University of Alberta

An Integrated Simulation-based Planning Approach for
Construction Projects

by

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To my dear and loving husband, Jeongdae

ABSTRACT

Cost and schedule integration can improve efficiencies in construction planning and control since they are key constraints in project delivery and closely related. This research provides a framework for cost and schedule integration, and transforms the model to simulation-based planning in which the uncertainties of project cost and schedule are evaluated through computer simulation. This has been achieved through explicitly incorporating risk, resource, and detailed operation into a work-packaging model. The developed framework has been implemented in the Simphony.Net modeling environment as a special purpose simulation tool called ISP (integrated simulation-based planning). The ISP's main framework is a simulation-based network analysis based on a precedence diagram method. The ISP tool application has been demonstrated with a hypothetical road construction project. The approach is useful for considering risks in the early stages of project planning for investigating a range of possible project completion times and cost estimates in multiple scenarios.

ACKNOWLEDGMENT

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LIST OF ABBREVIATIONS

AOA   Activity on Arrow method in CPM network scheduling

AON   Activity on Node method in CPM network scheduling

CDF   Cumulative Density Function

CPM   Critical Path Method

ISP   Integrated Simulation-based Planning

NPV   Net Present Value

PDF   Probability Density Function

PDM   Precedence Diagram Method

PERT   Project Evaluation and Review Technique

RBS   Risk Breakdown Structure

SPS   Special Purpose Simulation

WBS   Work Breakdown Structure

WP   Work Package

1 INTRODUCTION

1.1 Background

Construction projects, the success of which can be evaluated through cost, schedule, quality, and safety, are unique and temporarily involve many parties from various disciplines and backgrounds. Project management plays an important role in achieving successful delivery of construction projects. This is accomplished through "the application and integration of the project management processes of initiating, planning, executing, monitoring and controlling, and closing (PMI, 2004)." Among them, planning is a key process encompassing all the tasks between project initiation and the beginning of detailed design such as selecting objectives, defining project scope, establishing a work sequence, estimating resources, costs, and duration, and performing risk analysis (PMI, 2004; Gibson et al., 2006).

Many attempts have been made to improve the function of construction planning and control. One is to integrate cost and schedule. Currently cost and schedule employ two different control structures despite their close interrelation. Practitioners and researchers have been aware of the benefits of integrating the two elements in construction projects. Rasdorf and Abudayyeh (1991) indicated that an integrated cost and schedule control allows timely quality data collection and can be used as an historical data base for new projects. Jung and Woo (2004) suggest that cost and scheduling share many data in the controlling process, and that integrating them is useful in monitoring the construction process.

Project scope definition is one of the major tasks in the planning process, and the risks associated with the project are analyzed at this stage (Gibson et al., 2006). As the construction project becomes more complex, the uncertainties and inherent risks often hinder the successful realization of the project delivery; therefore, effective uncertainty management in project planning becomes crucial. The Monte Carlo simulation is a probabilistic technique which considers the dynamic and stochastic characteristics of construction projects, which might be caused by various risk factors during project execution. The most common construction industry methods that use the Monte Carlo simulation are range estimating and simulation-based network analysis. In general these tools are applied to construction projects independently in order to quantify the risks associated with cost and schedule, respectively (Isidore and Back, 2002). However Moussa et al. (2007) argues that considering risks related to project costs without accounting for the schedule and scope risks is an incomplete exercise, and emphasizes the need for integrated models that incorporate the complexity of project uncertainties.

1.2 Research Objectives and Contributions

In light of the need for integrated planning models for construction projects, the main objective of this research is to provide an integrated cost/schedule model, and transform the model to simulation-based planning in which the uncertainties of project cost and schedule are evaluated through computer simulation. The objective is achieved through:

(1) Incorporating an explicit risk identification and systematic assignment procedure to assist with deriving uncertainties for a work package.

(2) Incorporating the details of operation into work packages to calculate more accurate activity durations and investigate production optimization.

(3) Incorporating explicit resources during network scheduling in order to assist resource levelling and resource-driven cost estimating.

(4) Evaluating project schedule and cost using the Monte Carlo simulation, which generates a range of possible outcomes through iterative computer simulation.

(5) Providing an easy-to-use environment, which encompasses all the required features in one model.

Three major techniques used for these objectives are the work-packaging model, risk breakdown structure, and hierarchical modeling concept. The work-packaging model is adopted for cost and schedule integration. The method provides a unified view by integrating cost information into the work breakdown structure (WBS). The work packages become the common denominator for cost and scheduling. A risk identification procedure is incorporated in the model using a risk breakdown structure. The impacts of the risk factors on the schedule and cost are investigated using not only probability distributions but also systematically guided steps. The developed method adapts a hierarchical modeling concept to incorporate the details of operation into work packages. It maximizes the benefits of simulation-based planning since the simulation outputs from the operation analysis models are directly used in the planning-level simulation.

The research's main contribution is the development of an integrated frame work for simulation-based planning. The framework supports cost/schedule

integration through work packages, and incorporates their resources, uncertainties, and operation details in one model.

1.3 Research Deliverables

The ultimate deliverable of the research is a special purpose simulation (SPS) tool for the integrated simulation-based planning (ISP) using the Simphony.NET modeling environment[1]. The ISP tool is expected to help students or inexperienced professionals understand the fundamentals of simulation and construction planning through WBS creation, resource allocation, risk identification and assignment, and simulation-based schedule network analysis. The ISP tool's characteristics are summarized as follows:

- The ISP methodology in the research is implemented in the Simphony.NET development environment as an SPS tool, which offers a user-friendly simulation building environment.

- The ISP tool provides a WBS creation function which helps organize the scope of the construction project.

- The ISP tool carries out resource-driven cost estimating. The resources are defined independently with the unit cost information, and are assigned to WPs.

- The ISP tool helps the risk identification procedure using a risk breakdown structure. The risk factors defined during the identification can be assigned to the WPs and/or the resources.

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[1] See Section 4.1 for details about the special purpose simulation (SPS) tool and Simphony.NET modeling environment.

- The duration and cost information used in the ISP tool can be flexibly entered either deterministically or probabilistically from known probability distribution functions.

- The impacts of the risk factors are also considered during simulation based on the likelihood of the risk occurrence. The impacts are given independently or proportionally to the original duration and cost input.

- The tool was designed to incorporate a sub-model inside of each WP in the schedule network in order to perform an operational simulation and calculate more detailed WP durations. The sub-model can be other projects or partial models.

- The ISP tool performs stochastic precedence schedule network analysis. The simulation's outputs are statistics of completion time and the project's cash flow.

1.4   Thesis organization

The thesis is divided into six main chapters with a list of reference and a user's manual of the developed SPS tool. Chapter 1 provides the research background, objective, and contribution with a brief explanation about the ISP tool's characteristics.

Chapter 2 contains a literature review of previous research about the cost/schedule integration and project-level simulation. This chapter provides the limitations of the previous research and points out the integrated framework requirements.

Chapter 3 presents a conceptual framework of the ISP. It explains what the ISP's modules are and how they are connected with each other. This chapter

also provides a detailed explanation about risk analysis and the scheduling network module.

Chapter 4 explains the ISP tool's development environment and elements. It provides information about how the input and output data are processed internally.

Chapter 5 describes a hypothetical road construction example which used an ISP tool application. The chapter provides the project information for user input, a step-by-step procedure, and analysis result of the project.

Chapter 6 includes the conclusion, limitations, and possible future enhancement of the current research.

2 LITERATURE REVIEW

This chapter introduces previous research about cost and schedule integration, and simulation-based integration models. Section 2.1 focuses on data representation models for cost and schedule integration. Section 2.2 reviews some of the research efforts for the integrated simulation-based planning. Finally, the summaries from the literature review are listed in Section 2.3.

2.1 Cost and Schedule Integration Models

It is clear that there is interdependency between schedule and cost in a construction project, but currently most of the projects employ two different control structures: work breakdown structure (WBS) and cost breakdown structure (CBS). Because the difference in the level of detail used by each control structure makes it difficult to integrate both functions, each collection of data remains separate, which reduces the efficiency of obtaining meaningful data (Rasdorf and Abudayydh, 1991).

