a conventionally prepared schedule for the same case study.

3.3 Conceptual Model Formulation

3.3.1 Model Function

Launching from the review of the available literature, and the needed conditions to enhance the planning and scheduling policy of the RAPs, the desired model has to perform the RAPs more extensively, more dynamically, and to approach toward the realism as possible. The basic function of the formulated model is to control the workflow of a RAP through a group of preset conditions in an automated way. Such conditions guarantee to produce the optimal plan of the project's resources assignment and allocation. Moreover, the model's flexibility is supposed to be enough to generate different scenarios for one project, besides the ability to handle all of the attached details and information.

3.3.2 Formulation Criterion

Referring to the previous section, the model structure and components are mainly dependent upon the information that gathered from the related literature. The desired RAP simulation model is expected to integrate the following elements (Figure 3.1):

- § RAPs Scheduling Requirements. (Chapter 2, Section 2.2.3)
- § Adaptable with Simulation Principles. (Chapter 2, Section 2.4)
- § Covers the Deficiencies of the Conventional Scheduling Methods.

3.4 Typical Model Development

3.4.1 Case Study Selection

The qualitative approach is adopted in order to achieve the research objectives. A case study of a RAP will be selected to be applied within the formulated model. To have a more focused study, such selection has to be subordinated to both of the following items:

§ RAP Category identification: Discrete or Continuous. (Chapter 2, Section 2.2.1).

The category must be chosen so that getting the best illustration of a RAP that achieves the research objectives. In this case, a continuous RAP, such as an infrastructure project, is more advantageous to view the resource workflow issues clearly, and to clarify their effects on the project cost and duration.

§ The RAP processes data collection: Size and Availability. This task could be normally achieved by contacting a construction company that is specialized in the selected category of RAPs. The needed information is expected to be provided by interviews with the project engineers, and the saved records of the previously executed projects.

3.4.2 Model Building

The selected case study has to be properly positioned in the mold of the generalized conceptual model to produce a typical simulation model of that case category (Figure 3.1). This model is identified in terms of the RAP category and the simulation software. Then, a template for the selected RAP category will be ready to be easily utilized by a planner, avoiding the learning difficulties of the simulation technique software.

3.4.3 The Application Tool

While the typical simulation model of the case study has to be applied within a simulation software, it has been found that Arena – Basic edition, a simulation software (Chapter 2, Section 2.4.2), is the optimum tool to perform this purpose. The following marks are supporting this orientation:

§ **Software Availability:** A crucial point from the perspective of the personal and institutional financial capabilities. Arena is the only available simulation software in both professional and academic local environments.

§ **Software Knowledge:** Arena is advantageous to use when talking about the software training difficulties. It was injected in a basic course in the construction management program as a tool of simulation. Moreover, Arena is relatively simple to use due to its familiar interface and compatible features.

§ **Flexibility and Compatibility:** Arena is a general purpose simulation software tool, which able to handle a wide area of applications. The attached examples of Arena includes military, manufacturing, managerial, and other different applications. In addition of Arena's compatibility with the mostly used programs, it has the ability to perform simple and complex models as well.

§ **Utilities and Performance:** Arena is developed by *Rockwell Software*, a leading and professional software corporation. Besides including some of famous registered software trademarks, such as: Visio, Active X, Excel, Visual Basic. This business oriented origin is clearly distinguishing Arena from other individually – developed software that used as a simulation tool. Further, Arena has a very high level of detail in both input and output sets, besides including an optimization "add-in", which able to perform a number of scenarios and produce the optimum results.

3.5 Verification and Validation

After applying the RAP case study using the typical simulation model, which is framed in the conceptual model, and performed by Arena simulation software; several scenarios could be generated, and the best scenario will be picked. In order to emphasize the usefulness of results, they will be compared with their analogies in the conventionally applied schedules of the same case study.

4 MODEL FORMULATION

4.1 Introduction

The focus of the current chapter is to formulate the conceptual simulation model as a generalized template for the RAPs scheduling issues. As mentioned in the previous chapter, the model has to control the workflow through a group of preset conditions in an automated way, besides it must be flexible enough to deal with construction's stochastic environment and its various details. Hence, this chapter starts with clarifying the activity's needed information, and the explanation of its categories and the desired level of details. After that, it will handle the formulation criteria that controls the model building process. The third section of this chapter mainly defines the model's components and their functions based on the formulation criteria. Finally, a demonstration of the workflow mechanism of the generated model will be presented.

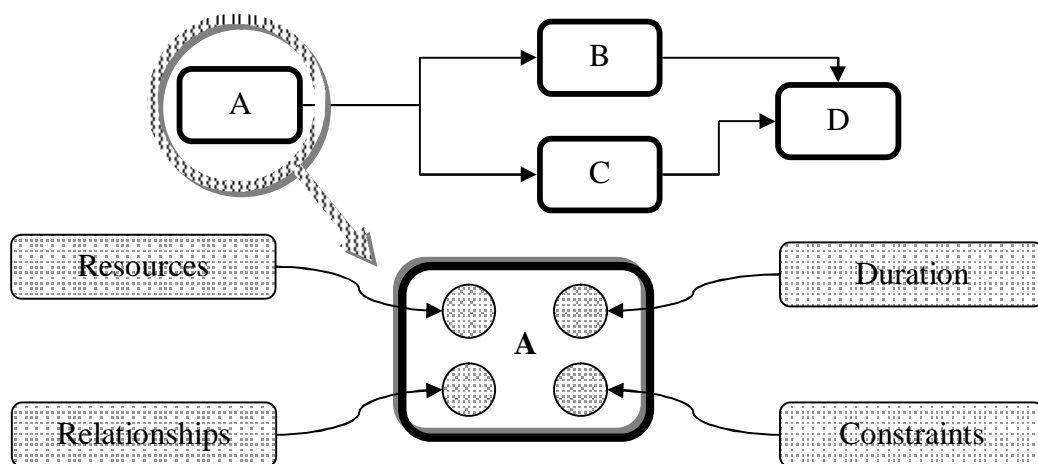
4.2 Input Data

Unlike most of the conventional scheduling methods, the simulation model of a RAP can be fed with more detailed information regarding duration, resources, technological issues, and priorities for any activity (Figure 4.1). This high level of detail of data leads to rich output reports, and deeper analysis for the four mentioned fields. Such advantages are considered as the tool to optimize the resources utilization, and study its effect on the cost and duration of a RAP (research objectives).

Duration data are basic inputs for any activity. While some scheduling methods like CPM deals with duration as a rigid deterministic input, simulation technique has the flexibility to operate with the statistical data of duration. The main source of this data is the saved records of analogical activities. Moreover, some simulation software can deal with many types of statistical patterns. Duration as an input is subordinated to special constraints that is dependent upon the project's contractual and execution conditions. These conditions could also affect the planning policy regarding resources usage and productivities, activity's priority to start, the execution sequencing, and the used technology .

Resources inputs are essential parts of a project's schedule. The assigned resources of each activity has to be defined in terms of: type, constraints, productivity rates, and cost rates. Simulation flexibility appears by injecting the concept of resources variety against time, in addition to the rich detailed resources inputs. Resources productivity rates, and resources constraints may control the activity's or the entire project duration and vice versa.

An activity, or a set of activities have also to be defined in terms of work priority. During work execution or after work completion, a decision has to be made to transform the focus on work and resources to another place. The transformation process depends on the work priority, which is set regarding the technological constraints, resources constraints, and time constraints. Unlike conventional scheduling methods, simulation can clearly and directly define priorities for activities. Thus, the mentioned overlapped dependencies among duration, resources, priority settings, and technological constraints, see Figure 4.1, complicates the data analysis to get the best RAP plan, which has an additional complexity due to its own nature. For this reason, most of the used scheduling techniques have partially or fully failed to either construct or analyze a RAP schedule successfully. Simulation technique gives the potentiality to perform the RAP data efficiently. The input and output features of simulation support this perspective.



Activity (A) is Eligible to be Simulated

Figure 4.1: Input Data for an Activity

4.3 Formulation Criterion

In order to optimize the resources' performance and allocation against cost and duration, a RAP model building has to be governed by three considerations: the RAP scheduling requirements (chapter 2, section 2.2.3), the simulation technique considerations (chapter 2, sections 2.4.1, and 2.4.3), and the solutions that are posed by this technique (chapter 2, sections 2.3, and 2.4). The three mentioned considerations are considered as the main sources to specify the shape and the level of the input data, and to set the model's elements and components, see Figure 4.2.

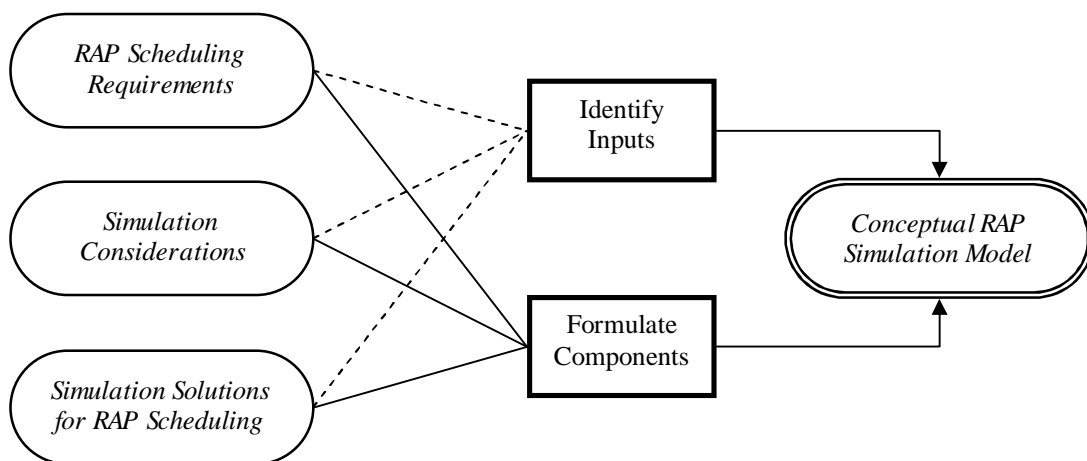


Figure 4.2: Model Formulation

4.3.1 RAP Scheduling Requirements

The nature of a RAP has a serious effect on the entire project work plan, launching from interrelationships, interdependencies, and overlapping for activities and the assigned resources. The RAP simulation model has to be flexible enough to satisfy these requirements.

Starting from activities, they may have multiple predecessors and successors, one activity may link to another activity at non-contiguous locations. Work interruption should be allowed through the "lag" concept, which may be useful for an activity and even for whole project. Also, activity overlap is an important criteria, more than one activity to occupy the same unit at the same time.

Regarding the project resources, the variable production rates, sizes and compositions at different work locations have to be taken into account. An activity may utilize multiple crews simultaneously, and one crew may perform multiple activities. Finally, The non-repetitive portion of project work should be incorporated into the framework of repetitive scheduling.

The demonstrated requirements of a RAP schedule need an automated system to be processed in. The desired simulation model has the potential to deal with the all mentioned considerations regarding the RAP scheduling policy. The amount and the quality of the input data, the automated way of performance, the advanced computational ability, optimization tools, and the stochastic environment, all of these options qualifies the RAP simulation model to fulfill the mentioned requirements.

4.3.2 Simulation Considerations

It has to be confirmed that the formulated model shall handle the simulation technique considerations as well as RAP scheduling requirements. The first feature of simulation technique is the dynamic environment. Simulation deals with the uncertain nature of the construction project as well as the dynamic assessment of resources, movement, and allocation. Secondly, the stochastic nature of construction is clearly reflected in simulation performance. While a project cannot be fully known until it has been executed, it will be considered as a stochastic model, which force planners to treat an activity duration as a random variable defined by a random distribution function.

The next challenge to qualify the model to be simulated is the user knowledge with the used simulation software. Hence, there is an amount of time and cost that is consumed to develop a simulation model, and to recruit the less user-friendly environment regarding the simulation software itself.

Finally, a simulation model can not optimize, but by performing a number of trial runs and comparing the results, an estimate of the optimum may be reached. So, the formulated model has to be eligible to be replicated in order to get the best results.

4.3.3 Simulation Solutions

Referring to chapter two, the conducted literature review has explained the defect points of the used scheduling methods in handling the RAPs, and suggested the solution of these defects as well. Simulation technique, the expected remedy, was always having the potentiality to solve any of the mentioned scheduling problems.

Launching from the most common used methods, the Network Scheduling is suffering from the risk of the sudden appearance of the processes' uncertainties during the project execution, the matter that lead to the real time decisions. Literature referred to the simulation capability to handle the uncertain nature due to having an attached probabilistic features. Also, Network Scheduling, such as CPM, cannot ensure the continuity in resource utilization because it cannot deal with the resource continuity constraint. While simulation was pointed by literature with the dynamic assessment, movement, and allocation of the used resources. CPM has been attacked for its inability to model non-value adding activities (idleness), such as waiting, inspecting, and moving. That matter could be simply covered by simulation through its advanced computational abilities. Another point, which is the early start schedule, it may not be optimal because floats attached to repeating activities represent significant amount of waste regarding resources. Simulation can remedy this point by generating numerous scenarios for the used resources in order to get the best plan. The cumbersome repetition of similar activities and relationships and the negligence of important production information, such as production rate and work location was also a clear deficiency in the CPM. This problem was solved by simulation through creating a single model for the project that can be analyzed including all the attached details, information, and constraints.

However, the LSM has solved the problem of injecting the production rates, and has a successful experience with the continuity of the used resources, it is still far from the execution environment. LSM did not consider the process's probabilistic inputs which may bring the risk of sudden uncertainties again to the picture. The limited modeling adaptability and ineffectiveness to model a system having a dynamic and stochastic environment (i.e. a construction project) was a shared drawback for both Network and Linear Methods; while, simulation is distinguished by having the advantage to cope with random and dynamic features essential for construction operations.

In LOB, a linear scheduling method, the "all activities critical" planning which may result in the "Rhythmic Production" principle, might not be applicable for the whole project, besides the generated risk regarding duration. The advantage of simulation here is the dynamic approach to perform the project model, the model does not have a fixed critical path, and the "Rhythmic" resources' productions are not a must.

Some contemporary scheduling approaches have been developed to support the dynamic resources allocation policies, and they succeeded to submit partial solutions for the RAP scheduling and its resources utilization. For instance, the dynamic programming technique have created a scheduling model that is able to identify an optimum crew formation and an interruption option. This valuable attempt of optimizing the resources utilization in a project is a partial solution, where it needs to be integrated with the other RAP scheduling requirements. The poor time aspects and demonstration, the ignorance of the realistic inputs (i.e. probabilistic duration data), and the inability to define the activities' priorities are considered as shared drawbacks between the dynamic programming and the design structure method DSM.

The Petri nets approach is almost the closest one to the suggested model. It has injected the probabilistic inputs, and developed such a sophisticated network model for a project schedule. Regarding resources allocation, one of the RAP scheduling requirements, resources – activities overlapping concept, was not sufficiently injected in the Petri nets model. Also, it does not consider the activities' priorities. However, Petri nets has submitted a networked model, this model was too complex to follow. The Proposed model automates the entire work flow, besides the RAP scheduling requirements fulfillment. The schedule illustration is supposed to be representative for time and technological issue, and some other details should be left to the software to analyze and produce the proper reports.

4.4 Model Structure and Workflow Mechanism

This section submits the proposed RAP model, that is eligible to be simulated. Initially, a typical RAP is consisting of a number of sub-models. Such sub-models are generally repeated along the project, taking into consideration the non-repetitive portions and the dissimilarity in duration, place, and resources distribution.

A sub-model is formulated by a sequence of activities with different relationships. These relationships might be direct, or local (i.e. in the same sub-model), or global (i.e. controls another activity in another sub-model) as shown in Figure 4.2.

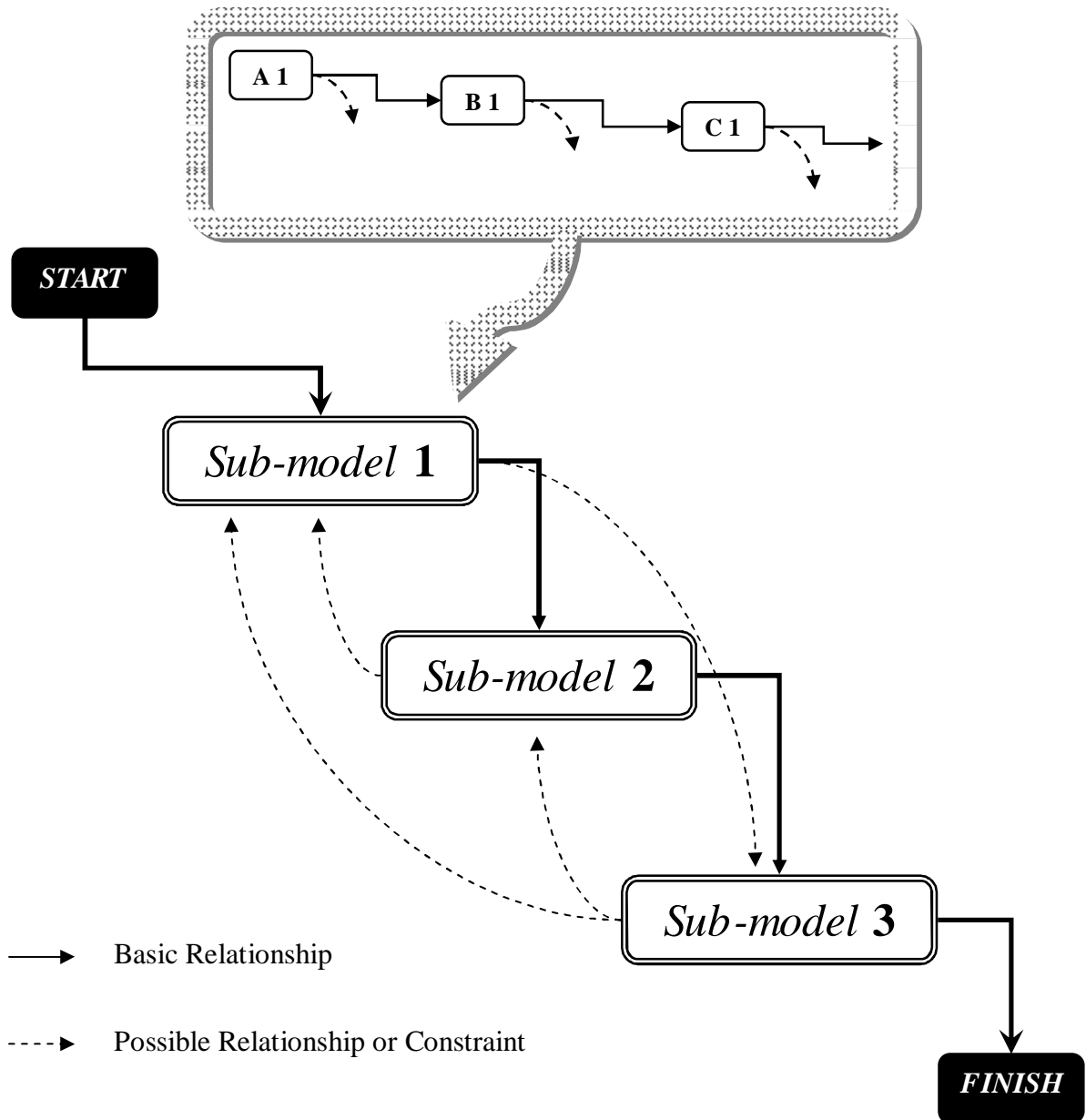


Figure 4.3: Schematic Representation of a RAP Submodel

A typical submodel consists of a number of interrelated activities. In order to guarantee the fulfillment of the stated formulation criteria of the model, a set of components and a controlled workflow mechanism have been proposed in the model, see Figure 4.4.

The project start event launches the project, then, the work flow passes through a priority check. Afterward, workflow is directed to the activity with the highest priority. The priority check icon has the symbol of a double framed diamond. The next station of work flow is the activity's process itself, considering all of the attached data of this activity (section 4.2). The next station is called: eligibility check (a single framed diamond). It comes directly after the activity processing, and it has two gates: yes and no. the yes-gate works if the activity is accomplished and eligible to convey resources to an extraction node. The no-gate keeps the work in process until it finishes the same activity. After that, the workflow will be exported through an extraction node (a filled circle), this process is controlled by the local and global preset logical relationships between activities. The solid line represents a direct and familiar relationship between two activities, and the dashed line demonstrates a non expectable relationship or constraint. The next point is the collection node (a hollow circle), which is considered as the inlet of the workflow of the next activity. The function of a collection node is to receive the sent workflows and re-convey it to the priority check. The priority check, again, starts to differentiate between the input workflow, which could be fed from any activity in the project (the colored dashed arrows), and initiates the one with the highest priority. Such priority has to be set in terms of duration, resources, and technology constraints. An activity in this model starts with a collection node, and ends with an extraction node. Workflow has the flexible environment so as to pass through any activity in any sub-model according its set priority.

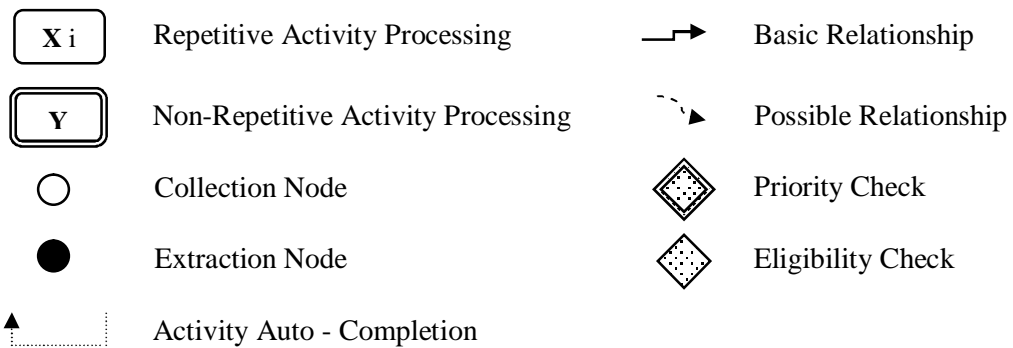
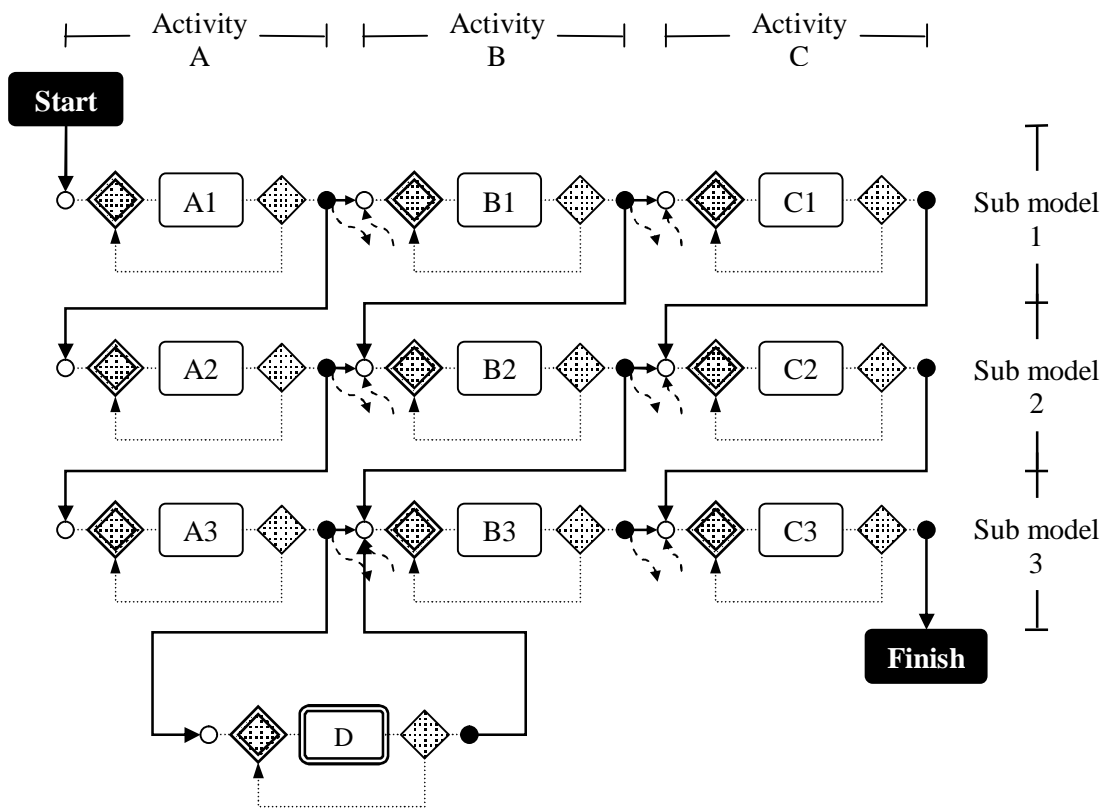


Figure 4.4: The Proposed RAP Conceptual Model

5 MODEL DEVELOPMENT

5.1 Introduction

As the previous chapter has presented a conceptual model to simulate a RAP, this chapter expresses such vision into a generalized template. To be more pragmatic, the desired template is a model that has been pre-defined in terms of RAP type and simulation tool. The developed model was designed for infrastructure projects using Arena simulation software. Representing simulation capabilities and advantages that enhances and extends the RAP resources planning strategy and scope is the main purpose of the current chapter. It begins with a preface to Arena software, then explains the model's characteristics, mechanism, and components.

5.2 Simulation By Arena

Section 2.4.2 in chapter two presented Arena as an esteemed general purpose simulation software that supports different needs through a project's life cycle. System Modeling Corporation, (1999) stated that Arena has an object oriented environment to define system logic and physical components. The power afforded by Arena extends its ability to be integrated with other technologies, such as databases, drawing, modeling products, or spreadsheets. Moreover, it has such familiar interface that is compatible with Microsoft software packages.

Arena's product family consists of Arena Basic Edition, Arena Standard Edition, Arena Contact Center Edition, Arena Packaging Edition, Arena Professional Edition, and OptQuest for Arena which is used for the optimization process. The desired RAP simulation model is built using Arena Basic Edition, version (5.00.02) 2000.

The "flowchart" is the general mechanism of simulation by Arena. The word "flowchart" has two main concepts behind; "flow" and "chart". Beginning with "chart", it is the main frame of the model that is built according to the logical aspects. "Chart" consists of graphical objects called "modules", which are the objects of both chart and data, that define the process to be simulated. All information required to simulate a process is stored in the "modules".

The second concept, "flow", represents the moving objects through a "chart". Such objects which are called "entities" are the items that are being served, produced, or otherwise acted on by a process.

Arena software adopts the "production lines" strategy, which could be represented by static "workshops", and moving "products". The projection of such concept on the construction environment makes the entire project represented as a single blank object "entity", that passes through the chart's modules "workshops" to be performed "leveled, excavated, paved, etc.", System Modeling Corporation (1999).

5.3 Arena Modules

The simulation model was built using the modules that located at the "basic process panel". As defined before in the previous section, the modules are such graphical objects that define the process, and containing all of the required information. Modules have two main types: "flowchart" modules and "data" modules. The "basic process panel" consists of eight flowchart modules, and six data modules (Figure 5.1). In the shown panel, each of the "flowchart" modules, with the yellow color, has a specific figure such as: rectangular, diagonal, etc., while "data" modules were represented with small tables. To build a flowchart in the Arena's environment, the required "flowchart" module has to be dragged and dropped via mouse cursor into the chart's area. All of the dropped modules must be connected from their both ends with one connection at least, except the "create" and "dispose" modules. A "data" module is simply table that can be fed with different data features. The "data" module's table could be opened by double clicking its icon at the "basic process panel".

5.3.1 Sub Models

Whereas the flowchart modules are considered as the elementary units of the model's structure, the built model composition consists of a networked group of them. Modules were aggregated according to the existing repetitive activities into global bodies called: Sub Models in order to have an appropriate model format and control the logical requirements. Therefore, each submodel represents a repetitive activity in the entire project, and has its particular content of modules, see Figure 5.1.

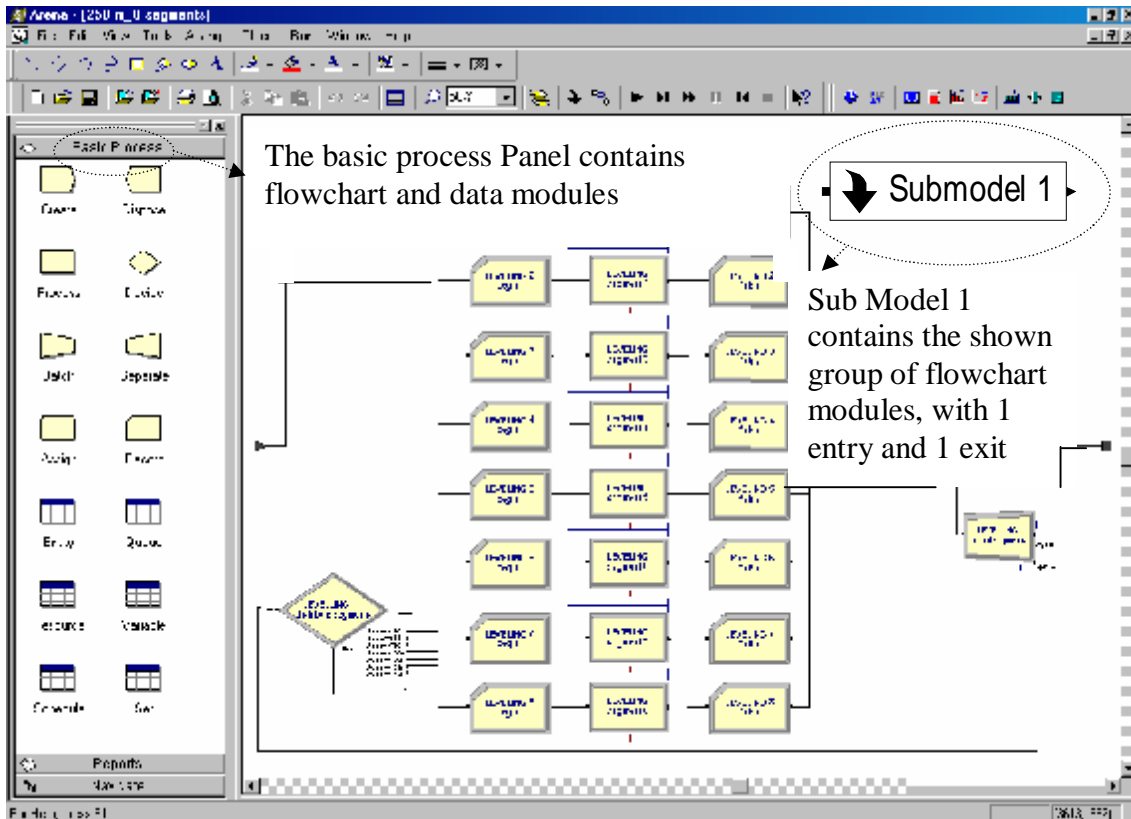

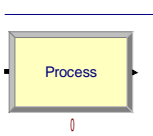
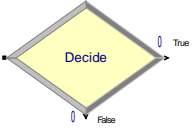
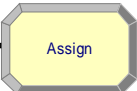
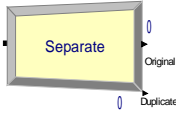
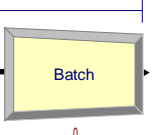




Figure 5.1: Arena Software Window

5.3.2 Flowchart Modules

Table 5.1 shows the flowchart modules' shapes and their functions. The "process" module represents the performance workshop of an activity. It is fed with the duration and resources data, and it is responsible to generate their outputs. The other remaining modules can be considered as service objects for the "process" modules, either to identify data, control the entity's logic and flow, or to record such important events during the simulation process. (Section 5.7 handles this issue in more details)

Table 5.1 Arena Flowchart Modules


Module	Figure	Brief Description
<i>Create</i>		The starting point for entities in a model.
<i>Process</i>		The main processing method in the simulation process including resources delay type identification, and assignments dialogues.
<i>Decide</i>		This module allows for decision making process in the system.
<i>Assign</i>		It is used for assigning new values to any of system variables during the simulation process.
<i>Separate</i>		This module can be used to either copy an incoming entity into multiple entities or to split a previously batched entity.
<i>Batch</i>		Intended as the grouping mechanism for the simulation model's entities.
<i>Record</i>		Collects statistics in the simulation model.
<i>Dispose</i>		The ending point for entities in a model (The termination of the simulation process).

5.3.3 Data Modules

The current category of modules has six types in the basic process panel. Only three are taken into consideration during the model building process: resource module, set module, and schedule module.

5.3.3.1 Resource Module

This data module represents the project's pool of resources that defines resources in the simulation system, including costing information and resource capacity. As Figure 5.2 shows, resources may have a fixed capacity that does not vary over the simulation run (i.e. project's life cycle) or may operate based on a schedule.



	Name	Type	Capacity	Busy / Hour	Idle / Hour	Per Use
1	Labour	Fixed Capacity	15	6.25	6.25	0.0
2	Mason	Fixed Capacity	1	8.75	8.75	0.0
3	Electrician	Fixed Capacity	1	11.25	11.25	0.0
4	Loader	Fixed Capacity	1	70	0	0.0
5	R.Comp. 25	Fixed Capacity	1	100	0	400
6	R.Comp. 08	Fixed Capacity	1	15	0	20
7	P.Comp.	Fixed Capacity	1	6.25	6.25	0.0
8	Paving Set.	Fixed Capacity	1	582.5	0	500
9	Grader	Fixed Capacity	1	120	0	500
10	excavator 1	Fixed Capacity	1	50	0	0.0
11	excavator 2	Fixed Capacity	1	50	0	0.0

Double-click here

- Fixed Capacity
- Based on Schedule

Figure 5.2: Resource Data Module

5.3.3.2 Set Module

Figure 5.3 presents the set data module which defines various types of sets, including resources. Sets can be used in the process modules via set dialogue. It is used for resources that alternate to perform similar operations.

5.3.3.3 Schedule Module

This data module may be used in conjunction with the resource module to define an operating schedule for a resource or with the create module to define an arrival schedule, see Figure 5.4. Work schedules could integrate breakdown patterns for equipments or learning curve factors for new workers.



Figure 5.3: Set Data Module

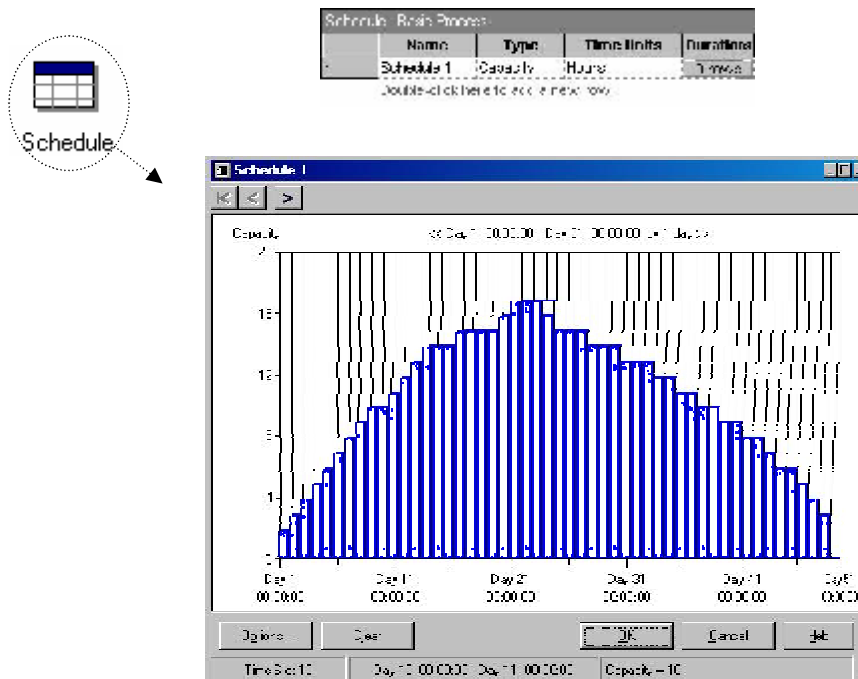


Figure 5.4: Schedule Data Module

5.4 Model Characteristics

The RAP simulation model, which is built by Arena, is especially designed for infrastructure projects. The reason of choosing this category of projects is to launch the applications of RAPs' resources planning using Arena with a simple illustration. Additionally, infrastructure projects have a few number of repeated activities, and such simple and clear logical aspects, in addition of its vital position in construction industry.

The model will be used as a generalized template in order to minimize the complicated aspects of the simulation software, and to empower users to utilize simulation advantages with minimum interpose. Moreover, this model is able to integrate additional qualitative data efficiently (compared with the used planning methods) and to generate several scenarios of the same project that give a valuable list of alternatives and solutions against the existing constraints.

In addition of "production lines" as the global strategy of simulation by Arena (section 5.2), the model poses the "working fronts" as a local strategy to simulate RAP projects. Such strategy mainly relies on handling a RAP project as a number of repetitive partitions. "Working fronts" concept is the key word to have an opened, overlapped and complicated environment regarding resources. Once the work is started at any of the fronts, it will be converted to a separate sub project that is eligible to receive resources. This matter could create a high level of competition among the project's "work fronts" and the used crews of resources.

The highly competed and complicated environment regarding resources is expected to produce qualitative steps forward in the RAP resources planning strategy. Such evolution is generated through processing highly sophisticated batches of data. The developed model's plan of a RAP is expected to cover the deficiencies of the commonly used methods.

Regarding flexibility, the model structure allows to attach additional activities, deals with unequal quantities for the repetitive parts, and seriously handles the real life uncertainties through the sophisticated data input features. Moreover, it processes the possible constraints and interactions regarding resources, costs, durations, and priorities at the most complicated conditions. Besides, having the ability to optimize any of the formulated cases against some specified constraints.

The volume of model's contents is constrained to the used hardware's specifications. There is a huge number of mathematical operations that is executed within the built model that requires a highly specified hardware to get an efficient simulation performance.

5.5 Planning Procedure

To achieve an effective resources planning utilizing the simulation technique, there are six main steps that are required to be carried out. Figure 5.5 illustrates these steps into a flowchart. The first step is gathering the Input data, which divided into two categories: "chart" and "flow" input data. The former category represents the permanent part of the simulation model. It consists of a list of activities that are commonly performed in an infrastructure project, and their logical relationships.

Also, the chart input data includes the identification of the combined crews of the used resources for each activity, and specifies the maximum number of work fronts that the project could be divided into. In contrast, the flow input data is the planner's experimental field in the model. It incorporates the case project's quantities of work, resources' capacities, and the rates of production and cost per resource.

The second step, model building, is to integrate the gathered data in order to formulate an applicable simulation model for some case project. The chart data builds the model's body skeleton, and the flow data activates this body through processing the fed inputs. Before being fed in the model, resources' production data of each case has to be converted into: "resources delays values" per "work front", using MS Excel.

The planner should specify a number of possible scenarios that the project could be executed in. These developed scenarios depend on the number of work fronts, which is inversely proportional to the front's size. Such parameter influences: the competition between activities on the used resources, and the elapsed time to make an activity eligible. The third step, which is the preliminary simulation process, is a multiple simulation process for a project's scenarios that were prepared by the planner. Contractual and execution constraints are the basic factors that control the selection of the most appropriate scenario of work, which could be observed using the "Process Analyzer" add-in that is located in the Arena's program "tools" list. In addition of this selection, the fourth step optimizes the selected case using Arena's "OptQuest" add-in. The optimization process relies on identifying the project's objective, requirements, resources constraints, and crews constraints, (will be handled in details in chapter 6).

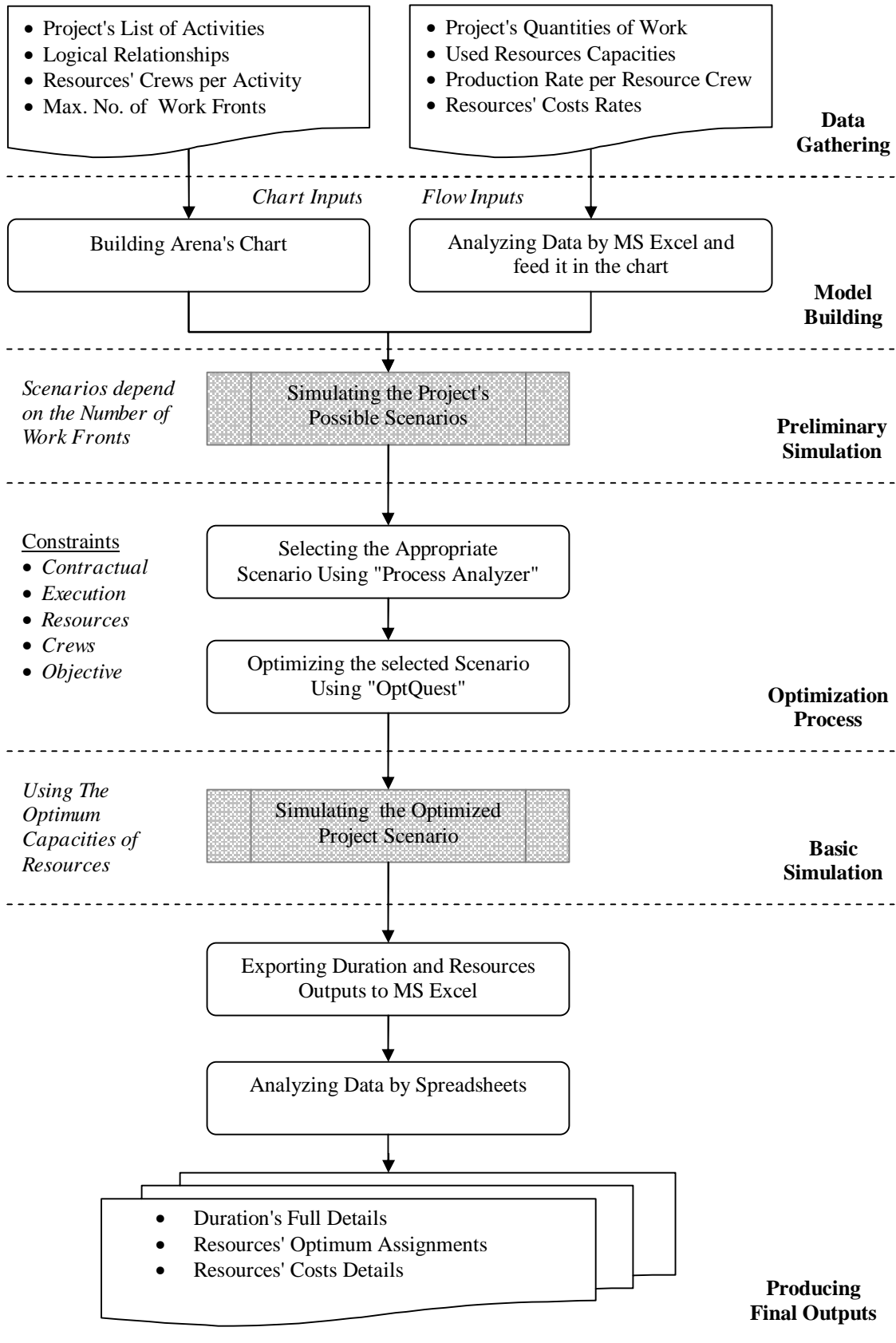


Figure 5.5: Resources Planning Procedure

The previous step produces the optimum resources capacities versus the desired objective and the defined constraints. This modified part of "flow inputs" (i.e. resources capacities) has to be fed back to the simulation model of the selected scenario. Step five simulates the optimum case, (the basic simulation process of the project).

The final step is to generate the simulation process results (i.e. duration and cost outputs) using MS Excel to formulate the final planning information and details regarding: duration, resources allocation, and resources costs.

5.6 Model Layout

The developed model consists of five infrastructure milestones: leveling, pipes work, sub grade, side walk, and road. They have simple global logic of relationships; pipe work directly depend on the leveling milestone, and similarly sub grade starts after the pipe work milestone. Both side walks and road milestones depend on accomplishing the sub grade, and this is the only branching junction in the model. Also, the milestones themselves contain a number of activities that are also directly sequenced into one streaming line of work.

The logic of the mentioned branching junction allows the work at two different milestones (side walks and road milestones) to be eligible to be performed at the same point of time (i.e. directly start after the sub grade milestone), therefore, both milestones compete on the similarly used crews of resources in their activities.

From more specific perspective, Figure 5.6 clarifies that such junction is actually branched from the Curb stone beams activity, which is the last activity in the Sub grade milestone, and after that, the work eligibility is given for the first two activities in the Side walks and Road milestones (i.e. R. Beams and SB1). Then, the parallel work flows are directly sequenced again in remaining activities for both Side walks and Road milestones up to the work accomplishment point.

Figure 5.6 demonstrates the layout of the model's milestones, and briefly describes their embedded activities. As the layout clarifies, the suggested short names of activities were chosen in order to simplify the naming process in Arena's sub models and modules.

Arena software is qualified to incorporate more additional non-value-added activities for each milestone, such as: meetings, submittals, material orders, and variation orders or any other uncertain events. Likewise, the model could be designed to perform an infrastructure project that is divided into more than eight work fronts (i.e. this model was designed with a maximum capacity of eight work fronts). However, the large number of modules that are used to generate this model, as detailed in Table 5.2, greatly increases the load on the used hardware, besides the great load of data processing that the optimization process performs using the "OptQuest" add-in.