Rasdorf and Abudayydh (1991) addressed the importance of cost and schedule control integration for effective construction-process management, and discussed various data representation models developed for the integration. In Teicholz's model (Teicholz, 1987), a given cost account in the CBS is mapped to one or more tasks in the WBS. Percent allocation is used in the mapping, in which a cost account has a specific percentage, proportional to a given resource amount allocated to a given task. Hendrickson and Au (1989) proposed a work-elements concept in which a work element defined by a matrix of work packages and cost accounts provides a link between the WBS and CBS. In the model, a cost account can relate to one or more tasks, and a task can relate to one or

more cost accounts by using a work element as a common denominator. Ibbs's and Kim's model (Kim 1989) proposed a new element integrating a work package in the WBS, a cost account in the CBS, and a design object on the drawing. The element represents a lowest-level construction task for building a specific design object, which is linked to a cost account and a work package.

Rasdorf and Abudayydh (1991) criticized those models for maintaining two different views of project data: CBS and WBS. As a result, they viewed the work-packaging model, originally developed by the US Department of Defense, as a possible solution for integrated control in the construction industry. The cost information is added to the WBS; therefore the work-packaging model can eliminate the CBS.

One modification of the work-packaging model, called the cost/schedule control system criteria (C/SCSC) uses work packages in the WBS as the basis for control. In the C/SCSC model, a work package has cost and time data, and may exist at a higher level than the actual activity level (Moder et al, 1983; Rasdorf and Abudayydh, 1991). Earned value management (EVM), which is widely used for project progress monitoring and cost control purposes, emerged as a financial analysis specialty of C/SCSC. By integrating project scope, schedule, and cost, EVM techniques indicate project performance at a particular point in time (Siu and Lu, 2011).

Rasdorf and Abudayydh (1991) combined a contractor's organizational breakdown structure (OBS) into the work-packaging context to provide a unified data organization. In the model, a control account generated by integrating the WBS and OBS becomes a depository of control data: a scope of work, code

number, planned start and end dates, a budget for resource consumption, actual start and end dates, and actual resource consumption.

Kang and Paulson (1998) proposed a unified construction information classification system (CICS) which consists of four facets: facility, space, element, and operation. They argue that the proposed CICS allows a project manager to control a project with common information for both estimating and scheduling.

Fayek (2001) suggested an activity-based job costing for integrating estimating, scheduling, job costing, and accounting. The method creates a unique code for each task by combining activity codes with traditional cost codes (e.g. MasterFormat).

Nassar et al. (2003) suggested the integrated project breakdown structure (IPBS) where cost control accounts are the basis for cost control and linked to the scheduling activities.

In order to achieve the thesis objective, the work-packaging model has been adapted for the cost and schedule integration. Since it creates a unified view of project data by adding cost information to WBS, the work packages in WBS become common denominators. In ISP, the work packages are designed to have not only schedule and cost but also resource and risk information; therefore, centering data around work packages is very effective in removing the project management burden.

2.2 Simulation-Based Integration Models

Computer simulation is a useful tool for designing and analyzing construction processes to understand their underlying behaviour regardless of a project's complexity and size (AbouRizk, 2010). The use of simulation language

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in the construction industry was popularized by CYCLONE (Halpin, 1977) and has led to many variations. Readers can refer to AbouRizk (2010) and Lee et al. (2010) for further details about the development history of the existing simulation system targeting construction projects.

The development and application of simulation in the construction industry have mainly focused on discrete-event process interaction modeling (operation-level simulation), and have matured over the years as a result of researchers' efforts to encourage industry to adapt the tool (Sawhney and AbouRizk, 1995; Moussa et al., 2007; AbouRizk, 2010). On the other hand, some researchers have investigated the use of project-level simulation in the construction industry, where simulation is viewed as a tool for project scheduling, cost estimating, and risk analysis. One example of project-level simulation is the activity-based construction (ABC) modeling and simulation method (Shi, 1999). Shi (1999) claimed that the ABC method, which uses a single element to represent a construction activity, simplifies the steps in simulation creation since it is similar to a CPM (critical path method) -based AON (activity on node) network building system. While Shi (1999) focused on incorporating the network scheduling technique into simulation, some researchers have tried to integrate the planning components such as scheduling, cost estimating, and risk analysis with the benefits of simulation.

In this section, some of the research efforts for the simulation-based planning are introduced. Section 2.2.1 reviews simulation-based research for integrating scheduling and cost analysis, while the literature presented in Section 2.2.2 tries to integrate scheduling and risk analysis into simulation. The research

that focused on developing an integrated platform for simulation-based planning is introduced in Section 2.2.3.

2.2.1 Scheduling and cost integration

Isidore and Back (2002) proposed a method for quantifying the relationship between the cost estimate and schedule of construction projects using the percentile ranking from concurrently simulated range estimating and a stochastic schedule analysis. The models' procedure (multiple-simulation analysis technique, MSAT) can be summarized as follows (Isidore and Back, 2002):

(1) The percentile level of either the cost estimate or the project schedule needs to be fixed. The percentile of the other can be determined based on the predetermined percentile. The procedure explained here uses the fixed percentile level (e.g., 95th percentile) of the project schedule.

(2) Range estimating and probabilistic schedule analysis are simulated concurrently through a Monte Carlo simulation. There are two sets in the iteration cycle. During the first iteration (e.g., 100 runs), the 95th percentile value of the project schedule and its corresponding cost estimate value are stored along with the ranking of the cost estimate value.

(3) The second iteration repeats the above process a certain amount of times (e.g., 25 runs). As a result, it is possible to obtain 25 cost estimate values and their percentile ranking corresponding to the 95th percentile project schedule.

(4) The mean cost estimate and its deviation are calculated from the result of above procedure. They are then used to calculate the cost estimate values' conditional percentile ranking. The conditional percentile ranking is used to calculate the desired cost percentile ranking related to the project schedule's 95th percentile value.

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(5) The regression relationship can be obtained between the cost estimate value and its conditional percentile ranking, which provides a faster calculation of other cost estimate options.

Although MSAT highlights the importance of reliably integrating range estimating and probabilistic scheduling, the weakness lies in the lack of consideration about the interdependency between an activity's schedule and cost. The method does not explain how to relate the cost and schedule information within an activity before the Monte Carlo simulation begins. Without this consideration, the effort to relate the result of the independent range estimating and probabilistic schedule analysis will not be effective.

Boskers and AbouRizk (2005) pointed out the limitation of the currently used range estimating technique, and proposed a simulation-based model that takes into account uncertainties in estimating capital construction projects spanning multiple years. The first step of the methodology is to break a project into work packages and associated activities, which is accomplished by adopting a hierarchical modeling concept. The work packages or activities are then sequenced based on their logical interdependency. The activity cost in current dollar value is defined as probability distribution, and the future inflation rate of the project is forecasted. Upon analysis, the activity duration sampled from probability distribution or given by users is used to break down the current cost of the activity into equal parts, each of which corresponds to a specified time step. To perform a cash flow analysis and calculate net present value (NPV), the expenses and revenues for each time period are summed up in actual dollar amounts. As a result of the Monte Carlo simulation, a cumulative density function (CDF) is obtained in which users can view the project's cost distribution.

Boskers and AbouRizk (2005) incorporate network scheduling and range estimating techniques which can be used for NPV analysis in the project's early stage. Unlike other project-level simulation research, which was developed as a standalone package or assisted by a commercial simulation software package, the proposed method was incorporated into a special purpose simulation template in the Simphony (Hajjar and AbouRizk, 1999) simulation environment. Although Boskers and AbouRizk (2005) tried to utilize a work breakdown structure in the model using a hierarchical modeling concept, it is not flexible enough to handle the complex construction projects, given that capital construction projects have rather complicated hierarchical structures and time frames.