Table 5.2 Arena Model Contents' Statistics

Submodel	Qty.	Flow Chart Modules for each Sub Model								total
		create	process	assign	decide	separate	batch	record	dispose	
Start	1	1	-	33	-	-	-	-	-	34
Distribute	1	-	-	-	-	1	-	-	-	1
Assemble	1	-	-	-	-	-	3	-	-	3
Handover	1	-	-	-	-	-	-	-	1	1
Launcher	1	-	8	2	2	1	-	16	-	29
Process	32	-	8	-	1	-	-	16	-	800
Testing	10	-	1	-	1	-	-	2	-	40
total	51	1	278	35	48	2	3	548	1	908

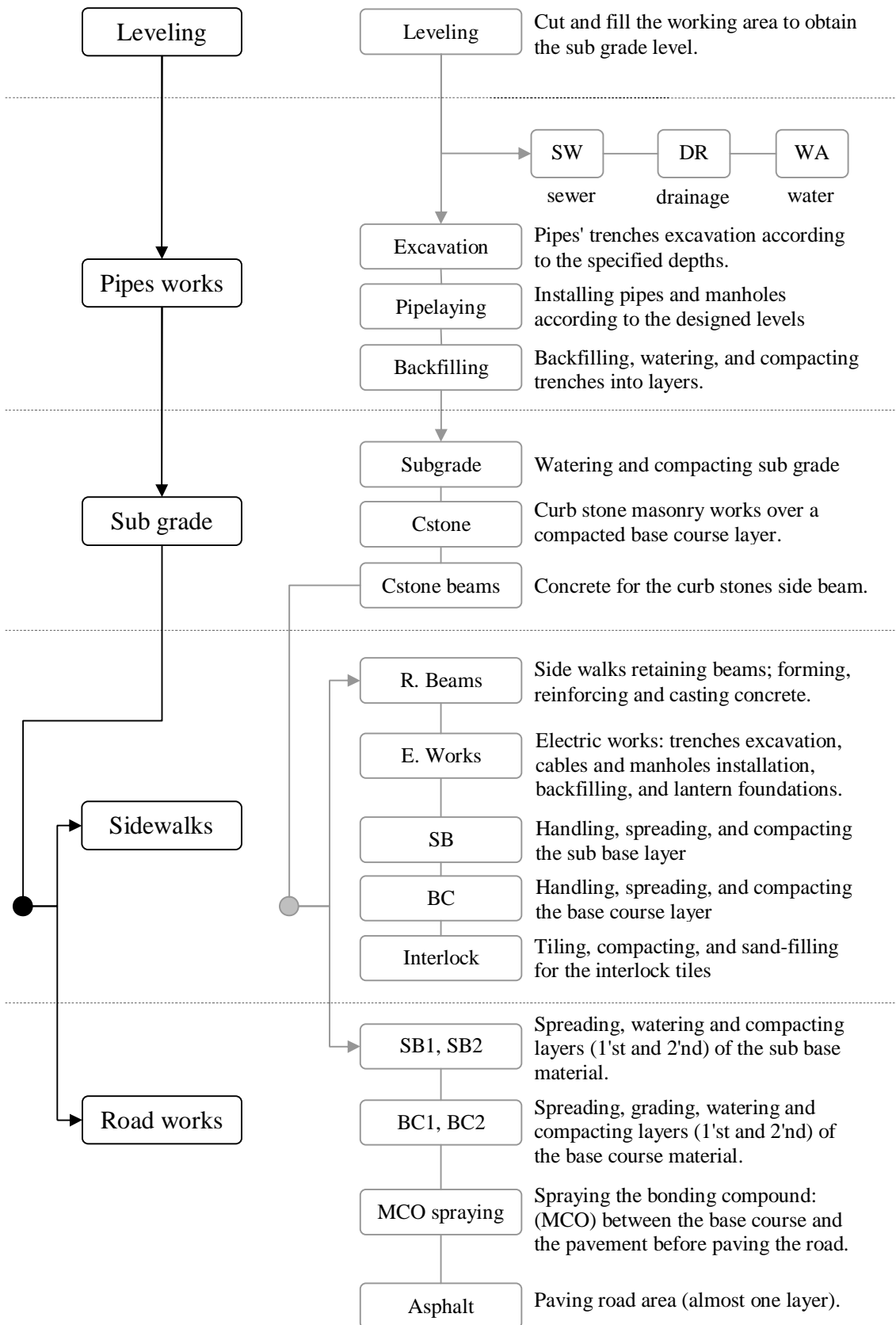


Figure 5.6: Simulation Model Activities Layout

5.7 Sub Models Contents

Referring to Section 5.3.1, which introduced Sub Models, their content is functioned to manage the flow of work between the work fronts in the same repetitive activity, and also to control the transmission of such flow (i.e. entities) to other eligible work fonts that are located in a successor activity. The composition of the infrastructure project activities generated seven main types of sub models: (Start - Launcher Process - Normal Process - Testing - Distribute - Assemble - Handing over). Table 5.2 demonstrated some statistics of the submodels content of modules. As shown, there is a single sub model from each type, except Normal Process and Testing sub models that were repeated. Sub models: Start, Distribute, Assemble, and Handing Over are just to prepare, control, and systemize the flow of data inside the model. Sub models: Launcher Process, Normal Process, and Testing represent the model's real core that generates the duration and resources outputs. Figure 5.7 illustrates the typical Arena infrastructure simulation model at its global perspective, and translates its general layout in Figure 5.6 into a simulation environment layout. The next sub sections handle each of the mentioned sub models in details.

5.7.1 Start Sub Model

This is the starting point of the model's simulation process. This sub model has two main functions; creation of entities, and identifying resources delay data for all activities, so, it is the only input field regarding duration data in the entire model. The Start sub model has the gray color with no entry points, and one exit point (see Figures 5.7 and 5.8). Having no entry points implies that this place does not receive entities, but generates them. Having one exit point implies one stream line of the conveyed entities. The Start sub model contains two main types of modules; create module and assign. There is only one create module which generates the entities. Assign modules are responsible to identify the resources delay values per a work front for all of the project's activities. Hence, there are (33) assign modules in this sub model that equal to the total number of the project's activities (Launcher process + Normal processes) excluding tests. (see Figures 5.7 and 5.7, and Table 5.2)

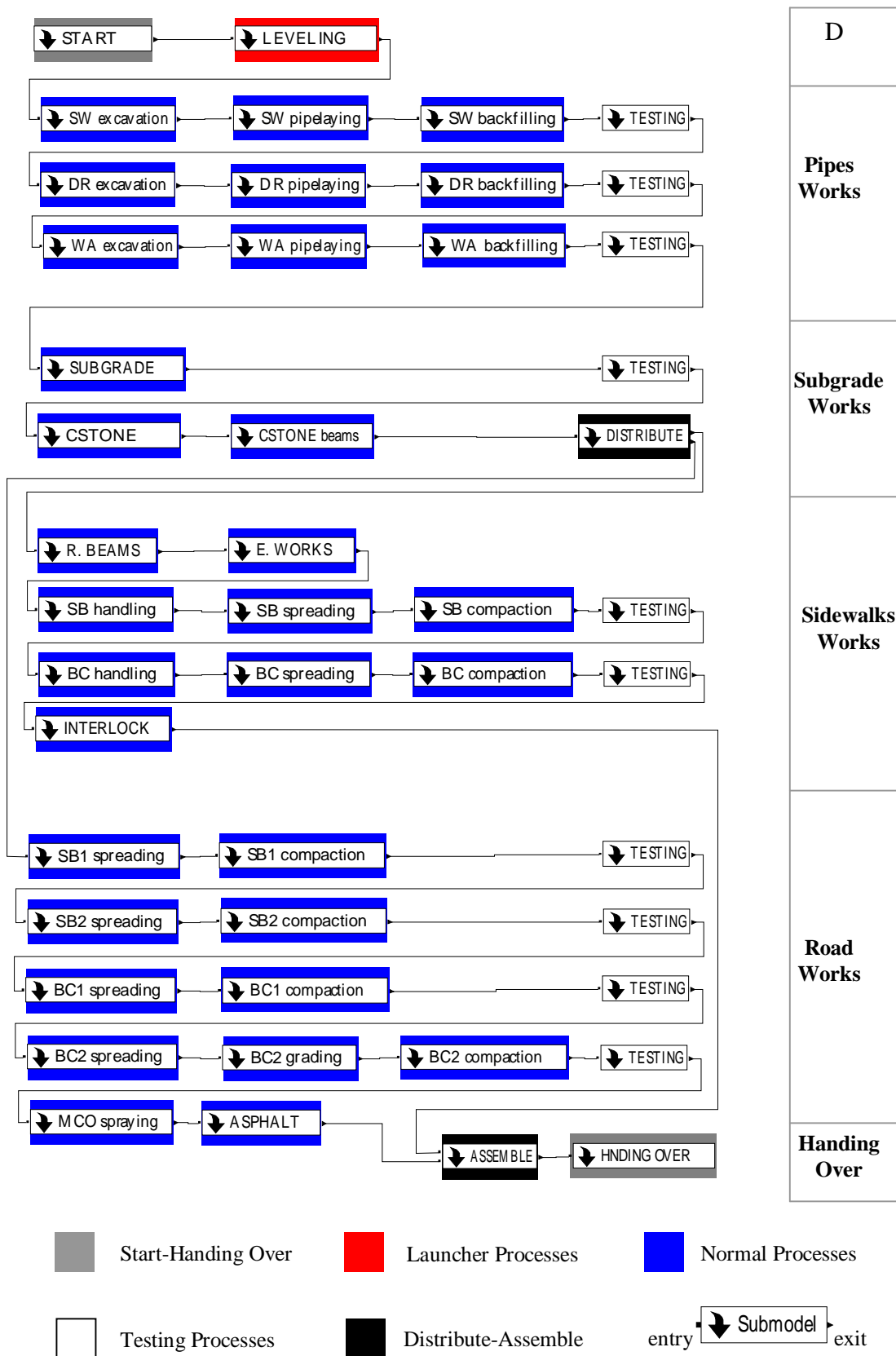


Figure 5.7: Arena's Infrastructure Simulation Model

At the beginning, the created entity that represents the project, flows in a blank case. Once it is delayed by one of the model's process modules, it will be labeled with their time and cost data. Create module, which shown in Figure 5.9, could generate a number of entities that are controlled in terms of creation timing. Entities consecution could be randomly distributed, based on schedule, or dependent on a specific expression. The case of planning a construction project requires the constant type of entities' creation, and only one generated entity.

Before being fed to the assign modules, production rates of the resources' crews have to be converted into resources' delay values according to the flowchart that was shown in Figure 5.5. In this sub model, once the entity is generated from the create module, it passes through the assign modules to be labeled with their delay data for each activity. Figure 5.8 clarifies the layout of the start sub model's content of modules. The logical order of the project's activities is not necessary for the arrangement of assign modules in the presented layout.

Appendix 1 guides the user of this model to add, delete, or modify values and variable. It describes in details the dependencies and interactions among the model components once a change in a value or a variable has been made by a user. This appendix also identifies those modules which a user can change their internal contents, and those that are not allowed to be changed in the entire model.

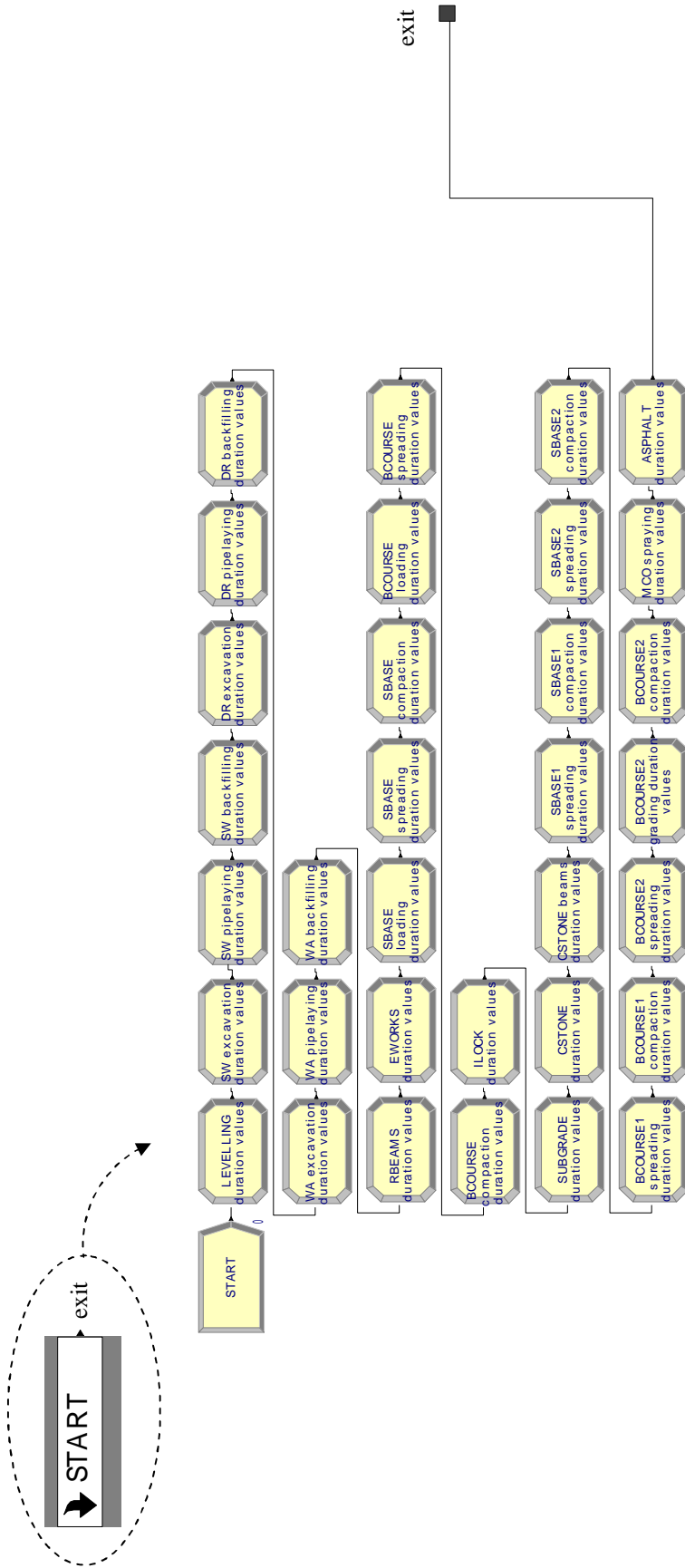


Figure 5.8: Start Submodel Contents

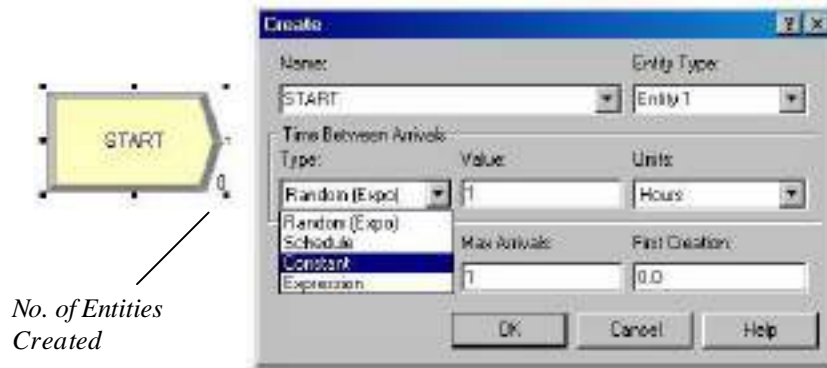


Figure 5.9: Create Module

One of the advantages of Arena software is to consider the realistic nature of data inputs. It could incorporate the field records of the resources' production inside the model. The "Input Analyzer" add-in, shown in Figure 5.10, is located at the tools menu. It is the mediator that produces the expressions of the fed data. For instance, after saving some "resources delay" records in as "txt" file format, the Input Analyzer has the ability to fit such records into different random distribution functions, such as: normal distribution. The desired expression of a normal distribution fit type is: NORM (12.6, 2.18), which means: (mean, standard deviation) as shown in Figure 5.10.

After the previous preliminary step, the delay data of each activity is ready to be fed within their particular assign modules. As illustrated in Figure 5.11, the assign module for the Leveling activity includes the identification of delay data for all of its work fronts (i.e. repetitive segments). Data expressions could have different values in the case of unequal repetitive work fronts (i.e. unequal quantities of work per work front).

The assign process creates an attribute that labels the entering entity (i.e. the project) with the input data expressions. Expressions values that were developed via Input Analyzer could be inserted into the assign modules through the Expression Builder window, see Figure 5.12.

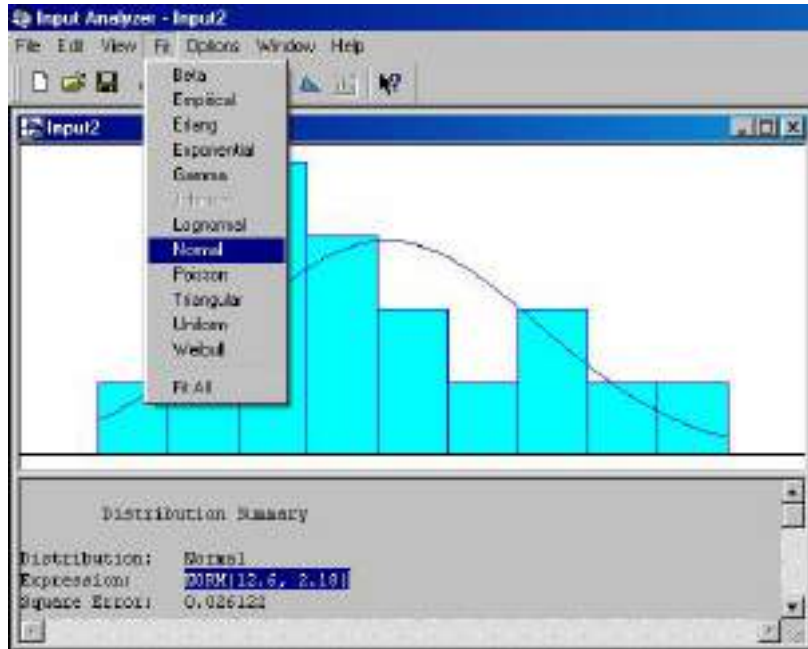


Figure 5.10: Input Analyzer

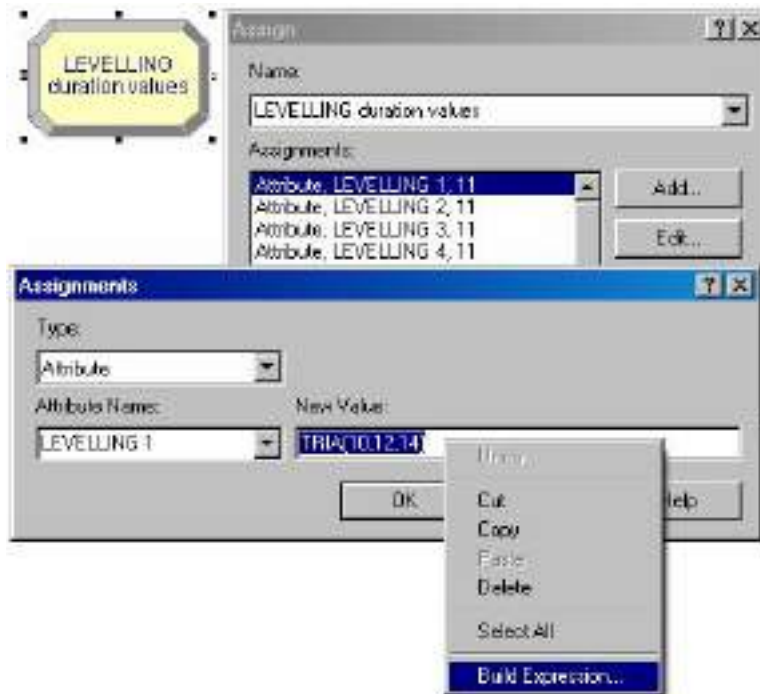


Figure 5.11: Assign Module – Sub Model: Start

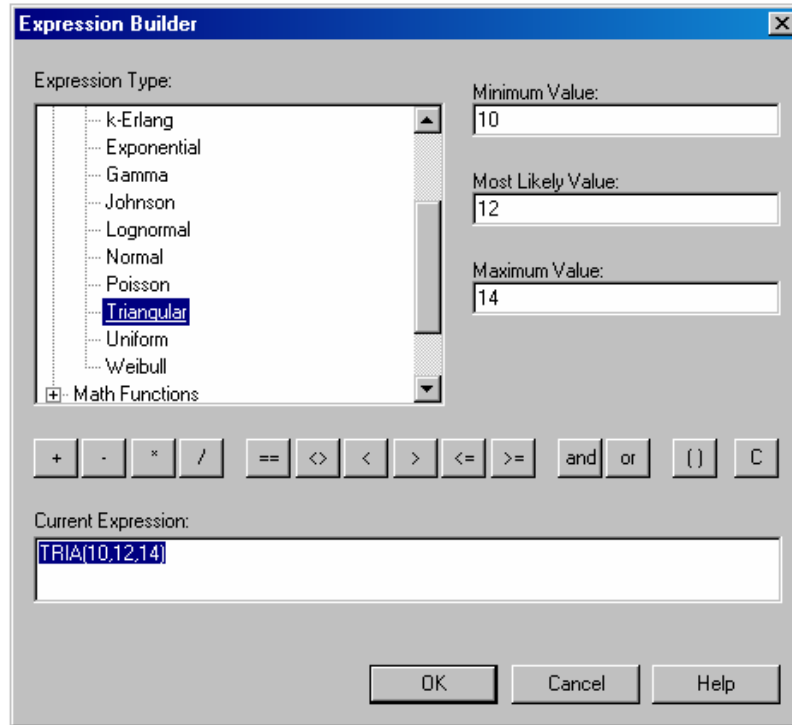


Figure 5.12: Expression Builder

5.7.2 Launcher Process Sub Model

As the start sub model was considered as the launching point of the model, the Launcher Process sub model is the starting point of work in the activities. In other words, the start sub model was the preparation phase of the generated entity. Launcher Process sub model has the red color with one entry point and one exit point. see Figures 5.7, and 5.13. The single entry point indicates the reception of the entity that is previously created and assigned with delay data in the Start sub model. One exit point indicates one stream line of entities' transmission to the next sub model.

The current sub model has three main functions that simultaneously occur; to perform the first activity in the project, to split the project into the specified number of the repetitive work fronts, and to make the other following activities eligible to start work.

Dividing the project into work fronts requires to split the incoming entity into a number of duplicates that equals to the work fronts' number. Hence, in the current sub model, only one entity enters and multiple entities exit to continue their flow inside the following sub models representing the project's work fronts.