2.2.2   Scheduling and risk analysis integration

Wales (1994) proposed a project-level simulation framework which incorporated CPM network scheduling and the effect of weather uncertainty in activity productivity. The author used SLAMSYSTEM (Pritsker Corporation, 1990) as a simulation engine, and automated the conversion of an existing CPM network to an equivalent simulation representation. The internal simulation clock progresses by increments of one day in the simulation-based CPM network. Weather conditions based on historical data are generated on a daily basis, and a trained neural network evaluates the scheduled tasks' productivity. The task progressions in the schedule are then adjusted based on the productivity estimated. This process repeats itself every day until the project completes. After completing multiple simulation runs, a range of possible project completion times is obtained.

Wales (1994) successfully demonstrated implementing a risk factor into a schedule network, but as the author indicated, the suggested framework has several limitations. First, the model does not account for resources or cost components, which are essential parts of project management. Another problem is that the method would only be effective on recursive risks, where enough data have been collected about the impacts to support the neural network productivity forecasting.

Wang et al. (2006) developed a simulation-based model, SimSAFE, to access an expected accident cost for each activity in a schedule network. This led to incorporating safety management into the schedule control. In the research, the 15 categories of accident causes including falls from elevation, collisions, and electric shock) and the 5 categories of injury (light, medium, severe, disabling, and death) are taken into account to calculate the degree of hazard for each activity. Historical data is used to calculate the accident cost, and the type of injury and likelihood of the accident causes occurring during each activity. Users qualitatively estimate information about how closely related the occurrence of each accident cause to factors such as safety training, site environment, and safety inspection. As a result of the simulation, it is possible to identify the expected accident cost of and factor-sensitivity information for each activity (or path, working zone) in a network system. The information can help with safety management.

According to the authors, the proposed method demands a lot of time-consuming inputs and requires abundant data to calculate the likelihood of each accident cause occurrence as well as the historical accident cost. In addition, the method focuses on only one type of risk: labourers' safety. However, those

limitations are commonly found in the research dealing with risk factors as seen in Wales' research (1994), which focused only on the impact that weather has on construction activities.

2.2.3   Simulation-based planning system

Some researchers have put more effort into developing integrated simulation-based planning systems. In general, the systems incorporate a discrete-event operation model into the higher level for planning, and provide a user-friendly interface.

Sawhney and AbouRizk (1995) developed the hierarchical simulation modeling (HSM) method for simulation-based construction project planning. The plan development using HSM includes four steps: (1) work breakdown structure (WBS); (2) resource library; (3) operation sequencing; (4) development of the process models. The WBS in HSM has a project level, operation levels, and process levels. The operation level is an intermediate level focusing on the construction method and implementation strategy, while the process level is the lowest level of the WBS and focuses on the work's technological sequence. Resources with information about quantity and cost are defined at any level of the WBS for the project, and initialized in the resource library. The sequencing links of the operation are serial, parallel, or cyclic links, which can be used at any level of the WBS. Process models using CYCLONE (Halpin, 1997) modeling methodology with enhancement are to be developed at the process level. The enhancement includes resource manipulation and process interdependence. The authors developed the graphical user interface module for model-building and automatically translated it into SLAMSYSTEM (Pritsker Corporation, 1990) simulation language.

The HSM's major advantage is the use of a hierarchical modeling concept which allows users to break a project into several operation and process levels. However, since the modules in HSM are based on several program languages and software environments, a more comprehensive framework is required to increase the method's applicability. On top of that, using a conventional network scheduling concept will make it easier to adopt simulation-based planning.

Moussa et al. (2007) developed cost and time network analysis (CTAN) to provide a modeling framework to integrate project cost and time for risk assessment. CTAN adapted a hierarchical modeling concept, the first level of which is a schedule network. Each of the activities in this layer can be broken down into a lower level network, activities or resources. Any risk events may affect the resources' cost and quantity, and the activity duration. Uncertainties in the network can be modeled through a precedence relationship between activities with lead/lag time or a probability branching which controls the realization of relationships or activities. The proposed model was implemented into the Simphony (Hajjar and AbouRizk, 1999) simulation environment. Although CTAN provides greater flexibility for the integrated planning, without a work breakdown structure or risk definition modules, the approach is rather non-systematic for the user who is not as familiar with project planning and simulation.

Lee et al. (2010) introduced an integrated simulation system, construction operation and project scheduling (COPS), developed using MATLAB (MathWorks, 2007a) programming and the simulation environment, SimEvent (MathWorks, 2007b). COPS has an operation analysis module where the best-fit-PDF (probability density function) is estimated from historical data of a task's duration. It also performs sensitivity analysis from all possible resource combinations of a

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certain range to provide information about hourly production and hourly cost for the optimum resource combination. When the operation model is combined with the project scheduling model using a hierarchical modeling concept, the optimum resource combination, best-fit-PDF of the operation completion time, and cost are automatically fed to the project scheduling model as parameters of an activity, and a stochastic simulation-based scheduling is performed. One of the drawbacks of the research is that the relationship used in the network scheduling is limited to a finish-to-start relationship. In addition, the authors addressed the difficulties of data acquisition for the best-fit-PDF.

2.3   Requirement of Integrated Simulation-Based Planning

From the literature review in the previous sections, the general requirements of integrated simulation-based construction planning can be summarized as follows:

- Cost and schedule integration requires a unified structure in order to improve the efficiency in project management.
- The work-packaging model is a feasible method for cost and schedule integration because the work packages in the WBS become common denominators for cost estimation and scheduling.
- The analysis core of the simulation-based planning is network scheduling, as seen in the literature. The industry is more likely to adopt it if the system adopts conventional network scheduling methods such as CPM, PERT, or PDM.
- Cost estimating is an important component in project planning. The cost information can be integrated into the simulation modeling through either the work packages in the WBS or resources used in the project.

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- The risk identification and analysis modules integrated into the simulation-based planning will help project managers to quantify risk-enabled duration and cost information.

- The integration between operation-level and project-level simulation is desirable to utilize simulation benefits such as production estimation and resource optimization at the operation level.

- In order to broaden the usability of the simulation-based planning tool, a comprehensive framework with user-friendly interface is required.

Based on the findings listed above, integrated simulation-based planning (ISP) was developed. The ISP's framework is explained in the next chapter.

3 FRAMEWORK OF INTEGRATED SIMULATION-BASED PLANNING (ISP)

This chapter is intended to provide an overview of integrated simulated-based planning (ISP)'s framework. Section 3.1 explains what ISP's modules are and how they are connected with each other. Section 3.2 provides detailed information of how the risk factors are accessed and assigned in ISP. Section 3.3 describes the network scheduling method and hierarchical modeling feature that ISP uses.