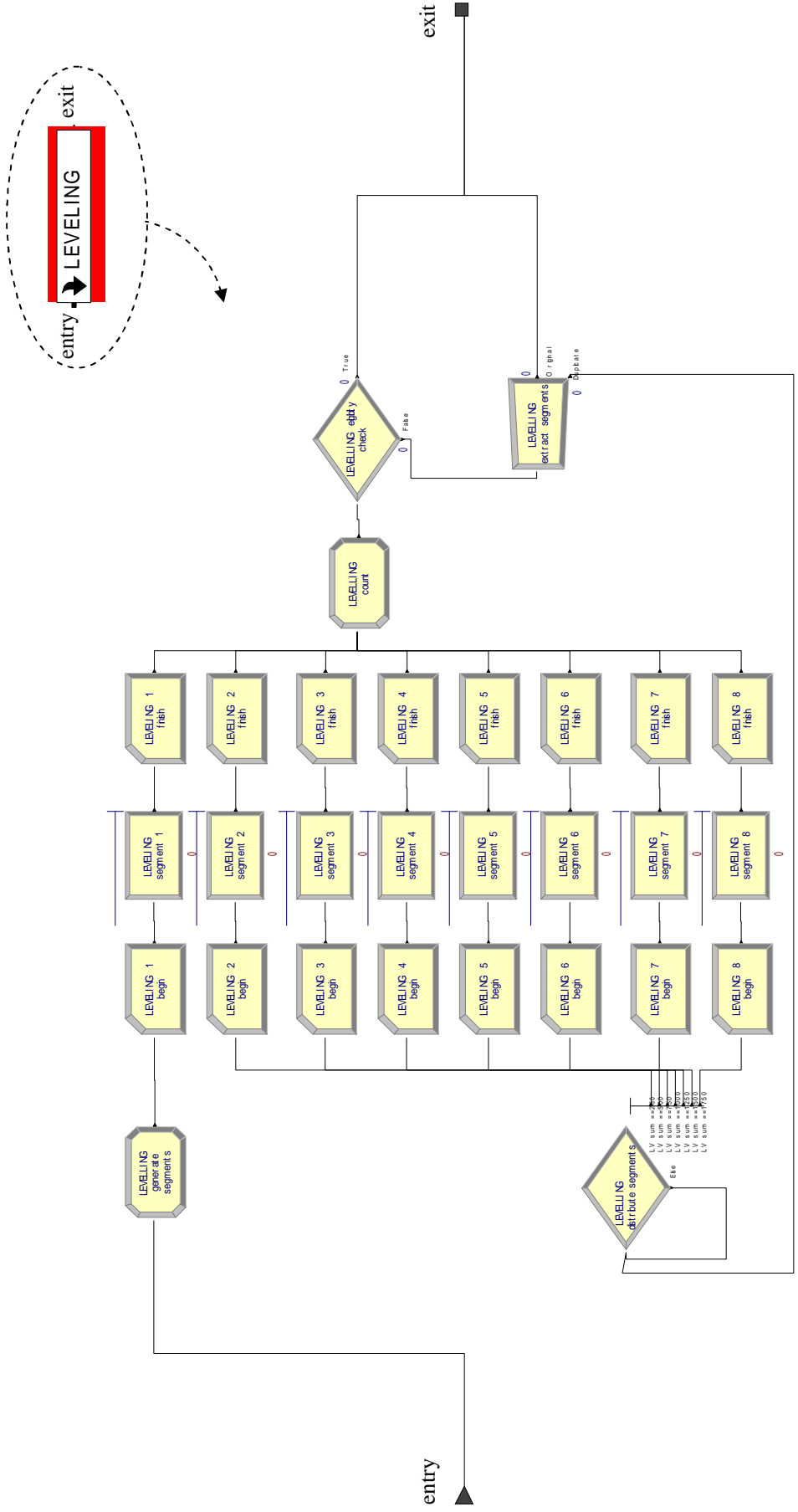


Figure 5.13: Launcher Process Submodel Contents

The Launcher Process sub model contains five types of modules: (assign - record - process - decide - separate). Figure 5.13 shows the layout and modules arrangement of this sub model. Actually, the combination of modules shown could be categorized into two cores according to their function, performance core, and splitting core.

5.7.2.1 Performance Core

This part of Launcher Process sub model is responsible to perform the activities. It mainly consists of three parts; process modules set, record modules set, and one decide module, which is directly connected to the process modules, see Figure 5.13. The process modules set is the basic part that is functioned to label the passing entities with the assigned resources' cost and delay data for each work front in the current activity. Figure 5.14 represents a typical process module. Firstly, this module has to be assigned with the needed resource crew to perform a work front in an activity.

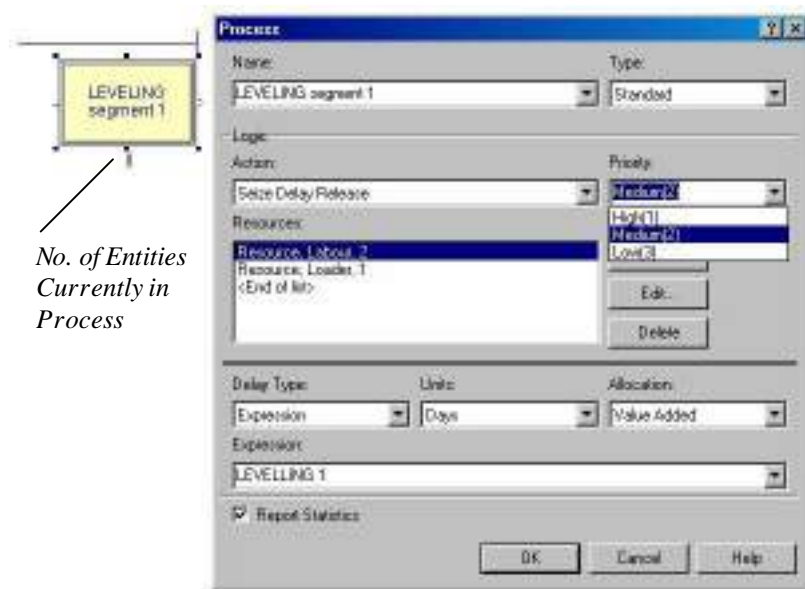


Figure 5.14: Process Module

For example, Figure 5.14 shows the first work front (i.e. segment1) of the leveling activity. It needs (2) labors, and (1) loader. These mentioned resources were initially fed to the resource data-module (section 5.3.2, Figure 5.2), which represents the project's resource pool, and then, they will be added to the process module through the resource dialogue, see Figure 5.15.

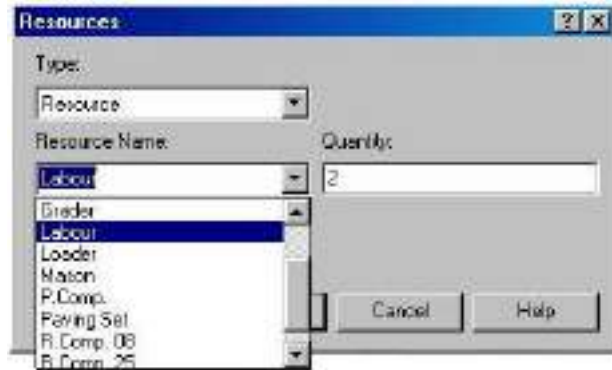


Figure 5.15: Process Module – Resource Dialogue

The assigned resources for an activity could also include a set. The set concept, which has a wide use, mainly relies on alternating a group of the same type of resources to their assigned processes according to a specific rule (Figure 5.16). For instance, the excavators set consists of: excavator 1, and excavator 2. Both of them were assigned firstly in the set data-module (i.e. set pool of resources). Once excavator 1 is busy, and there is an eligible activity that uses this set, excavator 2 directly starts to perform this new activity. When the set's selection rule is preferred order the allocation of both excavator will prioritize the highest ordered excavator. This feature of resources assignment is usefully applicable for the rent equipment. (see Appendix 1)

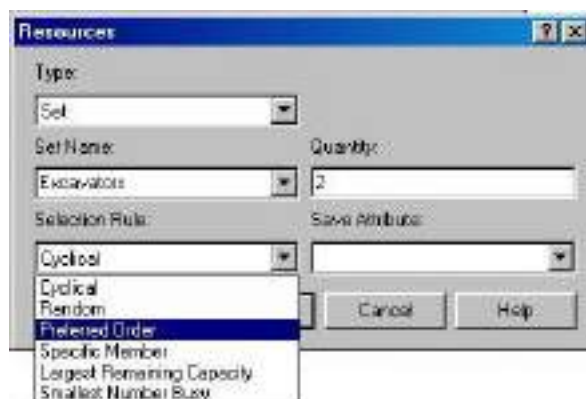


Figure 5.16: Process Module – Resource Sets Dialogue

Also, the priority level of a process could be identified to control one or more entities that wait at this module for the specified resources (Figure 5.14).

The secondly main fed data in the process module is the delay value of the assigned crew of resources. Whereas delay values were previously identified in the start sub model, their assignment in the "process" module is simply to type their attributes' names as an expression delay type (Figure 5.17).

For instance, LEVELING 1 is an attribute name that implies the delay value of leveling the first work front (see Figure 5.11). It could be used as an expression delay type for the process module: LEVELING segment 1 in the LEVELING sub model (i.e. Launcher process). After that, this delay value of such process module will be permanently linked with that value which is located in the "assign" modules of the "start" sub model. Such procedure of identifying delay data guarantees an external and independent position of adding or modifying data for the entire model activities.

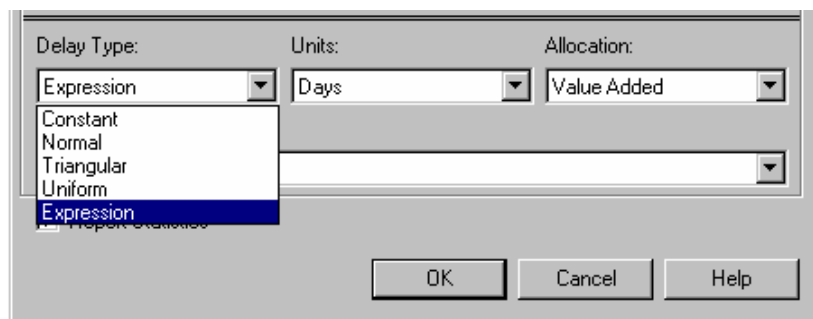


Figure 5.17: Process Module - Resources Delay Types

Figure 5.17 clarifies the available five cases of resources delay types. They graduate from the simplest formula (i.e. constant delay) to the most sophisticated (i.e. using the expression builder). This flexibility and variety in types of resources delays gives a wide support to apply such real life data and constraints. Regarding the set of record modules, it is mainly functioned to collect statistics in the simulation model. Various types of observational statistics are available, such as duration values during the simulation process. Simply, each of the process module is attached with one record module; to record the starting time of that process (when the entity enters that process), and so, one record module after; to record the process's completion point of time (when the entity exits that process). The used type of records is: an expression, in order to record a time value of TNOW (i.e. time now), as Figure 5.18 shows.



Figure 5.18: Record Module

The third part of the performance core is the decide module which is attached with the mentioned process modules' set, see Figure 5.13. This module is functioned to regulate the flow of the split entities inside a sub model. As shown in Figure 5.19, the used decide module has one entry point and several exit points. The used type is: N-way by condition, where N = the number of the connected process modules. The false exit of the decide module dispatches the entities with incompatible attributes.

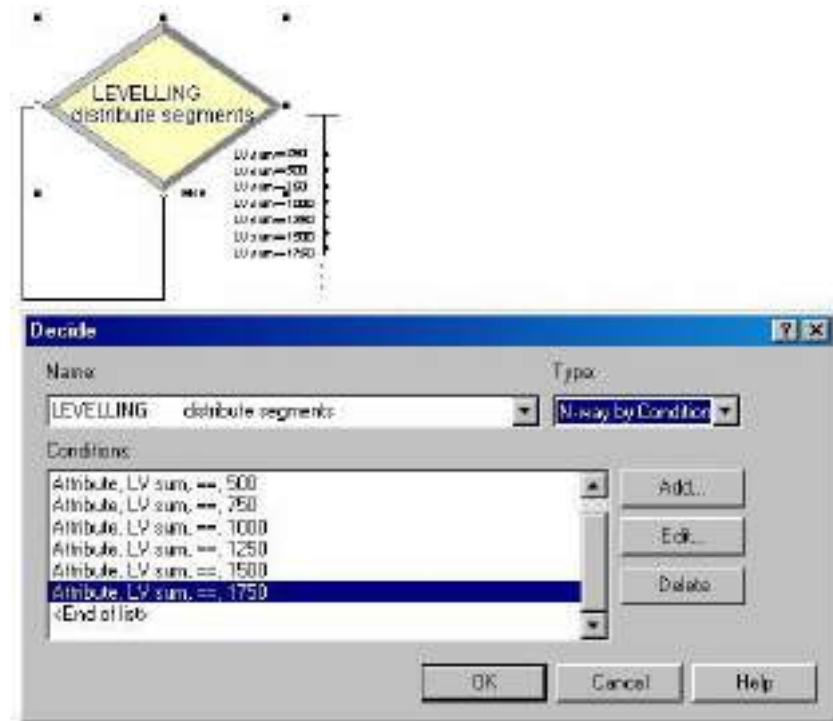


Figure 5.19: Launcher Process - Decide Module

Whereas a split entity represents a work front in the activity, the mentioned decide module directs such entities to their specified process modules. For instance, it is responsible to convey the secondly split entity to the process module that specified to perform the second work front in the leveling activity LEVLING segment 2, as Figure 5.13 clarifies. This action increases the flexibility of the entire model through creating such independent paths of the entity's duplicates, which allow to integrate inputs of unequal work fronts. (see Appendix 1)

The cumulative length from the project beginning point (0 m') to some work front in the entire project (X m'), is the main parameter that the decide module relies on. The basic embedded function is an "If-Statement", which constrains such length (i.e. work front) with its specified process module.

5.7.2.2 Splitting Core

This core is responsible to manage a programmed loop that splits an entity to the specified number of duplicates (work fronts) according to preset conditions. The arriving entity will be split periodically until it satisfies a pre-defined termination condition. In parallel with that process, each of the split entities will be performed at its specified process within the performance core.

The splitting process starts with giving an attribute (label) by an assign module called: generating segments (Figure 5.13) for the arriving entity that identifies its current length (LV sum = 0 m') and the project's total length (LV total = X m'), as shown in Figure 5.20. After that, the entity will pass through the performance core modules to be performed (work front execution).

The next step is to count such performed lengths of the project using another assign module, which gives a counter attribute that equals to (LV sum = LV sum + work front length). Once the entity passes through the counter assign module for the first time, its current attribute of its length (LV sum) will be changed from (0) to the value of the 1st work front length. (see Appendix 1)

Likewise, once it passes for the second time, such attribute will be changed from (the 1st work front length) to (the 1st work front length + the 2nd work front length), and so on, until it will get the value that equals to the total project's length; (LV total).

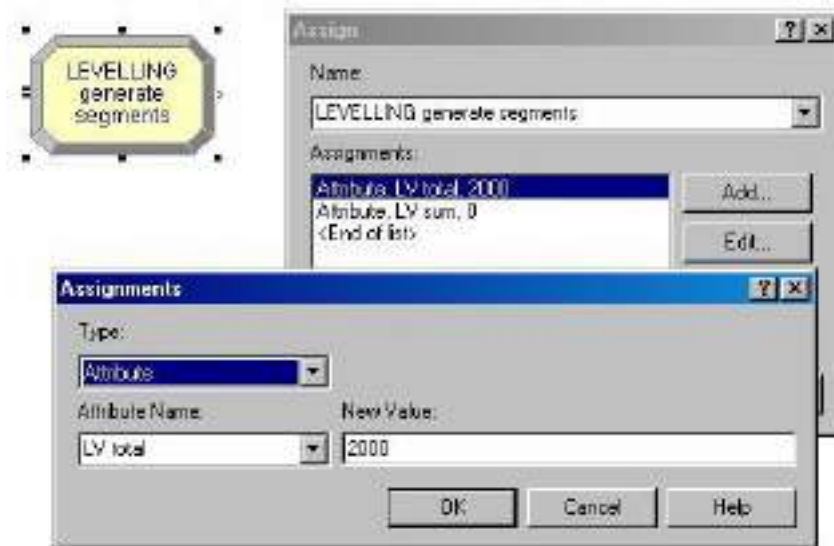


Figure 5.20: Assign Module – Sub Model: Launcher Process

The splitting process is governed by a decide module that is connected with a separate module (review Figure 5.13). Simply, such decide module has two logical gates; true and false. The false condition indicates that the splitting process is active. It will direct the entity to be split through the separate module into two duplicates, see Figure 5.21. The first duplicate will be conveyed to be performed in the next sub model (activity), and the other duplicate will be send back to the first point of the performance core which is the firstly explained decide module that is connected with the process modules set (Figure 5.13). After the performance of the second duplicate, it will pass again through the counter assign module to be labeled with a new LV sum value, which equals to: (its previous value + work front length).

The termination condition of the splitting process that was set in the decide module, is satisfied when all of the work fronts in the Launcher Process sub model were performed. In other words, when the counter assign module labels an entity with a cumulative value of (LV sum) that is equal to the (LV total). Hence, the true gate of the decide module will be activated to convey the last entity's duplicate to the next sub model directly without being split. (see Appendix 1)

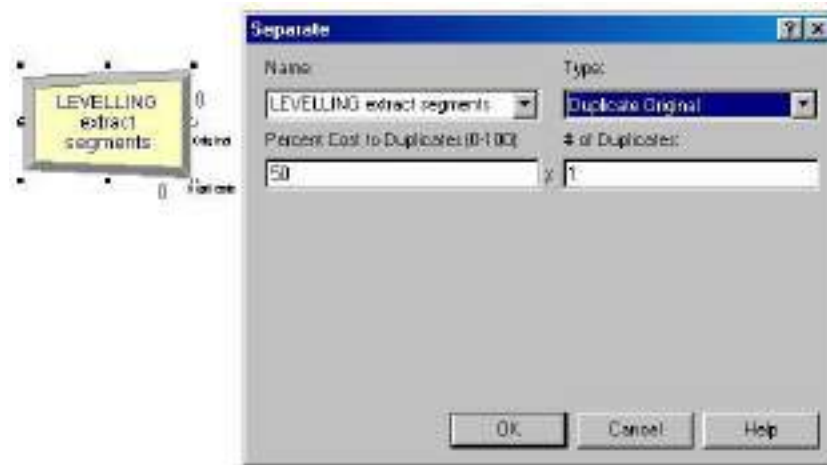


Figure 5.21: Separate Module

5.7.2.3 Flow Mechanism Summary

The operations that happened to an entity within the Launcher Process sub model could be summarized in three processes; performance process, splitting process, and transmission or conveying process. The (1st) activity (i.e. Launcher Process) leads the other activities with one work front accomplishment at least. In other words, the (1st) work front in the Launcher Process has to be performed in order to launch its (2nd) work front, and at the same time; to start the (1st) work front of the next activity.

The entity that arrived from the start sub model is performed for the first time representing the (1st) work front, and then split into two duplicates; the (1st) duplicate is conveyed to the next sub model representing its (1st) work front, and the (2nd) duplicate will be performed at the (2nd) process in the current sub model (i.e. 2nd work front). The (2nd) duplicate that is still inside the current sub model will be split again into two new duplicates; the (1st) is conveyed to the next sub model representing its (2nd) work front, and the other duplicate will be sent back to be performed as the (3rd) work front in the current activity, and so on, until satisfying the termination condition of this loop, which is performing all work fronts of the (1st) sub model.

What complicates these operations is to be overlapped and concurrent. For instance, while the (7th) entity's duplicate is performed in the LEVELING sub model (i.e. the first activity), the (2nd) duplicate, which exit such sub model earlier, is proceeded within the (11th) activity (i.e. SUB GRADE).

So, the complicated and overlapped environment in the simulation model reflects the real nature of the execution environment and allows an opened work strategy for all activities and resources regardless any other logical considerations which govern some conventional planning methodologies, such as: pull or push driven concepts (i.e. LSM and CPM), or rhythmic production (i.e. LOB).

5.7.3 Normal Process Sub Model

These sub models are the main units of the simulation model's structure. It was given the blue color, with one entry point; to receive the entities' duplicates from the previous activity, and also one exit point to transfer these duplicates into one stream line to the next sub model.

Normal Process sub model has a simple function when compared with the Launcher Process sub model. It is responsible to perform the arriving duplicates of entities and transfer them directly to the next activity. Such function represents the same function of the performance core in the previously explained sub model (i.e. Launcher Process).

The layout that is shown in Figure 5.22 illustrates the content of one decide module, a set of process modules, and a set of record modules, with the exact purposes that mentioned in the performance core of Launcher Process.

The current sub model can be considered as a fixed station that receives the corresponding entity's duplicates (i.e. the project's work fronts) and perform them in order to convey them to the next station (another Normal process sub model). The performance operation within this sub model is responsible to direct each entity's duplicate to its appropriate record and process modules. In other words, the Normal Process sub model directs each duplicate in the model into its specified path that; the firstly performed duplicate in the previous sub model is the firstly performed one in the current sub model, and so in the next sub model up to reach the last activity.

The direction process of an entity's duplicate mainly relies on the label that it was given by the counter assign module in the splitting core of the Launcher Process sub model. Each of the generated duplicates was given a unique label that indicates its work front's position (i.e. cumulative length LV sum).

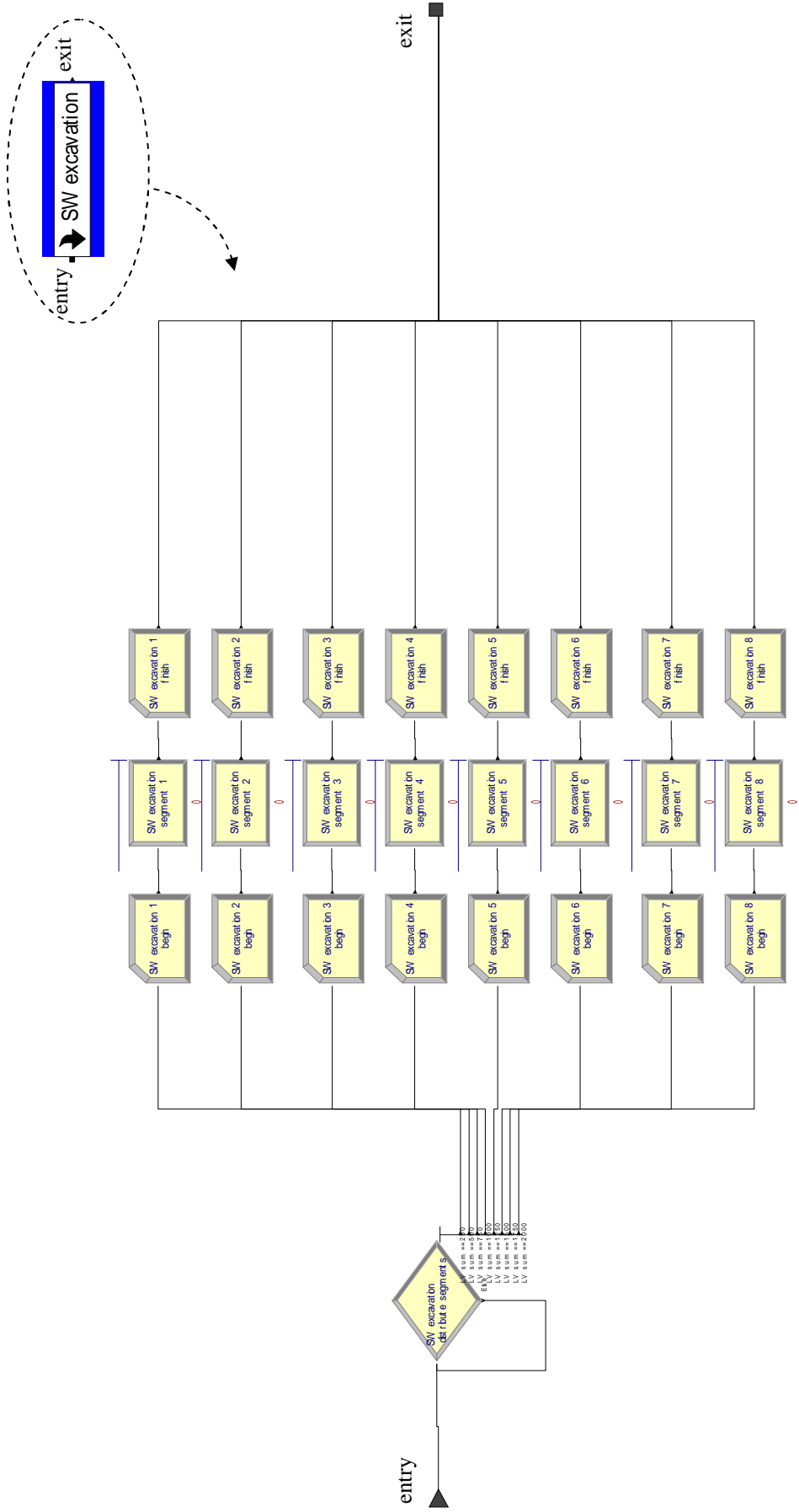


Figure 5.22: Normal Process Submodel Contents

Once an entity's duplicate is received, the only constraint that governs the simulation process inside this type of sub model is the availability of the assigned crew of resources that is responsible to perform the current activity.