3.1 Overview of ISP Structure
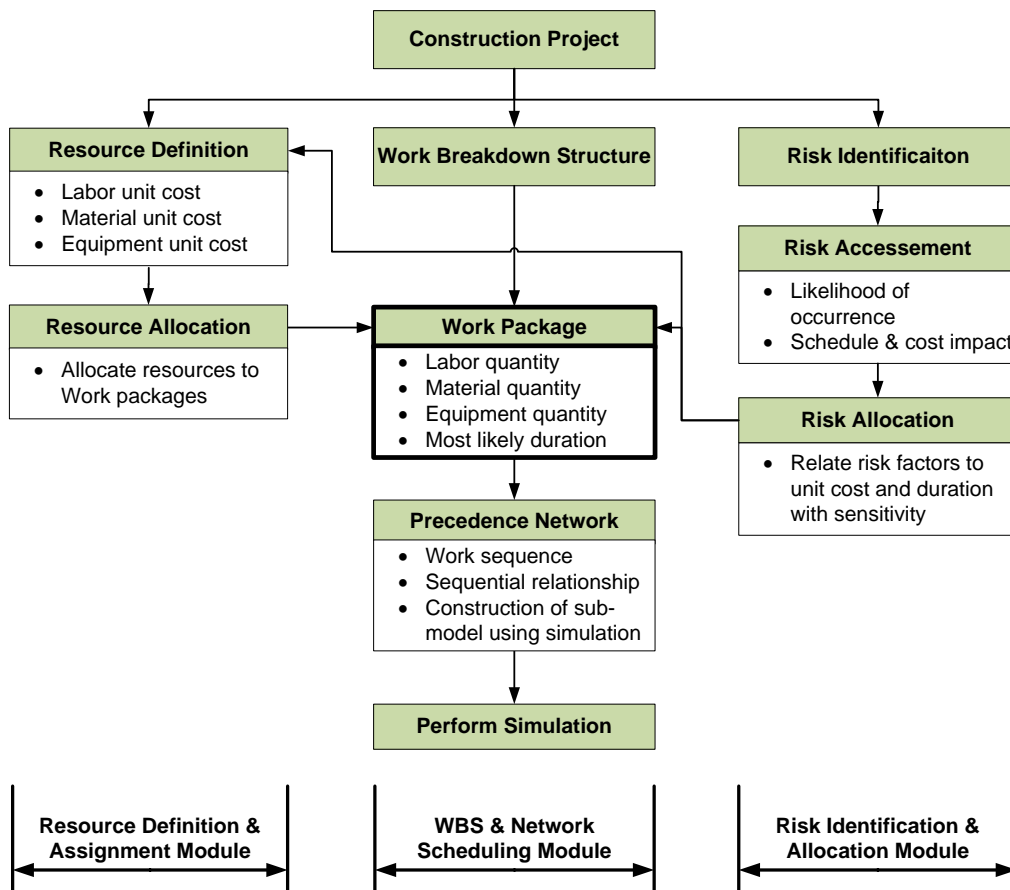
Figure 3-1 The framework of integrated simulation-based planning (ISP)

The main objective of the research is to provide a framework for risk-associated cost/schedule integration, and to evaluate project cost and schedule through computer simulation. Figure 3-1 shows ISP's overall framework, consisting of the work breakdown structure (WBS) and network scheduling module, resource definition and assignment module, and risk identification and allocation module.

The WBS and network scheduling module are the core of ISP. PMI (2004) defines the WBS as "a deliverable-oriented hierarchical decomposition of the work to be executed by the project team, to accomplish the project objectives and create the required deliverable." The WBS graphically portrays the total project scope, which is broken down into smaller, manageable pieces. The WBS's lowest level consists of work packages (WPs) where the project is managed and controlled. The cost and schedule integration model that ISP uses is based on the work-packaging model; therefore WPs have their own scope, schedule, and budget, and are the main objects for planning, controlling, and work performance. WPs with information about cost and duration are defined within the WBS, and become basic elements for communicating with other functions.

In order to perform resource-driven cost estimating, resource information for the project under consideration needs to be defined separately in the resource definition and assignment module. Each resource should have one type among labour, material, equipment, and user-defined type, and is assigned to WPs. For cost estimating, the dollar value of direct and/or indirect cost is specified for one resource quantity as fixed and/or variable cost. Indirect costs such as daily subsistence allowance, general supervision, and housekeeping are usually applied as a percentage of direct costs and spread over the project duration as

variable cost. The variable cost is a function of activity duration. A resource' variable cost is a unit cost per hour to be spent as the resource is utilized in a WP, while the fixed cost is the constant amount of money to initiate the resource and is spread out over the WP duration for cash flow calculation. It is assumed that resources are in unlimited supply in ISP, and the amount of the resources required for a certain WP is constant regardless of the variation in the WP duration.

Project uncertainties can be considered through the risk identification and allocation module. Risks are identified using a risk breakdown structure (RBS) and assigned to resources and/or WPs. The details of this module will be discussed in Section 3.2
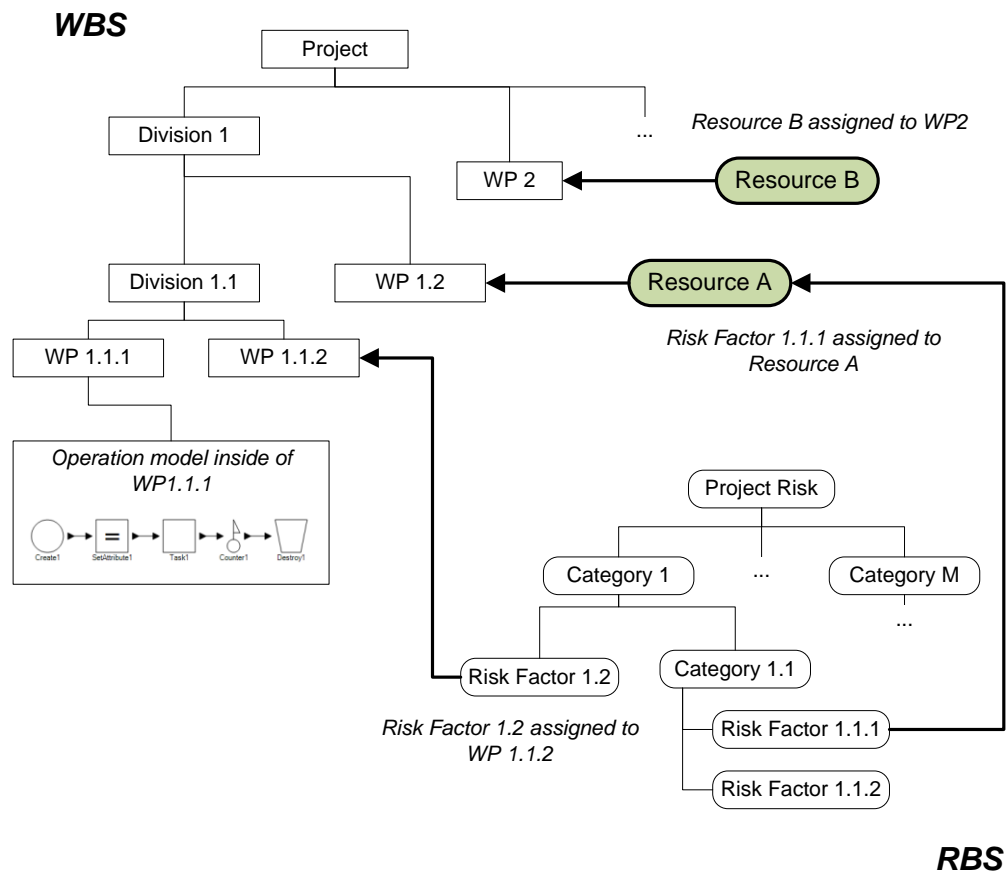
Figure 3-2 A conceptual model for resource and risk factor allocation to WPs in ISP

A WBS creation, resources definition and risk identification are carried out after the project scope definition. The resources, risk factors, and sequential relationships between WPs are assigned to a WP, and the WP may accommodate a detailed operation model. Figure 3-2 shows a conceptual diagram indicating how WBS, resources, and risk factors are linked each other in the ISP.

The ISP's simulation core is network scheduling based on a precedence diagramming method, where the nodes of the network represent WPs. Section 3.3 discusses the features used in the ISP's network scheduling module.

3.2 Risk Identification and Allocation

Projects in the construction industry are subjected to many risks and much uncertainty regardless of their nature, size, and place of execution. If risk occurs, it has a positive or negative impact on project objectives such as time, cost, safety, and environment. As indicated in Section 2.2.2, research that attempts to integrate the risk management function into network scheduling requires time-consuming data inputs based on historical data which is not often available, especially in a project's early stages. The risk management features that the ISP uses are devoted to structuring a risk identification procedure and risk factor allocation. The method is generic and designed for ease of use. This section presents the general overview of risk management followed by the introduction of a risk breakdown structure that ISP uses for risk identification. The method of the linkage between the risk factors and WPs (and/or resource) is also described.

3.2.1 An overview of risk management

The objectives of project risk management are to increase the probability and impact of positive events, and decrease the probability and impact of adverse events (PMI, 2004). Risk management is divided into four main stages: risk identification, risk analysis, risk mitigation, and risk control (AbouRizk, 2009; Abdelgawad, 2010).

- Risk Identification is a process of investigating risk events which might become threats or opportunities to the project. The typical techniques are standard checklists, expert interviews, facilitated brainstorming sessions, and the Delphi technique.