5.7.4 Testing Sub Model

Testing submodel is an important logical requirement that comes after some activities in the model. It is a colorless sub model with one entry point and one exit point, see Figures 5.23 and 5.7. The main function of this sub model is to dispatch a faulty executed work front, even partially or fully, for re-work or fixing.

At the level of the entire model, there are two main tests that are associated with the project activities; hydraulic tests and field density tests (compaction tests). The hydraulic test is assigned for the pipes work milestone and the field density test is frequently used within the Sub grade, Side walks and Road milestones. (see Figure 5.7)

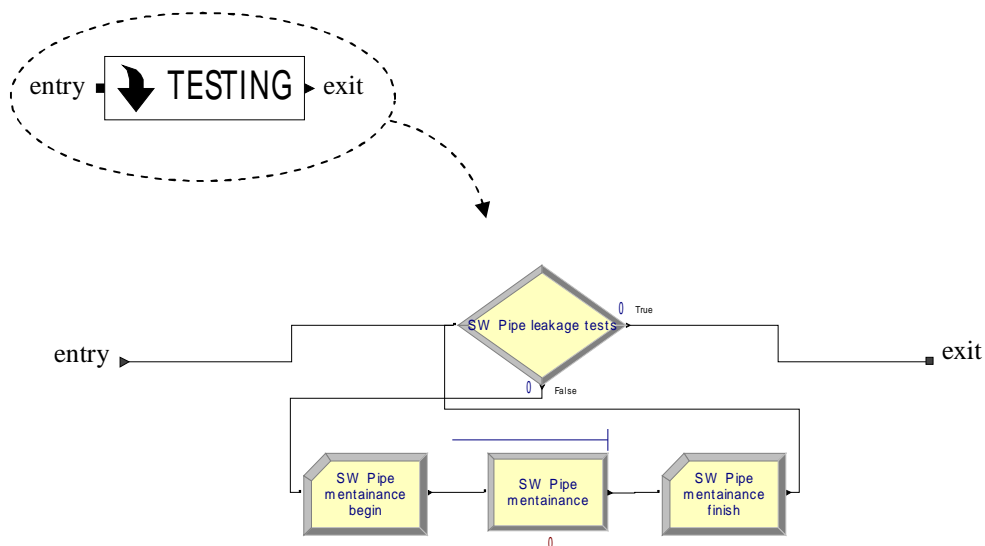


Figure 5.23: Testing Submodel Contents

The Testing sub model depends on a decide module that has the type of: 2-way-by chance (Figure 5.24). The decision depends on statistic records of (1%) failed hydraulic tests, and (2%) failed field density tests, (Al Tabbaa, 2005). For instance, the entity's duplicates that passes through the hydraulic tests sub models have a chance of (99%) to pass directly through the true gate and only (1%) chance to be moved to the false gate of the decide module that is embedded in the current sub model. (see Appendix 1)

The typical layout of the Testing sub model that was shown in Figure 5.23 clarifies that the true gate of the decide module will lead the duplicates directly to the next sub model, and the false gate will move the duplicates to enter the re-work station. Such a station consists of one process module that is attached with a single record module before, and another one after.

Once an entity's duplicate is considered as a faulty part of work, it will be identified in terms of the current time (i.e. time of starting the re-work process) by the first record module, and it will be performed within the process module using the specified resources' crew, and after that the time of accomplishment of this process will be captured by the second record module.

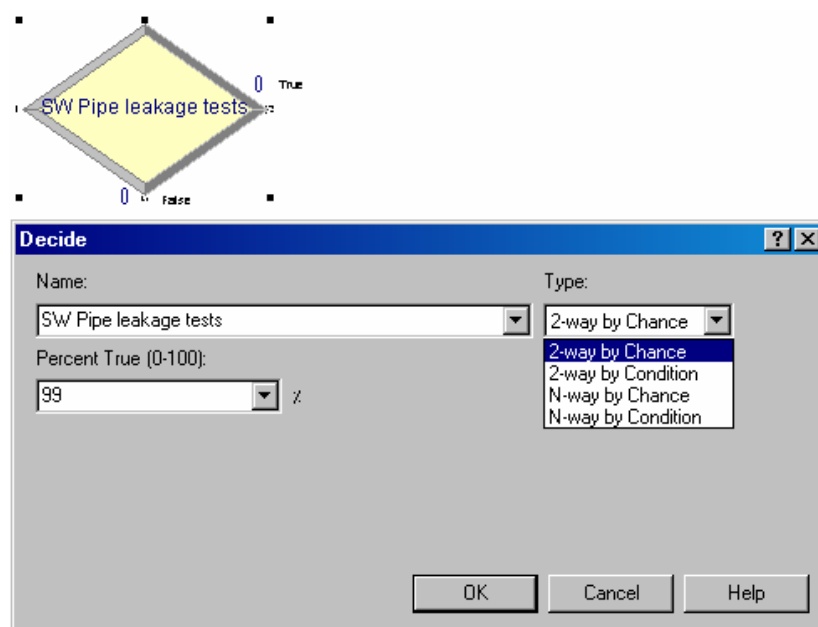


Figure 5.24: Decide Module: Testing Sub Model

5.7.5 Distribute Sub Model

As Figure 5.25 shows, the Distribute sub model takes the black color. It has one entry point and two exit points. So, it receives one work stream and distributes it into two work streams in order to satisfy the logical requirements of the model. The current sub model represents the logical junction that is located in the main layout of the project's milestones (Section 5.6).

The Distribute submodel consists of only one separate module, which is the same as the one used in the Launcher Process sub model (see Figures 5.13 and 5.21). In the entire model, there is one Distribute sub model located after the CSTONE beams sub model (see Figure 5.7). The incoming entity's duplicates enter this sub model to be doubled, and directed into two parallel independent paths that could receive, perform, and convey entities into two flow lines just after accomplishing the CSTONE beams work front.

When a project (i.e. an entity) is partitioned into eight work fronts (i.e. duplicates) Launcher Process produces eight duplicates of the generated entity. The eight duplicates are processed in the model's activities until reaching the Distribute submodel, which splits each of the arriving entities into two duplicates. After this process, there will be a total 16 entities; 8 are processed within the side walks milestone activities, and the other 8 duplicates are processed within the road milestone activities. This operation indicates that there is not any dependency relationship between the side walks and the road milestones that they could be performed simultaneously. The only conjoint parameter is the availability of the assigned crews of resources.

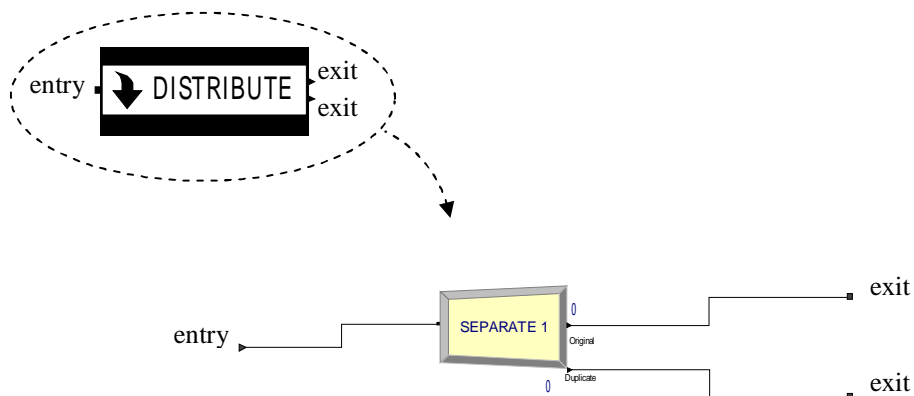


Figure 5.25: Distribute Submodel Contents

5.7.6 Assemble Sub Model

In contrast, the Assemble sub model, which is also black colored, has two entry points and one exit point. This sub model is designed to re-aggregate the split work streams into one line again and to batch the entity's duplicates into one entity that holds all of the desired records and information of the performed activities in the project.

The layout of the Assemble sub model consists of three batch modules as shown in Figure 5.26. A Batch module is intended as the grouping mechanism within the simulation model. Both modules Batch 5 and Batch 6 are designed to receive duplicates from both side walks and road milestones and aggregate them into one entity at each batch module. The third batch module, work batch, will receive the only one entity from the batch 5, and also one from the batch 6 and aggregates them into one entity in order to be disposed in the next sub model.

The batch size is the basic parameter that a "batch" module relies on. Figure 5.27 clarifies a typical "batch" module. For instance, if there are (8) work fronts (i.e. 8 duplicates), the batch size of both "batch 5" and "batch 6" will be: (8), and always the batch size of "work batch" is (2). Each of "batch 5" and "batch 6" will wait to receive its (8) entities, otherwise, the simulation process will not be ended. Likewise, the "work batch" module is obligated to wait for receiving (2) duplicates. (see Appendix 1)

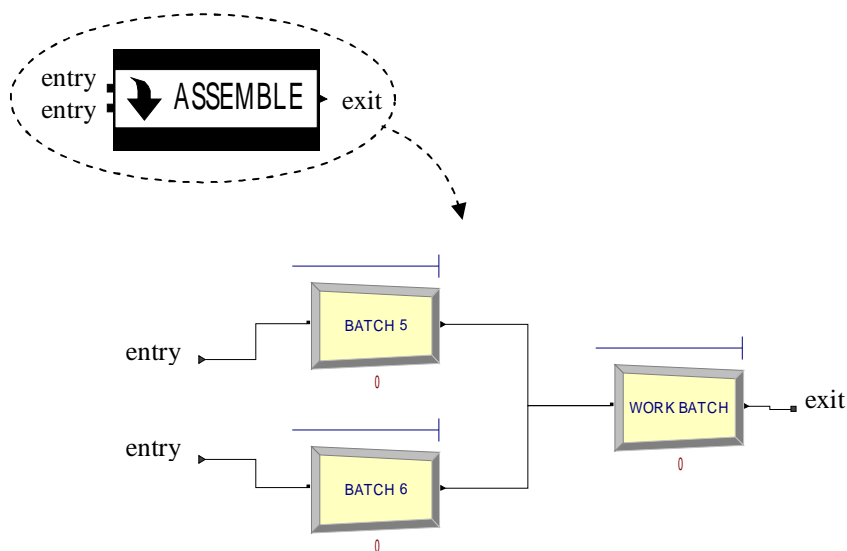


Figure 5.26: Assemble Submodel Contents



Figure 5.27: Batch Module

5.7.7 Handing Over Sub Model

This sub model represents the final step in the simulation process. It has the gray color, and have one entry point, and no exit points, Figure 5.28. Its main function is to end the simulation process. The single entry point is to receive the incoming single entity from the Assemble sub model. Having no exit points indicates that this sub model includes the termination point of the simulation process. Figure 5.29 illustrates the Dispose module that form the core of Handing over sub model.

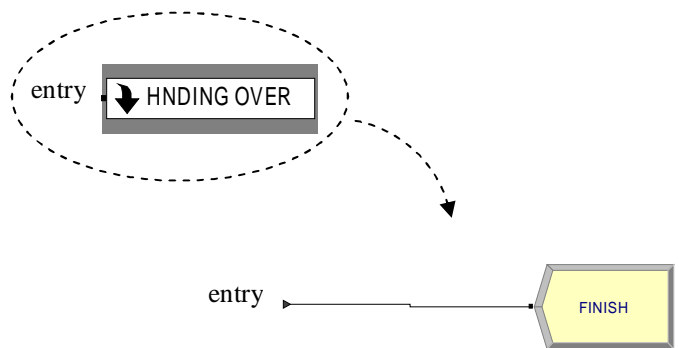


Figure 5.28: Handing Over Submodel Contents

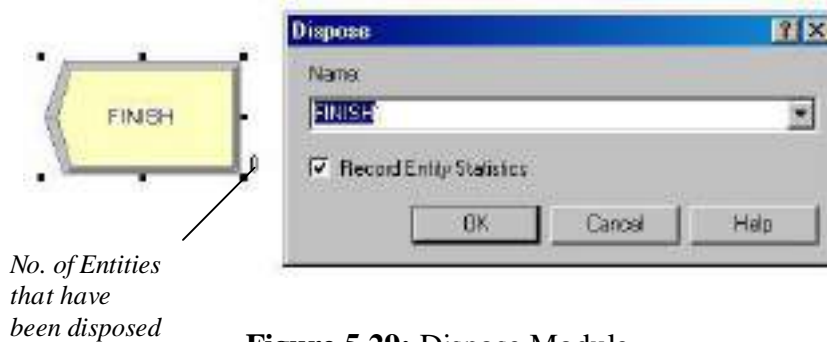


Figure 5.29: Dispose Module

6 MODEL VALIDATION

6.1 Model Verification and Validation

As explained in the previous chapter, the built model adopts the statistical approach for the data duration data, however, the selected case study has been already achieved using the traditional means of scheduling that adopts the deterministic approach. So, verifying the developed simulation model preliminarily requires a deterministic case of application. After assuring the model validity, the gathered statistical data can be performed safely and the results will be objectively accepted.

Actually, the gathered statistical duration records of the selected case study has never been used in preparing its schedule, however, such data is planned to be fed to the model in order to enhance and enrich the expected results. Conversely, the model verification process checks its logic and performance through a comparison versus the applied traditional schedule of the selected case study (MS Project), using the same deterministic data of duration.

The application of such verification case of the model presented the same duration results of the original schedule. Likewise, some activities of work in the simulation model was checked individually and gave the same results. So, the simulation model has a correct logical relationships for the RAP activities, and it is ready to perform more sophisticated data in order to enhance the schedule of the case study.

The validation process is to determine whether a simulation model is an accurate representation of the system, for the particular objectives of the study (Law, 2005). While the built simulation model was verified in terms of logical structure, the remaining step is to be activated to achieve the planned objectives of the research. The application of typical case study on the model is the best mean to achieve and justify the validation process.

6.2 The Case Study

As mentioned before, a typical infrastructure project has been selected to be a representative RAP application using simulation by Arena. Such project data was gathered from a leading contracting company with an extensive experience in the infrastructure work fields. A number of interviews was made with the project manager, who kindly provided all of the needed data and information to build and use this model. The project is mainly divided into five stages that were presented in the previous chapter (Figure 5.27). Bill of quantities and resources data are presented in Appendix 2.

6.2.1 Input Data

The built model of Arena depends on two main types of data: data to build the model, and data to use the model. Starting with the former, data to build an infrastructure project model using Arena represent the fixed part that only skilled users (i.e. familiar with Arena) can deal with. It is such flexible that it could be modified in terms of addition or omission of any of its components. This type of data, which the model has been designed to minimize its "user interpose", consists of: list of activities, work sequence and logical relationships, the assigned resources and crews per activity, and the possible number of work fronts.

The second type of the input data is: data to use the model. This type is divided into three sections: duration data (i.e. resources delays), resources data (i.e. capacities, assignments and costs), and priority identification if needed. Production rates of the assigned resources crews are the main sources of duration inputs. Once the work quantities are known, resources delays values could be simply calculated using Excel. All of the model's processes data regarding resources production rates, crews assignments, and delays values and types are attached in Appendix 3.

6.2.2 Running Scenarios

The designed model has a capacity of eight work fronts and the performed case of the built model was 2000 m length (Appendix 2). Hence, there are eight possible scenarios for the selected case study, however, four main scenarios of the project were assumed in the model runs to simplify the illustration of the outputs:

1. One work front (2000 m length)
2. Two work fronts (1000 m length each)
3. Four work fronts (500 m length each)
4. Eight work fronts (250 m length each)

Due to the change in work quantities (i.e. road length), each of the above mentioned cases has a particular list of resources production rates for each process in the entire model, see Appendix 3. However, the first two cases are expected to be far from the infrastructure work habits, their results could be useful to clarify the behavior and illustration of the "work fronts" concept.

Moreover, the model has only handled resources costs, and neutralized any other costs, such as: material, managerial, or permanent staff costs, due to their static effect on the overall cost value, and to decrease Arena's performance load on the hardware. Also, four of the used resources were considered as permanent resources that were owned by the executing company, and also there were other four resources that have a usage cost. (See Appendix 2).

6.2.3 Model Output

Arena provides another option to support the realistic trend of the results. In the "tools" menu, options, there is a "settings" dialogue for the "replications parameters". A model could be run for a specified number of replications in order to gain more confidence. This option is advantageous especially when there is a considerable variety in the input data figures.

In the current model runs; ten replications produced a tolerance that does not exceed $\pm 4\%$ of the resulted average values, which means a "96%" confidence ranges for the whole results.

According to section 5.2.3, the remaining suggested steps after data gathering and model building, were four steps: Preliminary Simulation – Optimization – Basic Simulation – Final Output Features.

6.2.4 Preliminary Simulation Processes

This phase simulates the assumed cases of the project. There are four possible situations that were mentioned in the previous section. The main purpose of this step is to specify the planning intention of the decision maker through the preliminary choice of the most appropriate case. The user is expected to depend on the project's contractual constraints and his expected execution means and capabilities as main sources of his decision in this stage. The simulation running output for the four cases of the project against both costs and total duration are demonstrated in Figures 6.1, 6.2, and 6.3.

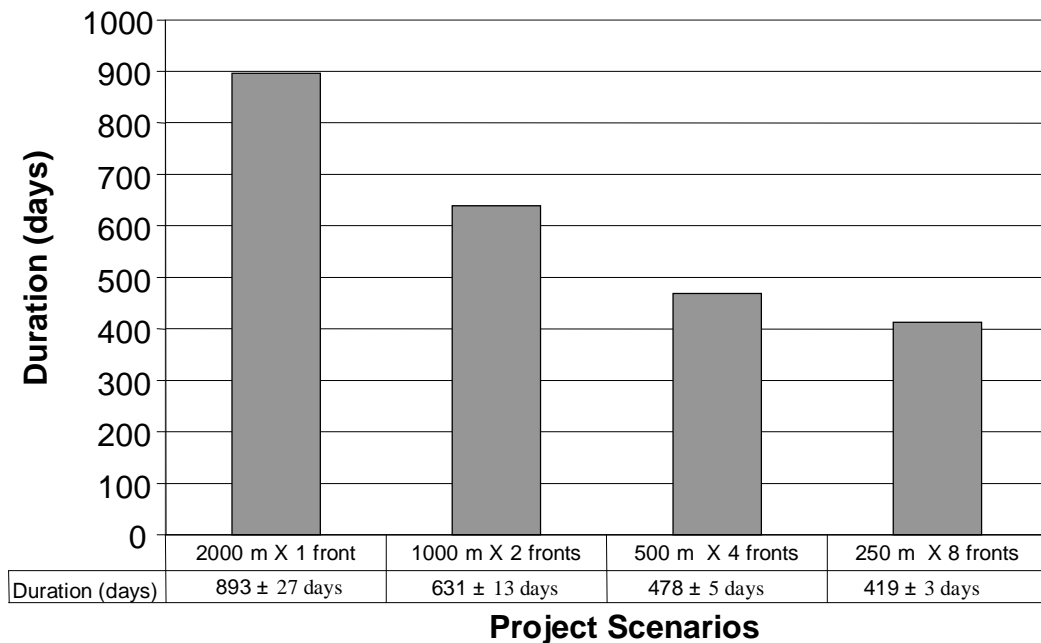


Figure 6.1: Project Duration According to the Preliminary Simulated Scenarios

Figure 6.1 presents the total duration for the four simulated scenarios of the case study. The method of executing the project (i.e. partitioning strategy) has a valuable influence on the total project duration. For example, when a project is divided into eight work fronts, it will take (419 days), which is the minimum duration among the simulated scenarios results.

The results shown in Figure 6.1 implies an inversely proportional relationship between the project duration and the number of work fronts. Accordingly, the greater number of work fronts is advantageous regarding duration and work continuity. However, this advantage is constrained to some other limitations such as resources capacities and availabilities, technical constraints of execution and/or the contractual limitations.

Figure 6.2a presents the total resources costs of each scenario, which is equal to the summation of the idle cost and the value added cost. The value added cost (VA cost) equals the busy cost (the cost of the resources work while it actually performs activities) and the usage cost (the additional cost of transportation, launching and/or maintenance of a resource at every start of its use). The idle cost represents the cost of a resource while it actually waiting to be seized by an activity.