- Risk Analysis is a phase of quantifying the effect of risk events on the project's objectives such as scope, cost, time, and quality. Quantifying risk factors are essentially presented with their severity as defined:

    Severity = likelihood of occurrence of a risk × magnitude of impact

- Risk Mitigation is steps taken to control risk events by assigning appropriate risk response strategies. Strategies for threats include mitigation, transfer, avoidance, or acceptance, while those for opportunities are exploiting, sharing, enhancing, or accepting.

- Risk Control is a process of monitoring the implementation of risk response strategies, evaluating their effectiveness, identifying new risk events, and tracking the contingency expenditure.

Among the risk management phases mentioned above, the importance of risk identification should not be disregarded, since it is the first step of risk management. Insufficiently or unrealistically identified risk events will mislead the management about the entire project.

3.2.2 Risk breakdown structure

The Project Management Institute (PMI) recommends using a comprehensive structure that provides effective and quality risk identification (PMI, 2004). According to PMBOK (PMI, 2004), risk breakdown structure (RBS) is "a hierarchically organized depiction of the identified project risks arranged by risk category and subcategory that identifies the various areas and causes of potential risks."

Many researchers proposed RBSs or checklists to help with risk identification. Among them, Tah et al. (1993) proposed an RBS for contractor risk assessment, the main categories of which are labour, plant, material, sub-contractor, site, performance, contractual, location, and finance. In addition, Tah et al. (1993) grouped the risk factors outside of the contractor's control as external risks. They are inflation, exchange rate fluctuation, technology change, and political risks. Dikmen and Birgonul (2006) suggested an RBS to identify risk sources for international construction projects. They were critical that many risk checklists and RBSs in literature misused risk sources (inflation and project scope change) and consequences (cost overrun and schedule delay). The first level of their RBS consists of project and country, and the project division is subdivided into categories including complexity, poor performance, and unavailability. The country division included seven sub-divisions, among them poor international relations, instability of political condition, and immaturity of legal system. Noticeably, a separate RBS for opportunities is proposed along with the RBS for risk.
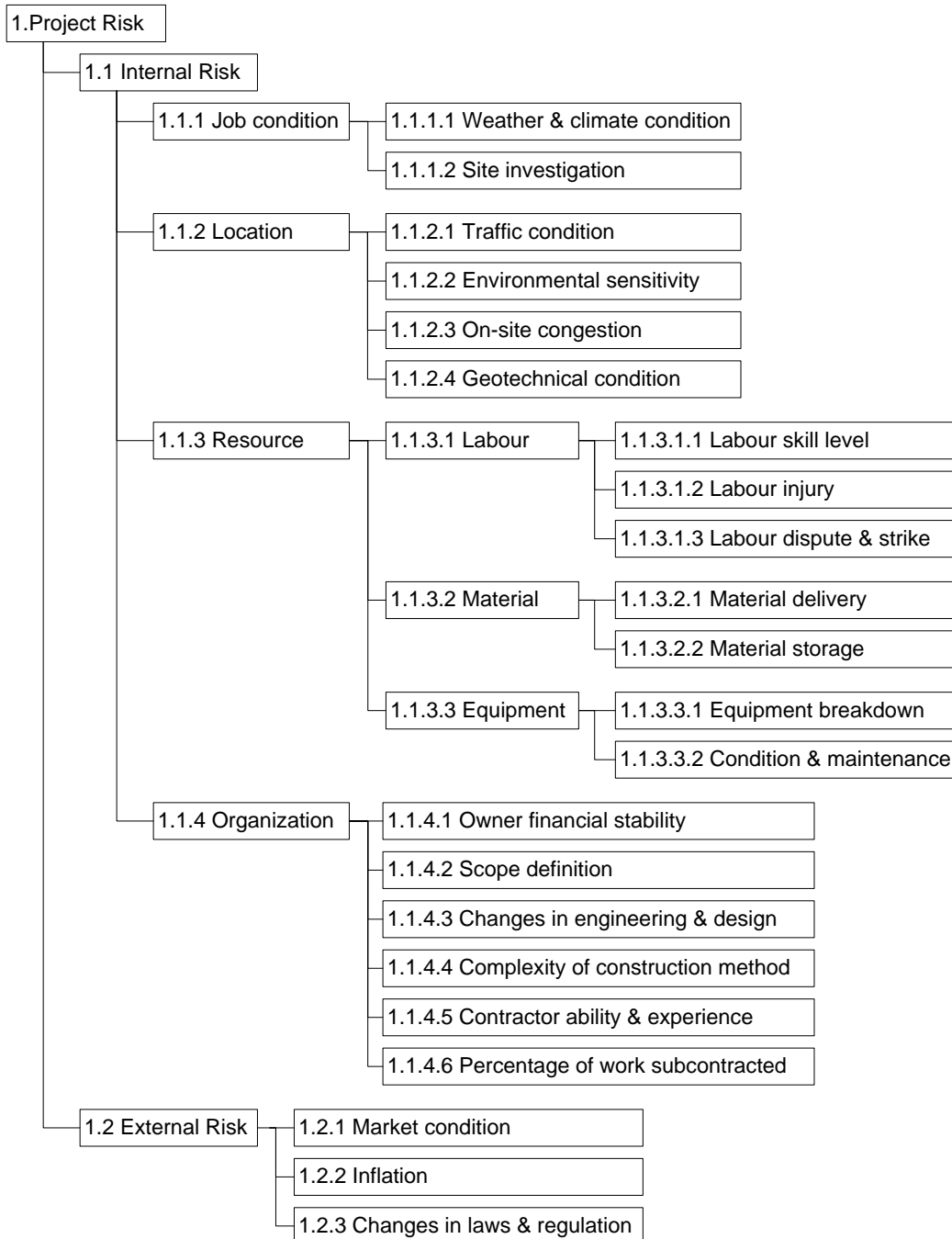
Figure 3-3 An RBS provided in ISP for a typical construction project

Figure 3-3 shows an RBS provided in ISP for a typical construction project to assist risk identification. The RBS has been derived from the literature review: Tah et al. (1993), Nasir et al. (2003), Dikmen and Birgonul (2006), and Schatteman et al. (2008). The intermediate levels of the RBS represent risk

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categories while the lowest levels are risk factors. Risk factors have a likelihood of occurrence during a specified time period and affect only the schedule and/or cost. The likelihood scale can be presented in probabilistic, linguistic, or other nominal or ordinal scale forms, which might differ by organization. Table 3-1 shows an example of a likelihood table (AbouRizk, 2009).

Table 3-1 Likelihood table for risk analysis (SMA Consuting Ltd.)

Descriptor	Explanation	Ordinal scale	Probability
Highly Likely	Almost certain that it will happen; very frequent occurrence	100	0.825
Likely	More than 50-50 chance	50	0.500
Somewhat likely	Less than 50-50 chance	25	0.250
Unlikely	Small likelihood but could happen	10	0.100
Very unlikely	Not expected to happen	3	0.030
Extremely unlikely	Possible, but would be very surprising	1	0.005

It is worth noting that the proposed RBS is an example of risk categorizations. If desired, the whole categorization might be altered depending on the organizations or types of a construction project.

3.2.3 Risk factor assignment

Probability distributions, the parameters of which are generally calculated based on historical data or expert judgement, are entered in simulation to incorporate risks into either the project schedule or estimating. However, there aren't often enough sample observations to select appropriate distributions in a construction project, and defining distribution parameters based on experts' subject judgment is not an easy task.
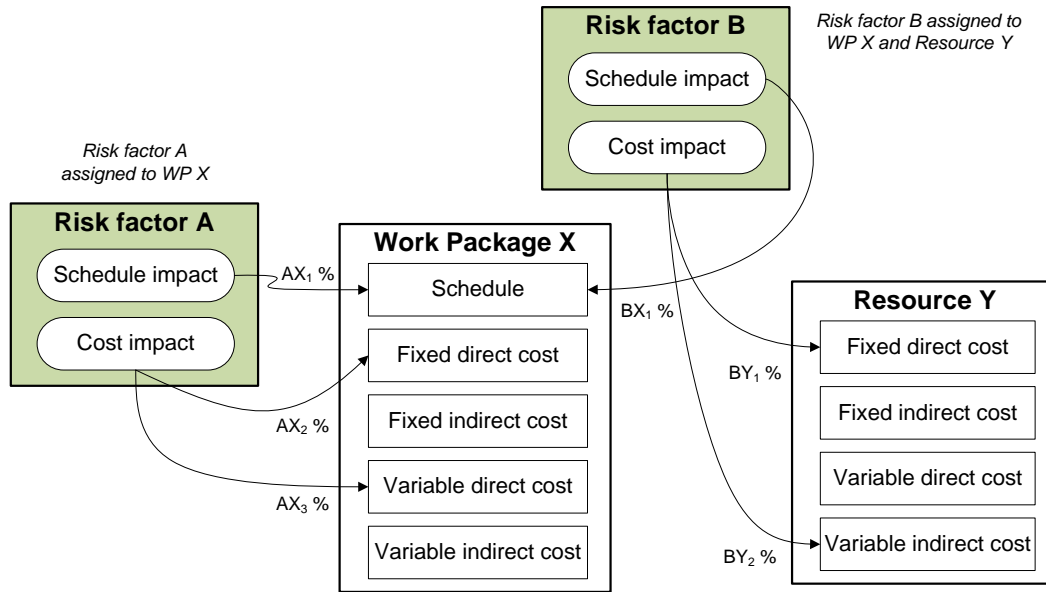
Figure 3-4 A diagram for the risk factor assignment in ISP

In ISP, the sensitivity against the schedule and cost impact of each risk factor can be specified upon assigning a risk factor on WPs or resources. The sensitivity is presented as a percentage of the original impact value. This feature is useful for distinguishing the impact of different WPs or resources influenced by the same risk factor. In a tunnel construction, for example, the whole length of the tunnel can be divided into several regions, each of which becomes a WP. Although each region is assigned the same risk factor (e.g., encountering with contaminated soil), different sensitivity values can be assigned based on the uncertainty of the site investigation related to each region.

Note that the schedule impact is only effective when the risk factor is assigned to WPs, while the cost impact affects WPs or resources' cost. Since four types of cost information (fixed direct, fixed indirect, variable direct, and variable indirect) are available in WPs and resources, a different sensitivity can be specified for each. For example, the cost impact of Risk factor A is assigned to the fixed direct cost of Work package X with sensitivity AX_2 and the variable

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direct cost with AX_3 sensitivity in Figure 3-4. Since Work Package X's fixed and variable indirect costs are not associated with sensitivity, Risk factor A's cost impact does not affect the indirect costs.

The default sensitivity value is 100 percent, which means that the impact specified in the risk factor definition process will be fully effective when the risk factor materializes while the WP is being executed. If a weaker impact is anticipated upon the risk occurrence, a value less than 100 percent can be assigned, and vice versa.

3.3 Schedule Network Analysis[2]

Network scheduling or schedule network analysis is an effective tool for project time management in which the time windows for tasks are calculated based on the sequences between activities. One of the earliest methods developed for this purpose is the critical path method (CPM), and it has been widely used in project management practices since its invention in the 1950s (Lu and AbouRizk, 2000). The classic CPM is a deterministic network analysis tool, which allows one duration value for each activity resulting in one estimate of the project completion time (Ahuja et al., 1994). The project evaluation and review technique (PERT) was developed in 1958 by US Navy for the Polaris missile system (Moder et al., 1983). Unlike CPM, PERT incorporates uncertainties in activity duration by using three time estimates: optimistic, most likely, and pessimistic. This method allows users to approximate the probability of a project completion time based on the mean and variance of each activity's duration (Ahuja et al., 1994). Conventional PERT, however, has as its weakness the

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[2] This section was extracted from an article and modified accordingly. The article was presented as a paper at the CSCE Construction Specialty Conference annual conference in Ontario, Canada, 2011.

implication that there is a unique critical path, although any number of paths could be critical, depending on the realization of random activity duration (Moder at al., 1983). In addition, some scholars argue that the mean project time calculated by PERT is usually an underestimate of the true value due to the ignorance of possible critical paths (Ahuja et al., 1994; Lu and AbouRizk, 2000).

It is believed that the one promising solution to PERT's drawbacks is to perform a formal stochastic simulation such as the Monte Carlo simulation (Ahuja et al., 1994; Lu and AbouRizk, 2000; Lee and Arditi, 2006). In the simulation-based network analysis, activity durations are randomly sampled from the distribution that a user specifies, and a schedule network analysis is performed. The procedure repeats itself many times, and generates a range of possible project completion times. By allowing users to consider the schedule risks associated in the project of interest, the simulation based network analysis results in a more accurate and realistic estimation of project completion time.

ISP's analysis core is simulation-based network scheduling. From the information defined through the WBS module, a schedule network is generated. The WPs defined in the WBS are converted into nodes in the network, where resources and risks are allocated. Users can arrange the nodes and modify the relationship between nodes in the network before simulation begins. In order to run multiple iterations during simulation, the desired number of iterations should be entered in the software package's specified field.

This section briefly describes a precedence diagram method which ISP adapts as a schedule network analysis technique, and how process interaction models are linked to ISP's project-level simulation through hierarchical modeling.

3.3.1 Precedence diagram method

A precedence diagramming method (PDM) is an extension of a conventional activity-on-node (AON) network diagram in which nodes represent activities while arrows indicate logical relationships between activities. When activities in the project are overlapped, the PDM simplifies the network model by using four types of relationships shown on the arrow with lead/lag time rather than splitting the activities into several sub activities as in an AOA (activity on arrow) network diagram (Ahuja et al., 1994). They are finish-to-start (FS_{ij}), finish-to-finish (FF_{ij}), start-to-start (SS_{ij}), and start-to-finish (FS_{ij}) relationships as shown in Figure 3-5. They are explained as follows when activity i precedes activity j (Ahuja et al., 1994);

- FS_{ij} : the succeeding activity j can start the lag time after the proceeding activity i is complete.

- FF_{ij} : the succeeding activity j can finish the lag time after the proceeding activity i is complete.

- SS_{ij} : the proceeding activity i must start lead time earlier than the succeeding activity j starts.

- SF_{ij} : the proceeding activity i must start lead time earlier than the succeeding activity j finishes.

Please note that a typical relationship used in AON is $FS_{ij} = 0$, meaning that an activity j can start immediately after its preceding activity i finishes. Using those relationships, especially SS_{ij} and FF_{ij}, repeating activities are often modeled.

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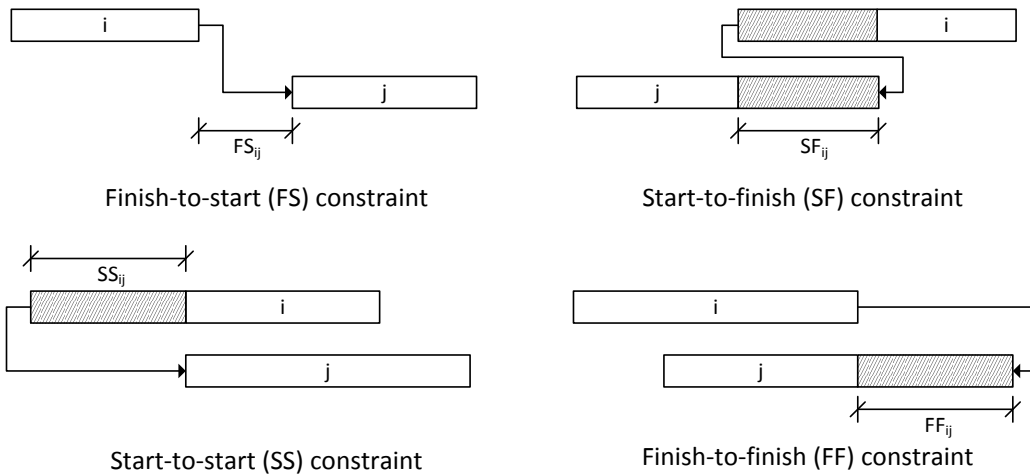
Figure 3-5 Precedence diagramming relationships with lead/lag time