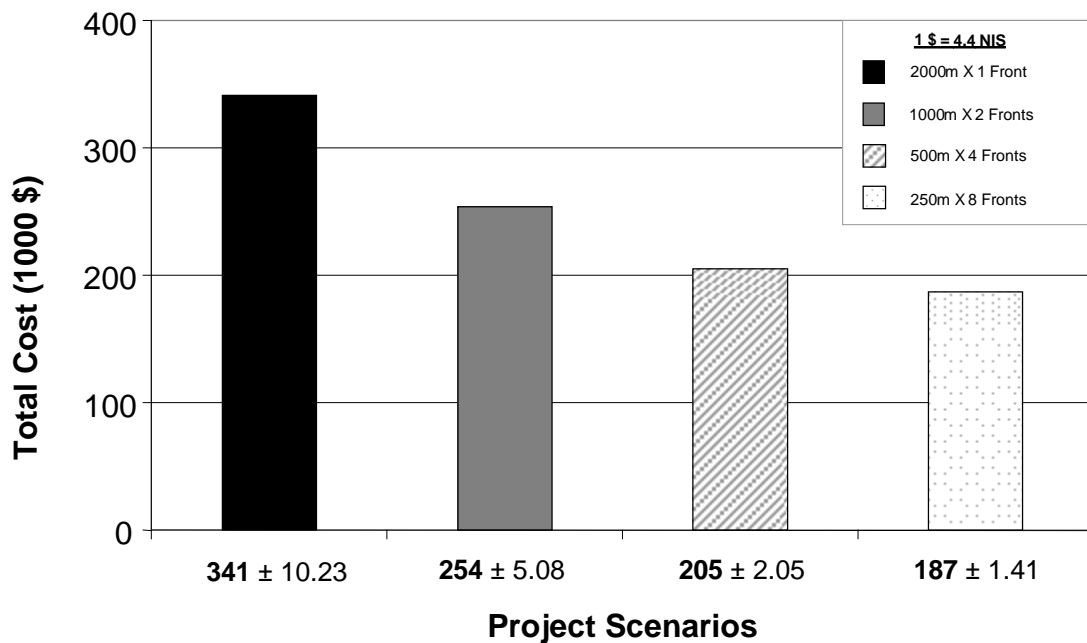
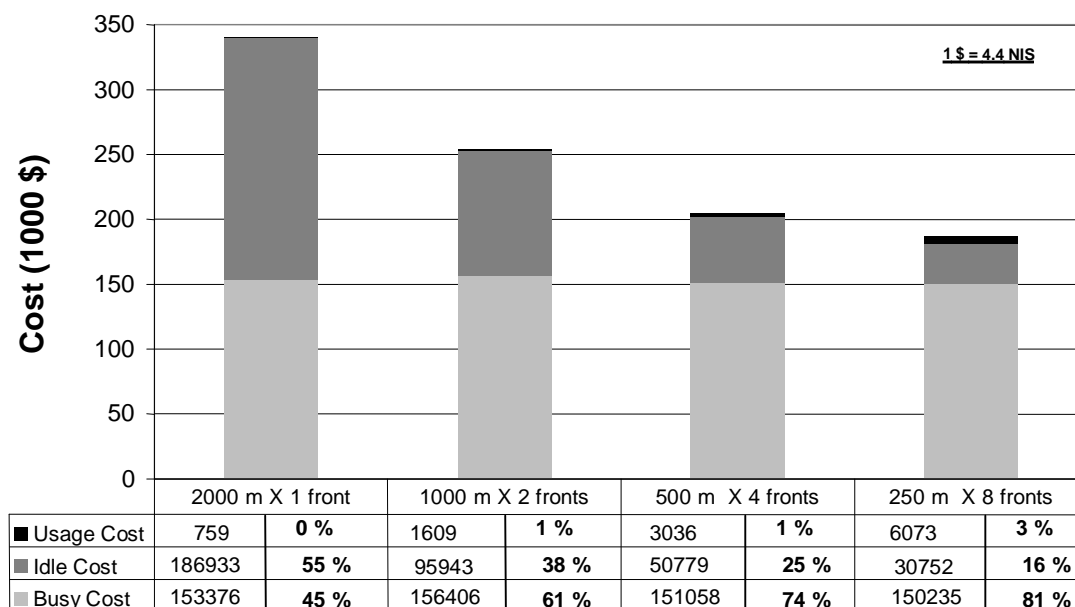


Figure 6.2a: Project Total Costs According to the Preliminary Simulated Scenarios

In Figure 6.2b, which details and interprets Figure 6.2a, the busy costs are relatively close to each other, and this is logical because there would not be a difference in the "busy" cases of the project scenarios. The usage costs could add a small difference to the busy cost. It mainly depends on the usage frequency of a resource, so, the highest value of usage cost is expected to be in the (250 X 8 fronts) scenario due to its high frequency of using resources.

Anyway, usage costs values are so small and could be neglected against the total costs. The considerable difference that is observed from Figure 6.2b is the idle cost. Such type of costs represents the idleness amount of a resource while it is waiting for an eligible activity to be performed. The idleness is considered only when having permanent resources (i.e. owned by the company) that are especially assigned for the current project, otherwise, a full detailed calendar might be prepared in order to rent such resources if available. So, the shown idle cost values assume that all of the owned resources were assigned only for the current project, and this is just to clarify the difference between scenarios in terms of resources utilizations. In other words, when a resource is in an idle state, it could be utilized in another project.



Project Scenarios

Figure 6.2b: Costs Proportions According to the Preliminary Simulated Scenarios

As can be seen from the costs percentages of each scenario, there are considerable difference in the simulated scenarios. For instance, the first scenario has an idle cost value that equal is to 55% of its total cost, while the fourth scenario idle cost is 16%.

6.2.5 Optimization Process

The optimization process has a valuable role in the proposed planning procedure once it presents the optimum resources crew for such sophisticated constraints. OptQuest for Arena is the optimization tool of the selected case which located at the tools menu. Such add-in imports all of the model's data from Arena to an independent environment, and performs numerous batch runs for it, see Figure 6.3.

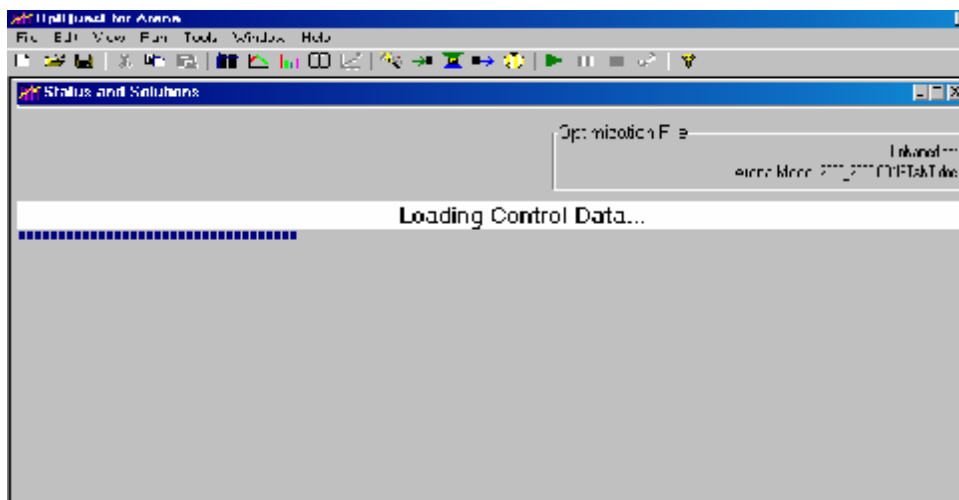


Figure 6.3: Importing Arena's Model by OptQuest

The optimization process mainly relies on the identification of the constraints and the objectives of the performed case. It begins with the identification of the resources constraints, which is called controls in the OptQuest environment. The controls, shown in Figure 6.4, have to be firstly specified in terms of minimum and maximum capacities; upper and lower bounds, and secondly in terms of work crews through constraints equations. For instance, each mason needs two labors at least, it means that the number of labor has to be more than double the number of masons, and so on, see Figure 6.5.

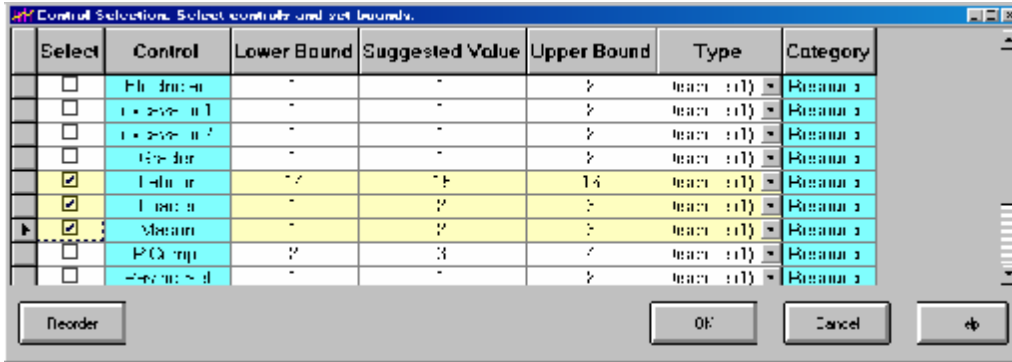


Figure 6.4: Selection and Bounds Settings Window for Resources to be Optimized

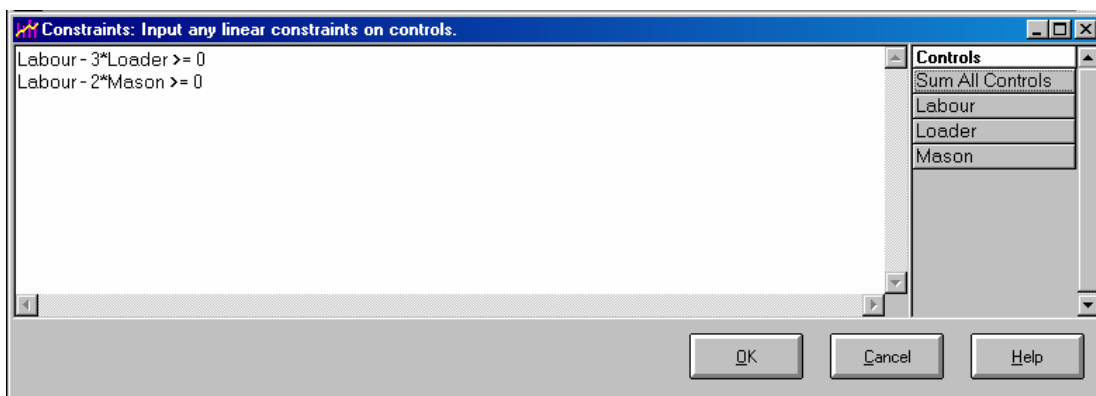


Figure 6.5: Window of Defining Constraints on Resources Crews

The second type of constraints is handled in the Status and Solutions window in the OptQuest and called Requirements, presented in Figure 6.6. Such Requirements have to be defined in terms of upper and lower bounds. Those Requirements are considered as global constraints of the project case where all of the outputs parameters response data could be constrained as requirements. For example, the total project value added cost should not exceed 650,000 NIS. Finally, only one objective is allowed to be defined in this OptQuest window, such as Minimize Objective could be chosen for the total duration or the total cost parameter.

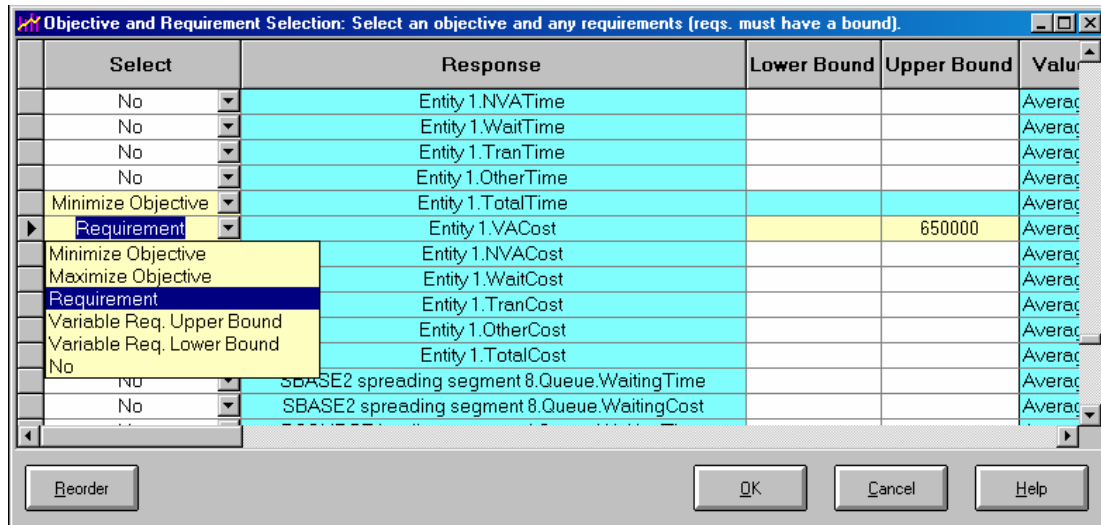


Figure 6.6: Objective and Requirements Selection Window

The optimization process was made for the (500m X 4 fronts) scenario. It is assumed to be the most proper scenario for the planner according to the preliminary simulation results as shown in Figures 6.1 and 6.2. The resources capacities of the preliminary simulated scenario and the delay values are located in Appendices 2 and 3 respectively. The OptQuest input data is shown in Table 6.1.

Table 6.1 The OptQuest input data for Scenario: 500m X 4 fronts

Control	Lower bound	Suggested value	Upper bound
Labor	14	15	50
Loader	1	1	5
Mason	1	1	5
Plate Compactor	1	1	35
Constraints	3*labor - loader >=0	3 labor with each loader	
	2*labor - mason >=0	2 labor with each mason	
	1*labor - p.comp >=0	1 labor with each plate comp.	
Requirements	650000 NIS < (Entity1)VA cost < 1000000 NIS		
Objective	Minimize Objective for: (Entity1) – total duration		

All of the previously mentioned steps were a preparation for the OptQuest optimization process. OptQuest then starts to optimize through performing a large number of simulation trials for the same model according to the fed constraints and objective.

The number of simulation runs could be specified, or a termination time could be set for the whole optimization process. First, the optimization process has too many probable simulation cases to be run for the performed scenario. Such cases are generated from the variable capacities of the optimized resources that were fed as the upper and lower limits, besides the other preset constraints. The optimization process starts with the original data of the fed scenario and seizes the first run results. After that it performs another run seeking for better results. Once a new run has better results compared with the first run, it will be seized instead of the first one, and so on until performing all possible runs. The best solution could be picked while observing the convergence and divergence behavior of the minimized objective. The main output of the optimization process is the best resources capacities against the selected objective and the defined constraints, see Figure 6.7.

Simulation	Minimize Entity 1.TotalTime	Requirement Entity	Labour	Loader	Mason	P.Comp.
1	468.521	678016.	15	1	1	1
2	468.577	678016.	16	1	2	2
3	325.887	678016.	18	3	3	18
4	301.214	678016.	20	5	5	20
Best: 6	290.995	678016.	26	3	5	5
Current: 9	385.702	678016.	32	3	1	31

Figure 6.7: Status and Solutions Window

Figure 6.8 shows the resources capacities status during the optimization process. User could observe the capacities behavior during the optimization process simultaneously. Figure 6.9 demonstrates the performance graph of the optimization process. The performance graph consists of the simulation runs as the x-axis and the objective values as the y-axis. This graph actually clarifies the feasible and unfeasible solutions of the objective and how many simulation runs it takes to reach such result.

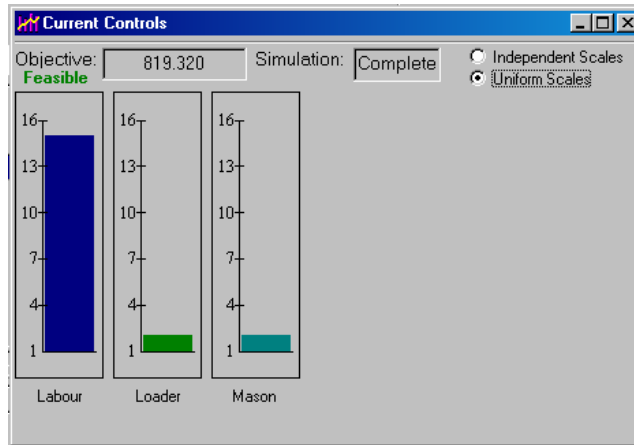


Figure 6.8: Controls Bar Graph

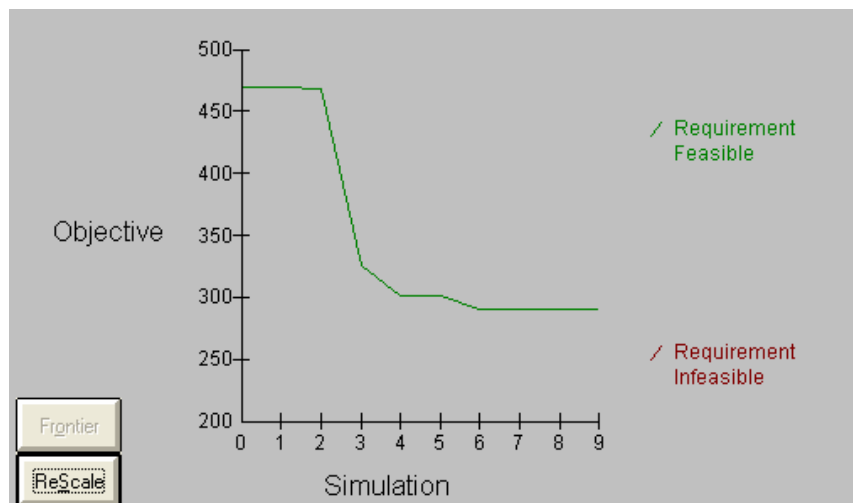


Figure 6.9: Optimization Performance Graph

6.2.6 Basic Simulation Process

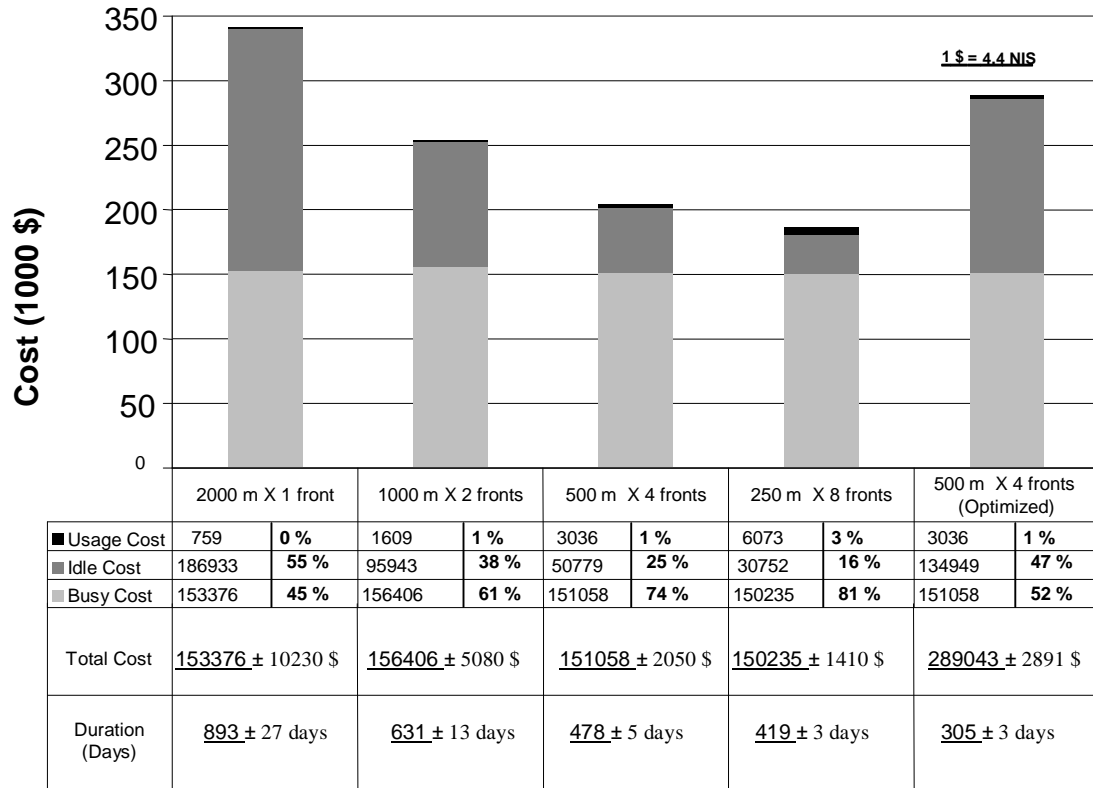
The Optimized case as performed in the previous section will be used to present a new situation for the preliminary selected cases regarding the resources combination. The new resources capacities that resulted from OptQuest will be fed-back again into Arena's model. The simulation run of this modified model case is the basic and final run, and considered as the main source of the project's resources plan and information. Table 6.2, Figure 6.10 presents a comparison between the optimized case of scenario (500m X 4 fronts).

Table 6.2 Comparison Between the Normal and Optimized Cases of Scenario (500m X 4 Fronts)

Item	500m X 4 Fronts Normal Scenario	500m X 4 Fronts Optimized Scenario
Permanent Resources Capacities		
Labor	15	26
Mason	1	5
Loader	1	3
Plate Compactor	1	5
Total Duration (days)	469	291
Busy Cost (NIS)	664655	664655
Idle Cost (NIS)	223428	593776
Usage Cost (NIS)	13360	13360

A substantial decrease in duration (about 38%) was achieved by the optimization process, while the value added costs (i.e. busy cost + usage cost) got the same values due to the constancy of the project's work quantities and activities. An increase of about 37% has occurred for the idle cost value due to the increase in the optimized resources capacities. The planner perspective has to be open enough to decide how to tune the company's resources. The idleness problem could be avoided either by renting all of the project's resources, or by coordinating the utilization of the permanent resources to get an acceptable investment value for them.

The idle costs is a challenge that has to be carefully handled, the duration reduction that gained by optimization is worth to increase costs in general. Such desired objective (minimize duration) could become "cost free" if the current project plan is integrated with a general utilization plan for the owned resources of the company. This plan has to set an investment strategy for the owned resources that does not only depend on the running projects of the company, but also may lend them to another company, for instance. Figure 6.10 demonstrates the duration and costs values comparison for all of the applied scenarios, including the optimized scenario.



Project Scenarios

Figure 6.10: Cost Proportions and Duration Summary According to the Simulated and Optimized Scenarios

6.2.7 Final Output Features

This is the final step of the suggested approach of RAPs resources planning. The simulated model's output results, which located at Arena's reports panel, concern two main parts of resources data: costs reports, and duration reports (resulted from "records" modules). Regarding costs reports, there are such clear and detailed information about busy cost, idle cost, and usage cost for each resource. (see Appendix 4)

The duration output data, which mainly consists of time of start and time of finish for each process, is available in a report category called user specified. It have to be transferred to MS Excel, where a group of linked spreadsheets that especially prepared for the simulated case. The spreadsheets performs the input start and finish time points that integrated with the other resources facts of the case, to produce practical planning features for the used resources.

Figure 6.11 presents a sampled usage frequency chart for the used labors in the entire project period. It illustrates the needed labors capacities per day for the performed activities processes during the mentioned period.

One of the shown days may include several activities that share similar resources such as labors, and that is the main reason to get this shape of labors usage pattern. Moreover, Table 6.3 is a detailed schedule for the used labor that analyzes the highlighted section in Figure 6.12, which represents the ninth week of work. The table specifically allocates the used number labors in the opened work fronts at that period. As shown, at the ninth week of work, only six work fronts of eight have been started.

The spreadsheets have the full details of the project's activities, in terms of time and resources information, the matter that makes them a simple source of the project's planning and scheduling reports that a user can simply form for any time point or for any of the used resources. Moreover, resources cost information through the project could be integrated with time information as well.