$a_j = D_j - FF_{ij}$
Interruption $= EF_j - ES_j - D_j$

$b_j = D_j - SS_{jk}$
Interruption $= LF_j - LS_j - D_j$
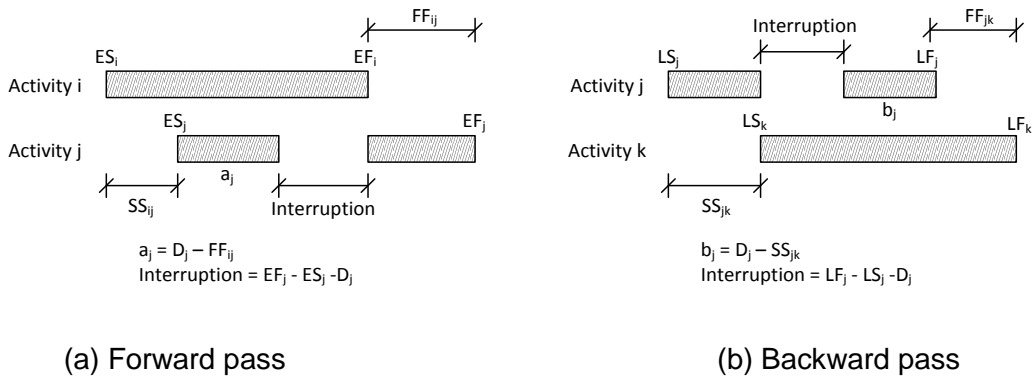
(a) Forward pass

(b) Backward pass

Figure 3-6 Interruptions in the precedence diagramming method (Ahuja et al., 1994)

Activities can be set as either interruptible or uninterruptible based on priorities or resource availability. In some cases, activities become interrupted due to logical constraints between activities in the PDM, especially when SS_{ij} and FF_{ij} relationships are used together. Thus, the interruption changes the activities' time frame. Figure 3-6 shows the possible interruption in activities during the forward and backward pass calculation.

The early start (ES_j) and early finish (EF_j) are calculated during the forward pass, and the late start (LS_j) and late finish (LF_j) are obtained from its

backward pass calculation. ISP uses the following equations to calculate the forward and backward pass of interruptible and uninterruptible activities (Moder et al., 1983 - modified). The activity being analyzed has the subscript j, and D_j is the duration of the current activity. Its predecessors with the subscript i are used during the forward pass calculation, while successors with the subscript k are used for the backward pass calculation.

- Uninterruptible activity (forward pass computation)

$$ES_j = MAX_{all\ i} \begin{Bmatrix} \text{Project start time} \\ EF_i + FS_{ij} \\ ES_i + SS_{ij} \\ EF_i + FF_{ij} - D_j \\ ES_i + SF_{ij} - D_j \end{Bmatrix} \quad ; \quad EF_j = ES_j + D_j$$

- Uninterruptible activity (backward pass computation)

$$LF_j = MIN_{all\ k} \begin{Bmatrix} \text{Project end time} \\ LS_k - FS_{jk} \\ LF_k - FF_{jk} \\ LS_k - SS_{jk} + D_j \\ LF_k - SF_{jk} + D_j \end{Bmatrix} \quad ; \quad LS_j = LF_j - D_j$$

- Interruptible activity (forward pass computation)

$$ES_j = \underset{all\ i}{MAX} \begin{Bmatrix} \text{Project start time} \\ EF_i + FS_{ij} \\ EF_i - D_i + SS_{ij} \ (\text{when } \alpha_i < SS_{ij}) \\ ES_i + SS_{ij} \ (\text{when } \alpha_i \geq SS_{ij}, \text{ or where } \alpha_i \text{ was not required}) \end{Bmatrix}$$

$$EF_j = \underset{all\ i}{MAX} \begin{Bmatrix} ES_j + D_j \\ EF_i + FF_{ij} \\ EF_i - D_i + SF_{ij} \ (\text{when } \alpha_i < SF_{ij}) \\ ES_i + SF_{ij} \ (\text{when } \alpha_i \geq SF_{ij}, \text{ or where } \alpha_i \text{ was not required}) \end{Bmatrix}$$

if $EF_j > ES_j + D_j$, then compute α for activity j

$$\alpha_j = \begin{cases} D_j - FF_{ij} \text{ ; if } EF_j \text{ was set by an } FF_{ij} \text{ constraint} \\ D_j - SF_{ij} \text{ ; if } EF_j \text{ was set by an } SF_{ij} \text{ constraint} \end{cases}$$

- Interruptible activity (backward pass computation)

$$LF_j = \underset{\text{all } k}{\text{MIN}} \begin{cases} \text{Project end time} \\ LS_k - FS_{jk} \\ LS_k + D_k - FF_{jk} \text{ (when } \beta_k < FF_{jk}) \\ LF_k - FF_{jk} \text{ (when } \beta_k \geq FF_{jk}, \text{ or where } \beta_k \text{ was not required)} \end{cases}$$

$$LS_j = \underset{\text{all } k}{\text{MIN}} \begin{cases} LF_j - D_j \\ LS_k - SS_{jk} \\ LS_k + D_k - SF_{jk} \text{ (when } \beta_k < SF_{jk}) \\ LF_k - SF_{jk} \text{ (when } \beta_k \geq SF_{jk}, \text{ or where } \beta_k \text{ was not required)} \end{cases}$$

if $LS_j < LF_j - D_j$, then compute β for activity j

$$\beta_j = \begin{cases} D_j - SS_{jk} \text{ ; if } LS_j \text{ was set by an } SS_{jk} \text{ constraint} \\ D_j - SF_{jk} \text{ ; if } LS_j \text{ was set by an } SF_{jk} \text{ constraint} \end{cases}$$

The total float (TF_j) is the number of time units which an activity may be delayed without extending the project completion date; therefore, an activity with a total float equal to zero is a critical activity. In an ordinary AOA or AON network, it is calculated (Ahuja et al., 1994):

Total float (TF_j) = late finish (LF_j) – early start (ES_j) – duration (D_j)

Due to the interruptions in PDM, two floats exist: start float (SF_j), and finish float (FF_j). The values are often different from each other and are calculated as shown below:

Start float (SF_j) = late start (LS_j) – early start (ES_j)

Finish float (FF_j) = late finish (LF_j) – early finish (EF_j)

The conditions of an activity being a critical activity in PDM are (1) $SF_j = 0$; (2) $FF_j = 0$; and (3) $LF_j - ES_j = D_j$. The tree criteria are used for the ISP criticality index calculation.

Criticality index for an activity is often expressed as a percentage and defined as the number of simulation runs in which the activity is critical, divided by the total number of the simulation runs (Lu and AbouRizk, 2000). Based on simulation experiments, Pritsker et al. (1989) commented that "there is a large positive correlation between the ranking of critical activities based on the ratio of average slack to activity duration standard deviation and the criticality index." However, this argument is not explored.

3.3.2 Hierarchical modeling

Commercial tools such as Microsoft Project and Oracle Primavera P6 exist for schedule network analysis. One noticeable benefit of using ISP in comparison with those commercial planning tools is that the schedule network can be analysed in conjunction with more detailed simulation models. The relationship or logical sequencing between WPs can be shown explicitly by creating a schedule network. Some WPs, however, need to be broken down into further detail by defining sub-activities with smaller time frames. For example, a general contractor in the construction industry might decide to subcontract some of the WPs, in which case the WPs become contract packages, and no further details are required for them in the case of a lump sum contract. But it will be useful to have a more detailed level of breakdown structure and scheduling for the WPs which the general contractor needs to manage. The decision on how detailed the level in the WBS should be for effective controlling is important, since constructing a detailed WBS requires more time and effort for controlling the

project. One of the solutions for dealing with the balance between the level of WBS detail and management effort is project hierarchical modeling. Using hierarchical modeling, a project can incorporate as much detail into consideration as desired in effective form (Boskers and AbouRizk, 2005).