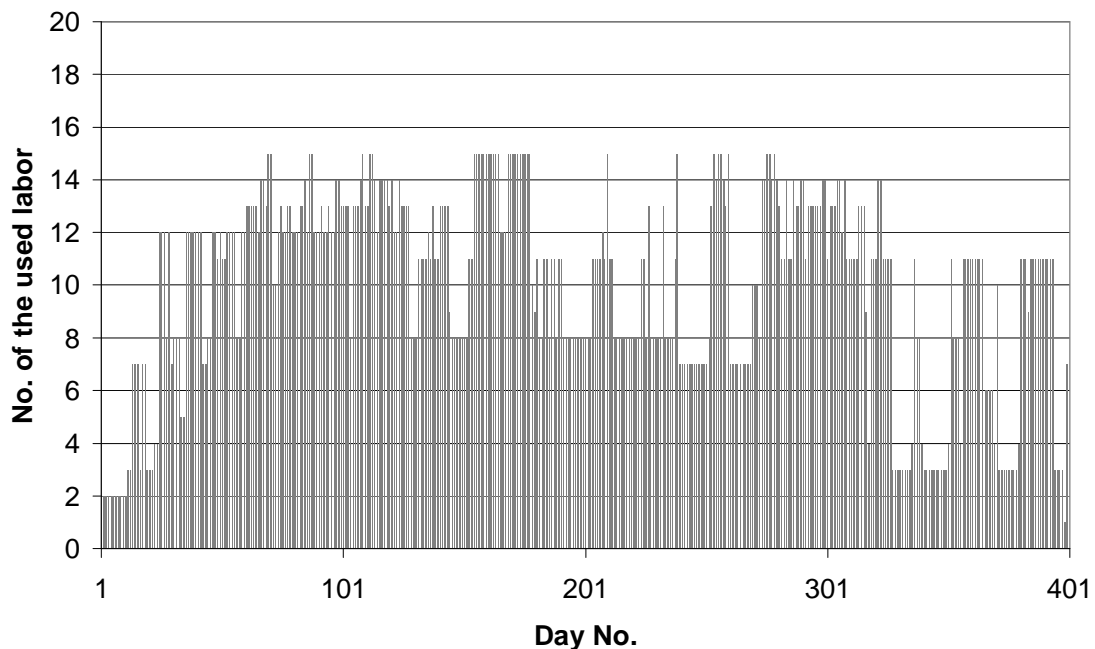


Figure 6.11: Labor Usage Frequency for the Entire Project

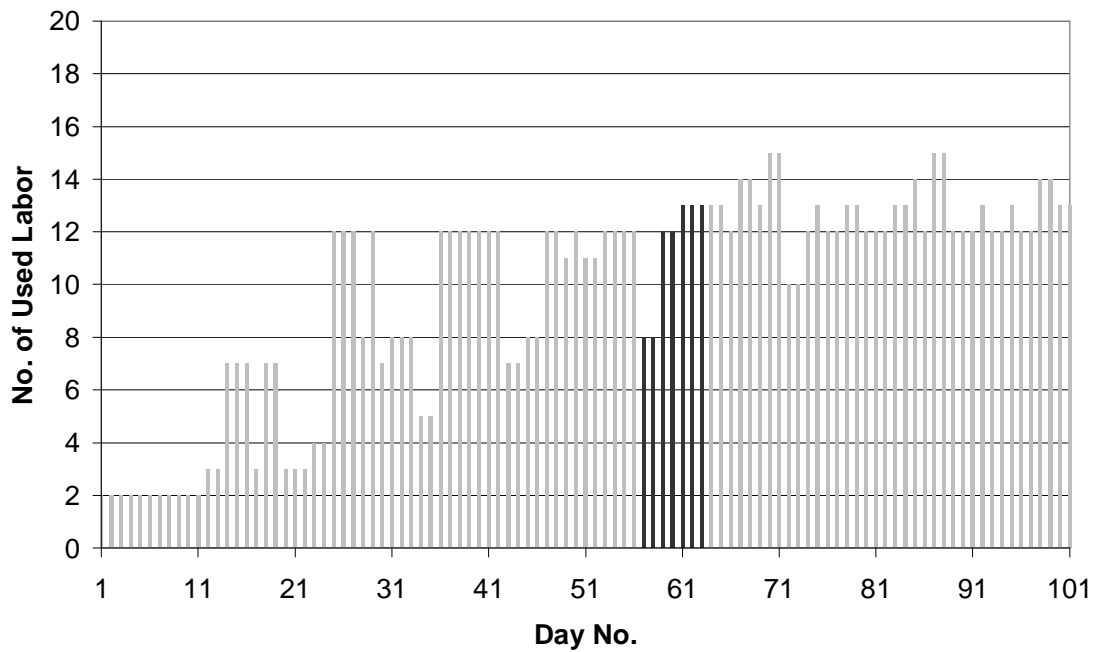


Figure 6.12: Labor Usage Frequency for the First 100 days

Table 6.3 Labors' Work Details for the Ninth Week of the Project

Week 9		Day 57	Day 58	Day 59	Day 60	Day 61	Day 62	Day 63
Activity	Location (work front)	No. of Used Labors						
Leveling	6	2	2	2	2	2	2	2
SW Excavation	5	1	1					
SW Pipe laying	5				5	5		
DR Backfilling	4			5				
WA Excavation	3	1	1	1	1			
WA Excavation	4					1	1	1
WA Pipe laying	3						5	5
C.Stone masonry	2					5	5	5
C.Stone beams	1	4	4	4	4			
Total		8	8	12	12	13	13	13

The MS Excel has been chosen to perform Arena and its OptQuest add-in results in order to establish an integrated system of construction simulation in general, besides being simply used and having such advanced utilities. MS Project could also be efficiently utilized to perform Arena's final output to produce the final planning features (see Appendix 4). The start and finish time points of each activity can be transferred to the MS Project that directly plots the project's schedule and produces the related reports, however, only the graphical utilities of such software will be utilized. In other words, the MS Project has to handle the transferred data as blank objects and just for presentation purposes. Moreover, MS Project does initially imply a CPM planning approach, while establishing an integrated simulation system between Arena and MS Excel is more independent and aptitude to be adjusted and elaborated by further researches.

6.3 Execution Strategy

Generally, CPM plans of a construction project have such common scheduling habits that keep the project's activities to be continuously performed, without the need to divide them into work fronts. Once an activity starts, it will be performed continuously with a specific rate until being accomplished without any interruption. In parallel, other overlapped activities are probably being performed at the same time, and sometimes share the same resources. Both work continuity and activities overlapping concepts can be applied in the bar chart plans by using the "lag" option in order to control the overlapped activities, however, such planning approach does not have the best results as reported by the literature in chapter two. For instance, the bar chart schedule of the case study gives a total duration of 600 days when applying this planning approach, which is considered a weak planning alternative when compared with the preliminary simulation results of the same case, besides producing only single planning attempt.

On the other hand, the application of work fronts strategy, which was accredited by the simulation model, increased the planning alternatives and clarified the behavior of the used resources throughout the executed activities. Dividing the case study into equal eight work fronts developed a number of possible scenarios (4 scenarios) that can be differentiated by a planner, and demonstrate the behavior of resources competition and overlapping intensity among the entire project's activities.

The highest overlapping intensity was found in the scenario with the maximum number of divided work fronts, and produced the minimum duration (419 ± 3 days). Back again to the CPM approach, if the work fronts strategy is applied within a CPM plan (i.e. MS Project bar chart), the project will be divided into eight work fronts, the total duration will be decreased from 600 days to 507 days, However, it does not reach the simulation model result (i.e. 419 days), as Figure 6.13 shows. Hence, it is clear that the restriction with the CPM concept for the performed case still causes a problem that interrupts the work automation and leads to a worthless increase in the project's total duration. Therefore, any attempt to reduce duration in the bar chart planning process will force the planner to quitclaim the CPM control in the schedule.

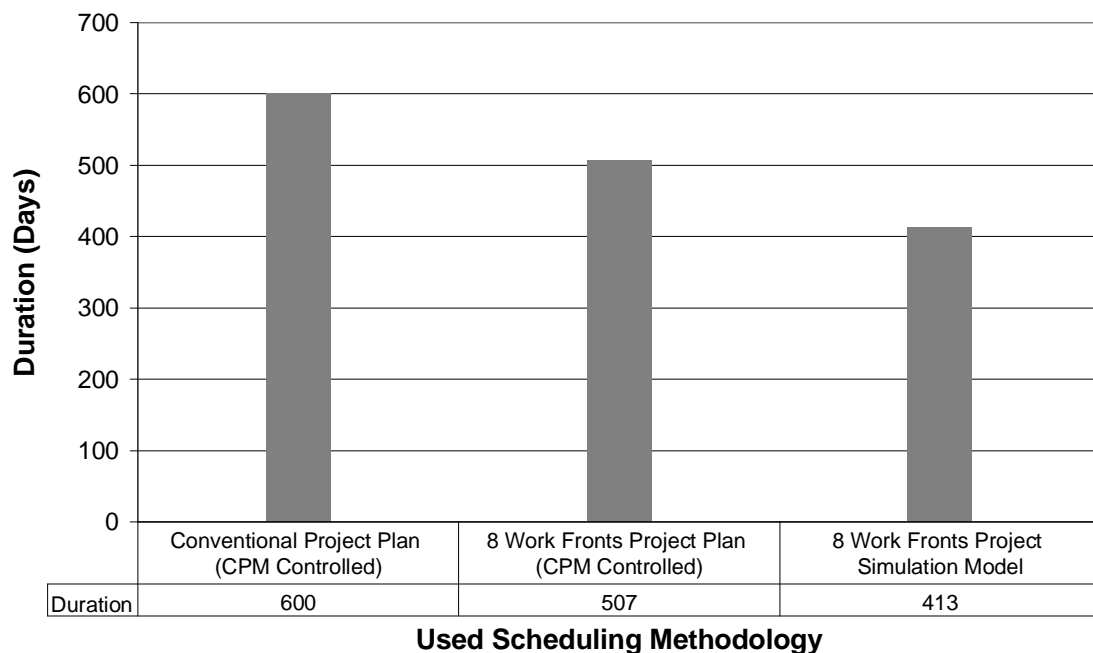


Figure 6.13: Execution Strategy Influence on the Project Duration

6.4 Input Features

As mentioned before in chapters; two and four, the planning inputs of the CPM software (i.e. MS Project) have a static nature. Deterministic duration values are fed to the work activities, while the developed simulation model provided an advanced statistical environment of inputting such data that reinforces the confidence level of the outputs.

Confident results could also have more support through activating the replications option, which summarizes the results of a number of simulation runs for the same model. Moreover, the developed simulation model has the ability to define such uneven levels of priorities for the performed activities. All of the mentioned characteristics of the simulation model input features make it advantageous regarding the outputs quality.

6.5 Resources Issues

The MS Project planning process is achieved through two main steps: feeding data and resources leveling. Always, the MS Project schedule changes after leveling the assigned resources due to the existence of some over-allocated resources. Such both uncoordinated steps may confuse the planner and put him in a trial and error planning environment. Moreover, resources leveling solutions may either complicates the plan by interrupting some activities, or quitclaims the CPM rule, which will be considered as a serious contradiction in that case (i.e. using a CPM software without applying the CPM rule).

The simulation model accredited the automation concept to manage the used resources during the simulation process. The planning process here is achieved by one integrated simulation run, where the performed activities just seize available crews of resources and wait for the busy crews. The whole simulation process deals with the available resources that were predefined in the resources data module (chapter five) without any over-allocation of any resource. Such characteristic of the simulation model does automate the resources to perform any eligible activity once its crew is available, regardless of any other constraints. Simulation evolution still has more to produce. The case study plan can be deeply experimented in terms of duration, costs, and resources capacities via optimization process. Besides presenting such detailed information about the resources idleness time and costs throughout the project, the simulation model could be automatically re-simulated for a number of runs in order to gain an optimum situation for the performed case. The optimization process integrates such actual constraints that the planner has during the planning phase, or expected to be exist in the execution phase.

Therefore, this planning option keeps the planner fully aware with all of the project components and their expected interactions' outputs, while the MS Project has no sense regarding the constraints, requirements, or objective of an applied case.

6.6 Costs Issues

Regarding costs issues, the main advantage of the simulation model in planning a RAP is the detailed breakdown of the value added and idle costs. It has the ability to specify the idleness time points of any resource that cause the idle cost during the project. Being aware with such information is the key solution for the decision makers to decide how they can manage the rent of resources or invest the owned resources in the planning phase. Conversely, the MS Project does not submit any valuable information about the resources idleness and their cost wastages, and have the clear image only for the project's value added features.

6.7 Output Features

The major advantage of the MS Project is the clear presentation capabilities. Moreover, the planners are familiar with its charts and reports. However, the current simulation model's final results are performed in MS Excel, they could be also transferred to the MS Project instead of MS Excel in order to get the final presentation charts and reports. Although, the MS Project has useful output presentations, the simulation model in the current research was integrated with Excel and succeeded to produce such useful information tables and charts. Furthermore, the current simulation model is well qualified to be elaborated and integrated with more advanced environments than Excel to handle the huge amount of the resulted information in terms of presentation. Lastly, the simulation model and the CPM have two divergent theories; the simulation model depends on the concept: resources perform activities, while CPM implies the concept: logical relationships control the work. In addition of the verification results, the mentioned conceptual difference supports the simulation model to be an advantageous planning tool. Making resources perform activities means being close to the real execution environment which starts from the resource production process, and this fact actually materializes the meaning of the word simulation.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Planning issues of repetitive activities projects "RAP" are such important, that they greatly influence a considerable sector in construction industry. A project's resources represent the dynamic parameter that controls the project's cost and time. While all of the planning strategies are mainly aiming to minimize both cost and time wastes, a RAP has the trait of cumulating such wastes due to its repetitive nature, the matter that directs the main planning priorities for resources utilization. So far, many researchable attempts have been carried out in order to develop suitable planning strategies for RAPs.

Many familiar planning methodologies are not conformable with RAPs due to their logical-oriented environments, while the RAP sensitivity towards it used resources requires a more dynamic tool that could perform an efficient resources planning against the existing or assumed constraints.

Simulation technique is the key solution to plan a RAP in terms of resources. It has the desired qualifications to handle resources at the most sophisticated cases. Additionally, its mathematical power could afford numerous planning alternatives, and optimize such cases according any specified constraints. Moreover, it has a massive and detailed output reports that can build a complete planning vision.

Despite being considered as a modern and suitable planning tool, the application of the simulation technique faces two main challenges; availability and learning. The former is a common challenge for many research areas at the local level, however, fortunately, "Arena" simulation software is available at its basic edition. Regarding controlling the second challenge, the research supposed to develop two types of models in order to minimize and simplify the user's interaction while he utilizes a simulation tool.

The firstly constructed model is a conceptual one that generalized for all types of RAPs and simulation software. The main purpose is to form a global perspective for planning RAPs using simulation. It mainly clarifies the mechanism of simulation technique when applied to plan a RAP. The second model is an applied case from the first. In other words, it has been designed for a specified RAP type (i.e. infrastructure projects), and

using a specified simulation tool (i.e. Arena). Although, this model is limited to apply infrastructure projects, its main frame and structure are such flexible and useful to be easily modified to apply another types of RAPs.

Two types of data were gathered regarding infrastructure projects. The first one was used to build the model; includes a list of the performed activities, their logical relationships, a list of the used resources or sets, and the combined resources crews per activity. The second type of data is to use that model. It consisted of: work quantity for each process, resources assignments types, crews' production rates, resources cost rates, the project's objective and resources' constraints, and the number of partitioned work fronts of the project.

The qualitative approach was more appropriate to be carried out to gather the model's data, because of the individuated and unique nature of any applied case (i.e. infrastructure project). In a leading local infrastructure contracting company, responsible engineers were interviewed, details of a typical infrastructure project were gained, and the related records of the achieved projects were utilized.

The concept of "working fronts" was injected in the developed model's structure. It is possible to divide an infrastructure project into one up to eight fronts, the matter which extends the competition on the used resources' crews among the work fronts. Multiple execution plans could be produced through applying several scenarios of the model. Increasing the number of work fronts, does increase and fasten the eligibility of the successor activities to be launched. The number of work fronts mainly depends on the total quantity of work and the minimum portion of site that possible to be executed without crowding or confusing the production process.

Arena has a relatively friendly user environment, furthermore, the model, which has been developed using Arena, provides a familiar and controlled input positions. Moreover, it empowers users to optimize any of the applied case parameters using OptQuest add-in. Finally, integrated MS Excel spreadsheets were specially functioned as fixed templates to perform Arena's output, and to present such supportive planning details regarding resources, cost and duration.

The resultant outputs of the applied case have clarified remarkable differences between simulation and critical path method "CPM", one of the commonly used planning methods. A considerable value of the project's duration has been saved by using the simulation model. The basic deficiency of CPM is to rely on the "critical path" theory. Commitment with such principle directly affects the leveling process of the over-allocated resources, and then causes confusable changes in the duration features. Simulation has managed that through starting to plan from the production process of the assigned crews as the control factor regardless any restriction with any preset rules. Resources are freely seized or released among activities, ruled by: a crew's availability and an activity's eligibility.

7.2 Recommendations

7.2.1 For Planners

Initially, repetitive activities projects require more concern regarding planning and scheduling. They have such an economic value in construction sector that worth to spend time and effort to achieve the best plan, and minimize time and cost wastes.

Simulation represents a powerful planning tool that have to be considered, as well as the optimization process which could produce several solutions from a group of pre-set constraints against a specified objective.

7.2.2 For Academicians

Simulation, as a modern technique, is suggested to be inserted in the bachelor's studying program and engineering management courses as well, in order to familiarize engineers with its uses and advantages in the construction management field, and to extend their horizons regarding the advanced issues of the planning and scheduling field.

As a resultant of the previously mentioned recommendation, Arena's different versions, add-ins, and updates have to be procured by the concerned institutions to facilitate both learning and application of this software. Also, the appropriate hardware that capable to perform such software's models efficiently has to be equipped.

7.2.3 For Further Research

However, this research has utilized simulation by Arena to develop the best RAPs execution strategy; the technique could be simply applied for other different repetitive and non-repetitive activities projects as well, through developing analogous models.

The suggested planning procedure requires to be automated and assembled into one integrated body to get such unified inputs and outputs positions, instead of transferring them from one place to another. Likewise, it will be a valuable achievement to integrate the mathematical power of simulation with its visual aspects. There is a need to utilize the animation and graphical potentials that embedded within simulation, to develop a "visual based schedule", which considered as a perfect project management tool.

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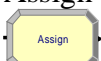



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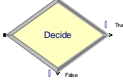
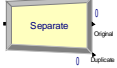

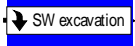


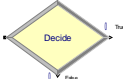
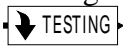




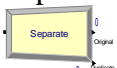
List of Appendices




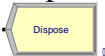
- Appendix 1:** Guides to Use The Simulation Model
- Appendix 2:** Case Project Gathered Information
- Appendix 3:** Simulated Processes Information
- Appendix 4:** Simulated Case Output Reports Samples

Appendix 1

Guides to Use The Simulation Model

SubModel	Module	User Action
Start 	Create 	No Action
	Assign 	<p>Add, delete, or modify duration values for a work front in an activity.</p> <p>This module is edited with a double click. If the user would like to increase the number of work fronts, he should click on the "add" button to specify the name and duration values of each new work front. The duration values for the entire work fronts has to be modified according to the new partitioning situation. Similarly, the user can decrease the number of work fronts in an activity by clicking on the "delete" button, taking into account the change in work quantities, and the duration values modifications.</p> <p>The "edit" button could be used to modify the duration values in a work front with no change in the number of partitions. This case might be useful to construct a group of non-equal partitions "work fronts" in an activity.</p>
Launcher Process 	Assign 	By editing this module, the user defines the starting length of the project (always LV sum = 0 m), and the total length of the project (LV total = 2000 m in the performed case study), which can be modified to any other length.
	Generate Segments	
	Record 	No Action
	Process 	The user can edit this module only to re-assign the used resources in this process. He can click: add, edit, or delete in order to modify the used resources crews number and combination.
	Assign Counter 	Counts and accumulates the performed lengths of the project (which is always LV sum = LV sum + work front length). The length of work front (number of partitions) can be decreased or increased. This module case is functioned to terminate the automated loop of splitting entities (partitioning) once LV sum equals to LV total.

SubModel	Module	User Action
Launcher Process 	Decide 	No Action
	Eligibility Check Separate 	No Action
	Decide 	<p>By editing this module the user can modify the direction of the flowing entities. This step has to be performed automatically when any modification in the work fronts numbers or values have been made.</p>
Normal Process 	Record 	No Action
	Process 	<p>The user can edit this module only to re-assign the used resources in this process. He can click: add, edit, or delete in order to modify the used resources crews number and combination.</p>
	Decide 	<p>By editing this module the user can modify the direction of the flowing entities. This step has to be performed automatically when any modification in the work fronts numbers or values have been made.</p>
Testing 	Record 	No Action
	Process 	<p>The default duration of re-make the faulty portion of work during a test is one day. The user can increase or decrease this duration. Also, he is able to add, edit, or delete any of the assigned resources in order to modify the used resources crews number and combination in this testing activity.</p>
	Decide 	<p>By editing this module the user can control the percentage of the expected faulty portions of work.</p>
Distribute 	Separate 	No Action

SubModel	Module	User Action
Assemble 	Batch 	Changing any the "work front" values, such as size, number of work fronts, etc., must need a change in the batching size in this module. The number of work fronts has to equal to the batch size in both modules called: BATHC 4, and BATCH 5. The batch size in the third batch module (WORK BATCH) always equals to 2.
Handing Over 	Dispose 	No Action

Appendix 2

BILL OF QUANTITY (for a 2000 m Length Project)

Serial	Item	Unit	Quantity
1	Leveling, cut, and fill (20-40 cm)	m ²	58000
2	Sub Base (Kurkar) spreading (2 layers x 15 cm)	m ²	40000
3	Sub Base (Kurkar) spreading (1 layer x 10 cm)	m ²	18000
4	Base coarse spreading (2 layers x 10 cm)	m ²	40000
5	Base coarse spreading (1 layer x 10 cm)	m ²	18000
6	Curb stone	m'	9200
7	Retaining beams (20 x 20 cm)	m'	4000
8	Interlock tiles	m ²	18000
9	Asphalt pavement	m ²	40000
10	75 mm Water pipes	m'	2000
11	110 mm Water pipes	m'	2800
12	125 cm Water manhole	unit	5
13	100 cm Water manhole	unit	5
14	75/25 Water house connection pipes	m'	200
15	110/25 Water house connection pipes	m'	240
16	200 mm Sewage pipes	m'	1200
17	160 mm Sewage pipes	m'	800
18	100 cm Sewage manhole	unit	32
19	60 cm Swage manhole	unit	80
20	355 mm Drainage pipes	m'	1800
21	100 cm Drainage manhole	unit	36
22	3-eyes Drainage outlets	unit	36
23	6-eyes Drainage outlets	unit	34
24	Lantern bracket	unit	40
25	Base board pole unit	unit	40
26	Lighting lantern	unit	20
27	N2XY cable	m'	2000
28	60 cm Electric manhole	unit	4

RESOURCES POOL

1 – Resources

Serial	Resource	Capacity	Cost/hour (NIS)	Cost per use	Status
1	Labor	15	6.25	-	Permanent
2	Mason / Form worker	1	8.75	-	Permanent
3	Electrician	1	11.25	-	Part Time
4	Loader	1	70	-	Permanent
5	Roller compactor 25 t	1	100	400	Rent
6	Roller compactor 08 t	1	15	20	Rent
7	Plate compactor	1	6.25	-	Permanent
8	Grader	1	120	500	Rent
9	Asphalt paving set	1	562.5	800	Rent
10	Excavator 1	1	50	-	Rent
11	Excavator 2	1	50	-	Rent

2 – Sets

Set	Selection Rule	Members	
Excavators	Preferred order	1	Excavator 1
		2	Excavator 2

Appendix 3

Simulation Processes Breakdown

1 – Milestone: LEVELING

Leveling							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	2	Resource	Triangular	500	700	1000
2	Loader	1	Resource				

Duration Values (Delay) - Days:	Per	250 m length	14.50	10.36	7.25
	Per	500 m length	29.00	20.71	14.50
	Per	1000 m length	58.00	41.43	29.00
	Per	2000 m length	116.00	82.86	58.00

2 – Milestone: PIPE WORKS

SW Excavation							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	1	Resource	Triangular	100	125	150
2	Excavators	1	Set				

Duration Values (Delay) - Days:	Per 250 m length	2.50	2.00	1.67
	Per 500 m length	5.00	4.00	3.33
	Per 1000 m length	10.00	8.00	6.67
	Per 2000 m length	20.00	16.00	13.33

SW Pipe Laying							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	5	Resource	Triangular	110	140	170
2	Excavators	1	Set				

Duration Values (Delay) - Days:	Per 250 m length	2.27	1.79	1.47
	Per 500 m length	4.55	3.57	2.94
	Per 1000 m length	9.09	7.14	5.88
	Per 2000 m length	18.18	14.29	11.76

SW Backfilling							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	5	Resource	Triangular	160	200	240
2	Excavators	1	Set				
3	Plate Compactor	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	1.56	1.25	1.04
	Per 500 m length	3.13	2.50	2.08
	Per 1000 m length	6.25	5.00	4.17
	Per 2000 m length	12.50	10.00	8.33

TESTING: Field Density SW Backfilling					
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)
1	Labor	1	Resource	Constant	Work Front
2	Plate Compactor	1	Resource	Constant	Work Front

Duration Values (Delay) - Days:	Per 250 m length	1
	Per 500 m length	1
	Per 1000 m length	1
	Per 2000 m length	1

DR Excavation							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	1	Resource	Triangular	100	120	150
2	Excavators	1	Set				

Duration Values (Delay) - Days:	Per 250 m length	2.25	1.88	1.50
	Per 500 m length	4.50	3.75	3.00
	Per 1000 m length	9.00	7.50	6.00
	Per 2000 m length	18.00	15.00	12.00

DR Pipe Laying							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	5	Resource	Triangular	120	140	160
2	Excavators	1	Set				

Duration Values (Delay) - Days:	Per 250 m length	1.88	1.61	1.41
	Per 500 m length	3.75	3.21	2.81
	Per 1000 m length	7.50	6.43	5.63
	Per 2000 m length	15.00	12.86	11.25

DR Backfilling							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	5	Resource	Triangular	150	190	210
2	Excavators	1	Set				
3	Plate Compactor	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	1.50	1.18	1.07
	Per 500 m length	3.00	2.37	2.14
	Per 1000 m length	6.00	4.74	4.29
	Per 2000 m length	12.00	9.47	8.57

TESTING: Field Density DR Backfilling					
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)
1	Labor	1	Resource	Constant	Work Front
2	Plate Compactor	1	Resource	Constant	Work Front

Duration Values (Delay) - Days:	Per 250 m length	1
	Per 500 m length	1
	Per 1000 m length	1
	Per 2000 m length	1

WA Excavation							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	1	Resource	Triangular	100	120	150
2	Excavators	1	Set				

Duration Values (Delay) - Days:	Per 250 m length	6.55	5.24	4.37
	Per 500 m length	13.10	10.48	8.73
	Per 1000 m length	26.20	20.96	17.47
	Per 2000 m length	52.40	41.92	34.93

WA Pipe Laying							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	5	Resource	Triangular	110	140	170
2	Excavators	1	Set				

Duration Values (Delay) - Days:	Per 250 m length	5.95	4.68	3.85
	Per 500 m length	11.91	9.36	7.71
	Per 1000 m length	23.82	18.71	15.41
	Per 2000 m length	47.64	37.43	30.82

WA Backfilling							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	5	Resource	Triangular	160	200	240
2	Excavators	1	Set				
3	Plate Compactor	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	4.09	3.28	2.73
	Per 500 m length	8.19	6.55	5.46
	Per 1000 m length	16.38	13.10	10.92
	Per 2000 m length	32.75	26.20	21.83

TESTING: Field Density WA Backfilling					
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)
1	Labor	1	Resource	Constant	Work Front
2	Plate Compactor	1	Resource	Constant	Work Front

Duration Values (Delay) - Days:	Per 250 m length	1
	Per 500 m length	1
	Per 1000 m length	1
	Per 2000 m length	1

3 – Milestone: SUB GRADE WORKS

Sub Grade Compaction							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	1	Resource	Triangular	1500	3000	5000
2	Roller Compactor 25t	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	4.83	2.42	1.45
	Per 500 m length	9.67	4.83	2.90
	Per 1000 m length	19.33	9.67	5.80
	Per 2000 m length	38.67	19.33	11.60

TESTING: Field Density Sub Grade					
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)
1	Labor	1	Resource	Constant	Work Front
2	Roller Compactor 25t	1	Resource	Constant	Work Front

Duration Values (Delay) - Days:	Per 250 m length	1
	Per 500 m length	1
	Per 1000 m length	1
	Per 2000 m length	1

Curbstone Masonry							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	5	Resource	Triangular	80	90	100
2	Mason	1	Resource				
3	Plate Compactor	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	14.38	12.78	11.50
	Per 500 m length	28.75	25.56	23.00
	Per 1000 m length	57.50	51.11	46.00
	Per 2000 m length	115.00	102.22	92.00

Curbstone Beams							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	4	Resource	Triangular	80	90	100
2	Mason	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	14.38	12.78	11.50
	Per 500 m length	28.75	25.56	23.00
	Per 1000 m length	57.50	51.11	46.00
	Per 2000 m length	115.00	102.22	92.00

4 – Milestone: SIDEWALKS WORKS

Sidewalks Works: Retaining Beams							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	5	Resource	Triangular	80	90	100
2	Mason	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	6.25	5.56	5.00
	Per 500 m length	12.50	11.11	10.00
	Per 1000 m length	25.00	22.22	20.00
	Per 2000 m length	50.00	44.44	40.00

Sidewalks: Electric Works							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	5	Resource	Triangular	200	220	250
2	Electrician	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	1.25	1.14	1.00
	Per 500 m length	2.50	2.27	2.00
	Per 1000 m length	5.00	4.55	4.00
	Per 2000 m length	10.00	9.09	8.00

Sidewalks Works: Sub Base Loading							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	1	Resource	Triangular	1500	1800	2000
2	Loader	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	1.50	1.25	1.13
	Per 500 m length	3.00	2.50	2.25
	Per 1000 m length	6.00	5.00	4.50
	Per 2000 m length	12.00	10.00	9.00

Sidewalks Works: Sub Base Spreading							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	5	Resource	Triangular	600	800	1000

Duration Values (Delay) - Days:	Per 250 m length	3.75	2.81	2.25
	Per 500 m length	7.50	5.63	4.50
	Per 1000 m length	15.00	11.25	9.00
	Per 2000 m length	30.00	22.50	18.00

Sidewalks Works: Sub Base Compaction							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	1	Resource	Triangular	1800	2000	2200
2	Roller Compactor 08t	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	1.25	1.13	1.02
	Per 500 m length	2.50	2.25	2.05
	Per 1000 m length	5.00	4.50	4.09
	Per 2000 m length	10.00	9.00	8.18

TESTING: Field Density Sidewalks Works: Sub Base					
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)
1	Labor	1	Resource	Constant	Work Front
2	Roller Compactor 08t	1	Resource	Constant	Work Front

Duration Values (Delay) - Days:	Per 250 m length	1
	Per 500 m length	1
	Per 1000 m length	1
	Per 2000 m length	1

Sidewalks Works: Base Course Loading							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	1	Resource	Triangular	1500	1800	2000
2	Loader	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	1.50	1.25	1.13
	Per 500 m length	3.00	2.50	2.25
	Per 1000 m length	6.00	5.00	4.50
	Per 2000 m length	12.00	10.00	9.00

Sidewalks Works: Base Course Spreading							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	5	Resource	Triangular	450	600	800

Duration Values (Delay) - Days:	Per 250 m length	5.00	3.75	2.81
	Per 500 m length	10.00	7.50	5.63
	Per 1000 m length	20.00	15.00	11.25
	Per 2000 m length	40.00	30.00	22.50

Sidewalks Works: Base Course Compaction							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	1	Resource	Triangular	1800	2000	2200
2	Roller Compactor 08t	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	1.25	1.13	1.02
	Per 500 m length	2.50	2.25	2.05
	Per 1000 m length	5.00	4.50	4.09
	Per 2000 m length	10.00	9.00	8.18

TESTING: Field Density Sidewalks Works: Base Course					
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)
1	Labor	1	Resource	Constant	Work Front
2	Roller Compactor 08t	1	Resource	Constant	Work Front

Duration Values (Delay) - Days:	Per 250 m length	1
	Per 500 m length	1
	Per 1000 m length	1
	Per 2000 m length	1

Sidewalks Works: Interlock Tiling							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	8	Resource	Triangular	200	250	300
2	Plate Compactor	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	12.00	9.00	8.00
	Per 500 m length	24.00	18.00	16.00
	Per 1000 m length	48.00	36.00	32.00
	Per 2000 m length	96.00	72.00	64.00

5 – Milestone: ROAD WORKS

Road Works: Sub Base 1 Spreading							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	3	Resource	Triangular	1000	1500	2000
2	Loader	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	5.00	3.33	2.50
	Per 500 m length	10.00	6.67	5.00
	Per 1000 m length	20.00	13.33	10.00
	Per 2000 m length	40.00	26.67	20.00

Road Works: Sub Base 1 Compaction							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	3	Resource	Triangular	1500	3000	5000
2	Roller Compactor 25t	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	3.33	1.67	1.00
	Per 500 m length	6.67	3.33	2.00
	Per 1000 m length	13.33	6.67	4.00
	Per 2000 m length	26.67	13.33	8.00

TESTING: Failed Density Road Works: Sub Base 1					
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)
1	Labor	1	Resource	Constant	Work Front
2	Roller Compactor 25t	1	Resource	Constant	Work Front

Duration Values (Delay) - Days:	Per 250 m length	1
	Per 500 m length	1
	Per 1000 m length	1
	Per 2000 m length	1

Road Works: Sub Base 2 Spreading							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	3	Resource	Triangular	1000	1500	2000
2	Loader	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	5.00	3.33	2.50
	Per 500 m length	10.00	6.67	5.00
	Per 1000 m length	20.00	13.33	10.00
	Per 2000 m length	40.00	26.67	20.00

Road Works: Sub Base 2 Compaction							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	3	Resource	Triangular	1500	3000	5000
2	Roller Compactor 25t	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	3.33	1.67	1.00
	Per 500 m length	6.67	3.33	2.00
	Per 1000 m length	13.33	6.67	4.00
	Per 2000 m length	26.67	13.33	8.00

TESTING: Field Density Road Works: Sub Base 2					
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)
1	Labor	1	Resource	Constant	Work Front
2	Roller Compactor 25t	1	Resource	Constant	Work Front

Duration Values (Delay) - Days:	Per 250 m length	1
	Per 500 m length	1
	Per 1000 m length	1
	Per 2000 m length	1

Road Works: Base Course 1 Spreading							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	3	Resource	Triangular	250	350	500
2	Loader	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	20.00	14.29	10.00
	Per 500 m length	40.00	28.57	20.00
	Per 1000 m length	80.00	57.14	40.00
	Per 2000 m length	160.00	114.29	80.00

Road Works: Base Course 1 Compaction							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	3	Resource	Triangular	1500	3000	5000
2	Roller Compactor 25t	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	3.33	1.67	1.00
	Per 500 m length	6.67	3.33	2.00
	Per 1000 m length	13.33	6.67	4.00
	Per 2000 m length	26.67	13.33	8.00

TESTING: Field Density Road Works: Base Course 1					
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)
1	Labor	1	Resource	Constant	Work Front
2	Roller Compactor 25t	1	Resource	Constant	Work Front

Duration Values (Delay) - Days:	Per 250 m length	1
	Per 500 m length	1
	Per 1000 m length	1
	Per 2000 m length	1

Road Works: Base Course 2 Spreading							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	3	Resource	Triangular	250	350	500
2	Loader	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	20.00	14.29	10.00
	Per 500 m length	40.00	28.57	20.00
	Per 1000 m length	80.00	57.14	40.00
	Per 2000 m length	160.00	114.29	80.00

Road Works: Base Course 2 Grading							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	3	Resource	Triangular	1500	3000	5000
2	Grader	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	3.33	1.67	1.00
	Per 500 m length	6.67	3.33	2.00
	Per 1000 m length	13.33	6.67	4.00
	Per 2000 m length	26.67	13.33	8.00

Road Works: Base Course 2 Compaction							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	3	Resource	Triangular	1500	3000	5000
2	Roller Compactor 25t	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	3.33	1.67	1.00
	Per 500 m length	6.67	3.33	2.00
	Per 1000 m length	13.33	6.67	4.00
	Per 2000 m length	26.67	13.33	8.00

TESTING: Field Density Road Works: Base Course 2					
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)
1	Labor	1	Resource	Constant	Work Front
2	Roller Compactor 25t	1	Resource	Constant	Work Front

Duration Values (Delay) - Days:	Per 250 m length	1
	Per 500 m length	1
	Per 1000 m length	1
	Per 2000 m length	1

Road Works: MCO Spraying							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	1	Resource	Triangular	Project	Project	Project

Duration Values (Delay) - Days:	Per 250 m length	1.00	1.00	1.00
	Per 500 m length	1.00	1.00	1.00
	Per 1000 m length	1.00	1.00	1.00
	Per 2000 m length	1.00	1.00	1.00

Road Works: Asphalt Paving							
Serial	Resources Crew	Capacity	Type	Data Type	Production rate (unit/day)		
					Min.	Mode	Max.
1	Labor	7	Resource	Triangular	3000	4000	5000
2	Asphalt paving set	1	Resource				

Duration Values (Delay) - Days:	Per 250 m length	1.67	1.25	1.00
	Per 500 m length	3.33	2.50	2.00
	Per 1000 m length	6.67	5.00	4.00
	Per 2000 m length	13.33	10.00	8.00

Appendix 4

Arena Output Reports Samples

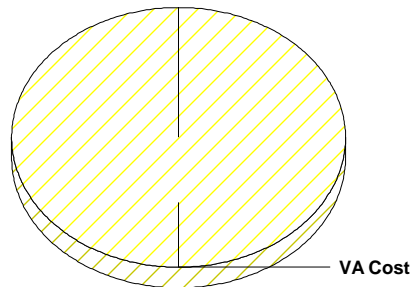
Category Overview

THESIS

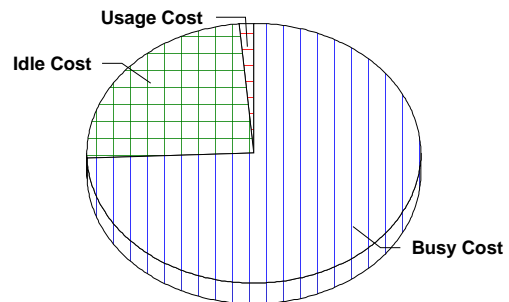
Replications: 1 Time Units: Days

System Summary

All Entities	Average
NVA Cost	0
Other Cost	0
Tran Cost	0
VA Cost	678,015.55
Wait Cost	0
Total Cost	678,015.55



All Resources	Average
Busy Cost	664,655.55*
Idle Cost	216,143.08
Usage Cost	13,360.00*
Total Cost	894,158.63



* these costs are included in Entity Costs above.

System	Average
Total Cost	894,158.63
Number Out	1.0000

Entity

Time

NVA Time			Minimum	Maximum
	Average	Half Width	Value	Value
Entity 1	0.00	(Insufficient)	0.00	0.00
Other Time			Minimum	Maximum
	Average	Half Width	Value	Value
Entity 1	0.00	(Insufficient)	0.00	0.00
Total Time			Minimum	Maximum
	Average	Half Width	Value	Value
Entity 1	469.52	(Insufficient)	469.52	469.52
Transfer Time			Minimum	Maximum
	Average	Half Width	Value	Value
Entity 1	0.00	(Insufficient)	0.00	0.00
VA Time			Minimum	Maximum
	Average	Half Width	Value	Value
Entity 1	1102.66	(Insufficient)	1102.66	1102.66
Wait Time			Minimum	Maximum
	Average	Half Width	Value	Value
Entity 1	1528.48	(Insufficient)	1528.48	1528.48

Process

Time

Total Time			Minimum	Maximum
	Average	Half Width	Value	Value
ASPHALT segment 1	2.9006	(Insufficient)	2.9006	2.9006
ASPHALT segment 2	20.8573	(Insufficient)	20.8573	20.8573
ASPHALT segment 3	2.5565	(Insufficient)	2.5565	2.5565
ASPHALT segment 4	2.3658	(Insufficient)	2.3658	2.3658

VA Time			Minimum	Maximum
	Average	Half Width	Value	Value
ASPHALT segment 1	2.9006	(Insufficient)	2.9006	2.9006
ASPHALT segment 2	3.0853	(Insufficient)	3.0853	3.0853
ASPHALT segment 3	2.5565	(Insufficient)	2.5565	2.5565
ASPHALT segment 4	2.3658	(Insufficient)	2.3658	2.3658

Wait Time			Minimum	Maximum
	Average	Half Width	Value	Value
ASPHALT segment 1	0.00	(Insufficient)	0.00	0.00
ASPHALT segment 2	17.7721	(Insufficient)	17.7721	17.7721
ASPHALT segment 3	0.00	(Insufficient)	0.00	0.00
ASPHALT segment 4	0.00	(Insufficient)	0.00	0.00

Process

Cost

Total Cost			Minimum	Maximum
	Average	Half Width	Value	Value
ASPHALT segment 1	14867.90	(Insufficient)	14867.90	14867.90
ASPHALT segment 2	15763.62	(Insufficient)	15763.62	15763.62
ASPHALT segment 3	13199.25	(Insufficient)	13199.25	13199.25
ASPHALT segment 4	12273.98	(Insufficient)	12273.98	12273.98

VA Cost			Minimum	Maximum
	Average	Half Width	Value	Value
ASPHALT segment 1	14867.90	(Insufficient)	14867.90	14867.90
ASPHALT segment 2	15763.62	(Insufficient)	15763.62	15763.62
ASPHALT segment 3	13199.25	(Insufficient)	13199.25	13199.25
ASPHALT segment 4	12273.98	(Insufficient)	12273.98	12273.98

Wait Cost			Minimum	Maximum
	Average	Half Width	Value	Value
ASPHALT segment 1	0.00	(Insufficient)	0.00	0.00
ASPHALT segment 2	0.00	(Insufficient)	0.00	0.00
ASPHALT segment 3	0.00	(Insufficient)	0.00	0.00
ASPHALT segment 4	0.00	(Insufficient)	0.00	0.00

Resource

Usage

Number Busy			Minimum	Maximum
	Average	Half Width	Value	Value
Electrician	0.01977112	(Insufficient)	0.00	1.0000
excavator 1	0.2543	(Insufficient)	0.00	1.0000
excavator 2	0.1565	(Insufficient)	0.00	1.0000
Grader	0.03219688	(Insufficient)	0.00	1.0000
Labour	8.7260	(Insufficient)	0.00	15.0000
Loader	0.8148	(Insufficient)	0.00	1.0000
Mason	0.5458	(Insufficient)	0.00	1.0000
P.Comp.	0.4672	(Insufficient)	0.00	1.0000
Paving Set	0.02323260	(Insufficient)	0.00	1.0000
R.Comp.08	0.03864155	(Insufficient)	0.00	1.0000
R.Comp.25	0.1941	(Insufficient)	0.00	1.0000

Number Times Used	Value
Electrician	4.0000
excavator 1	23.0000
excavator 2	13.0000
Grader	4.0000
Labour	448.00
Loader	28.0000
Mason	12.0000
P.Comp.	20.0000
Paving Set	4.0000
R.Comp.08	8.0000
R.Comp.25	20.0000

Utilization			Minimum	Maximum
	Average	Half Width	Value	Value
Electrician	0.01977112	(Insufficient)	0.00	1.0000
excavator 1	0.2543	(Insufficient)	0.00	1.0000
excavator 2	0.1565	(Insufficient)	0.00	1.0000
Grader	0.03219688	(Insufficient)	0.00	1.0000
Labour	0.5817	(Insufficient)	0.00	1.0000
Loader	0.8148	(Insufficient)	0.00	1.0000
Mason	0.5458	(Insufficient)	0.00	1.0000
P.Comp.	0.4672	(Insufficient)	0.00	1.0000
Paving Set	0.02323260	(Insufficient)	0.00	1.0000
R.Comp.08	0.03864155	(Insufficient)	0.00	1.0000
R.Comp.25	0.1941	(Insufficient)	0.00	1.0000

Resource

Cost

Busy Cost	Value
Electrician	835.47
excavator 1	47756.62
excavator 2	29394.51
Grader	14512.43
Labour	204852.64
Loader	214224.99
Mason	17940.05
P.Comp.	10969.03
Paving Set	49086.89
R.Comp.08	2177.16
R.Comp.25	72905.76

Idle Cost	Value
Electrician	41421.43
excavator 1	0.00
excavator 2	0.00
Grader	0.00
Labour	147288.19
Loader	0.00
Mason	14926.43
P.Comp.	12507.02
Paving Set	0.00
R.Comp.08	0.00
R.Comp.25	0.00

Usage Cost	Value
Electrician	0.00
excavator 1	0.00
excavator 2	0.00
Grader	2000.00
Labour	0.00
Loader	0.00
Mason	0.00
P.Comp.	0.00
Paving Set	3200.00
R.Comp.08	160.00
R.Comp.25	8000.00

User Specified

Tally

Expression	Average	Half Width	Minimum Value	Maximum Value
ASPHALT 1 begin	247.26	(Insufficient)	247.26	247.26
ASPHALT 1 finish	250.16	(Insufficient)	250.16	250.16
ASPHALT 2 begin	408.53	(Insufficient)	408.53	408.53
ASPHALT 2 finish	429.38	(Insufficient)	429.38	429.38
ASPHALT 3 begin	316.12	(Insufficient)	316.12	316.12
ASPHALT 3 finish	318.68	(Insufficient)	318.68	318.68
ASPHALT 4 begin	467.16	(Insufficient)	467.16	467.16
ASPHALT 4 finish	469.52	(Insufficient)	469.52	469.52