Figure 3-7 conceptually illustrates how hierarchical modeling works. As shown in the figure, each WP in hierarchical modeling can accommodate more detailed sub WPs, activities, or simulation models which describe the WP's process. Project scope management and status reporting for cost and time control are dictated through the WP level using sequential relationships. A WP's substructure can be modeled in order to investigate constructability and production optimization through low level network analysis and simulation modeling.
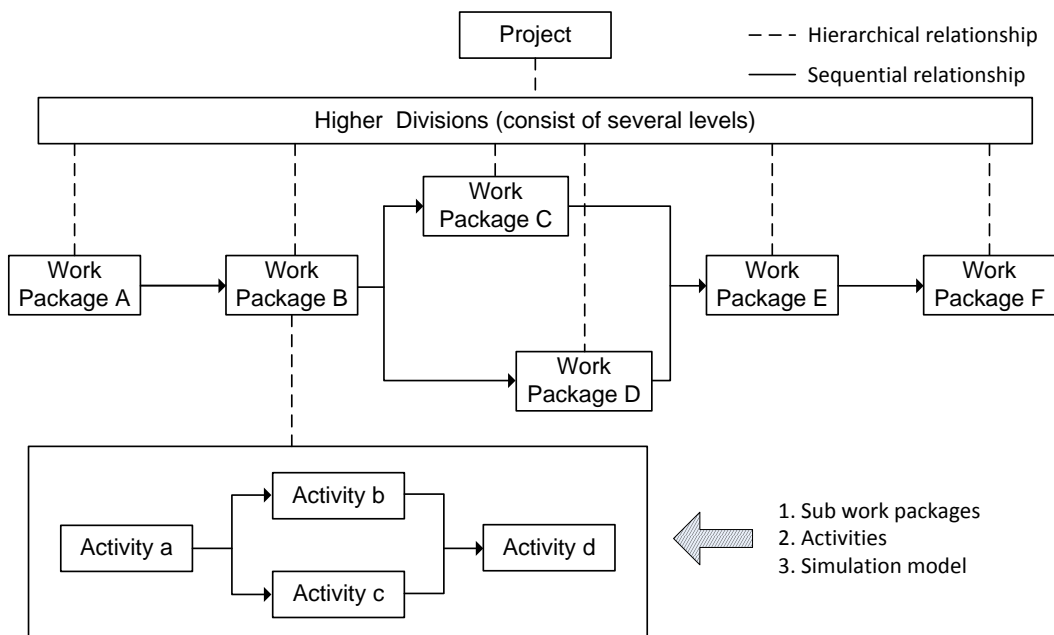
Figure 3-7 An illustration of project hierarchical modeling (Hong and AbouRizk, 2011)

ISP adapted an approach similar to hierarchical modeling. It was designed to incorporate other simulation models as a WP's substructure in the network, in order to visualise the activity at a more detailed level, and calculate more detailed activity durations. In high-rise residential building construction, for instance, one can divide the scope of work into WPs, such as site work, excavation, foundation, framing, form work, mechanical work, electrical work, and interior work. A schedule network is built based on the logical interrelationship between the WPs and the completion time estimated for each package. Assume, for example, that the building is located in a congested area, and requires a deep basement for resident parking. Since the excavation is a lengthy process and consists of many activities, one might want to build a process interaction model in order to analyze the process's production rate. Once a network scheduling model is built using the ISP tool, the simulation model for the excavation can be created inside of the excavation WP using the Simphony.NET general purpose template or the earth-moving SPS template. As a result, the project manager can have better insight into the excavation's productivity issues, and obtain more accurate durations for the excavation work package, since the simulation model created inside is what's dictating the excavation duration.

During an ISP iteration, the process interaction model is analyzed first, and transfers its completion time to the main ISP schedule network. Afterwards, the ISP starts the overall analysis including sampling WP durations from any given probability distribution, materializing risk factors based on their likelihood, and applying the impacts on the activity durations or resource unit costs. The aforementioned procedure repeats as the number of iterations the user specified, and generates a range of possible project completion times and costs.

4 DEVELOPED SPS TOOL FOR THE ISP IMPLEMENTATION

This chapter is intended to provide descriptions of how the ISP concept has been implemented into the computer program. Section 4.1 explains the ISP tool's algorithm and development environment. Section 4.2 presents the ISP tool's elements and how they are related to each other in that environment. Section 4.3 gives information about input and output data processing.

4.1 The Structure of the ISP Tool
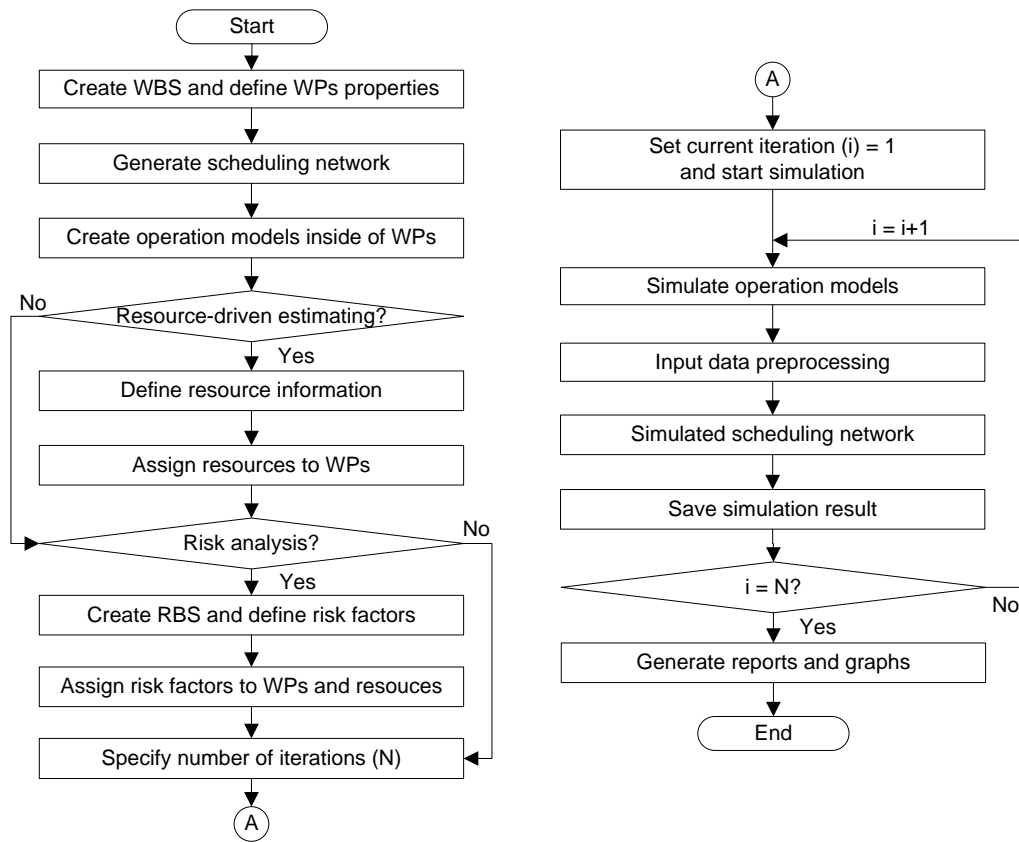
Figure 4-1 The flowchart of the ISP tool

The developed ISP concept described in Chapter 3 is incorporated into a computer simulation program. The program has been developed based on the

flowchart shown in Figure 4-1. It explains how the ISP concepts are linked with each other in an integrated model.

Simphony.NET 4.0 was used as a platform for developing the SPS tool for ISP. Simphony was developed with the objective of providing a standard, consistent, and intelligent simulation environment which can be used as a platform for creating general process interaction models and developing special purpose simulation (SPS) tools (Hajjar and AbouRizk 1999). It is a Microsoft Windows-based computer system and has continuously evolved since it was first introduced publicly in 1999. Figure 4-2 shows Simphony.NET's main interface.
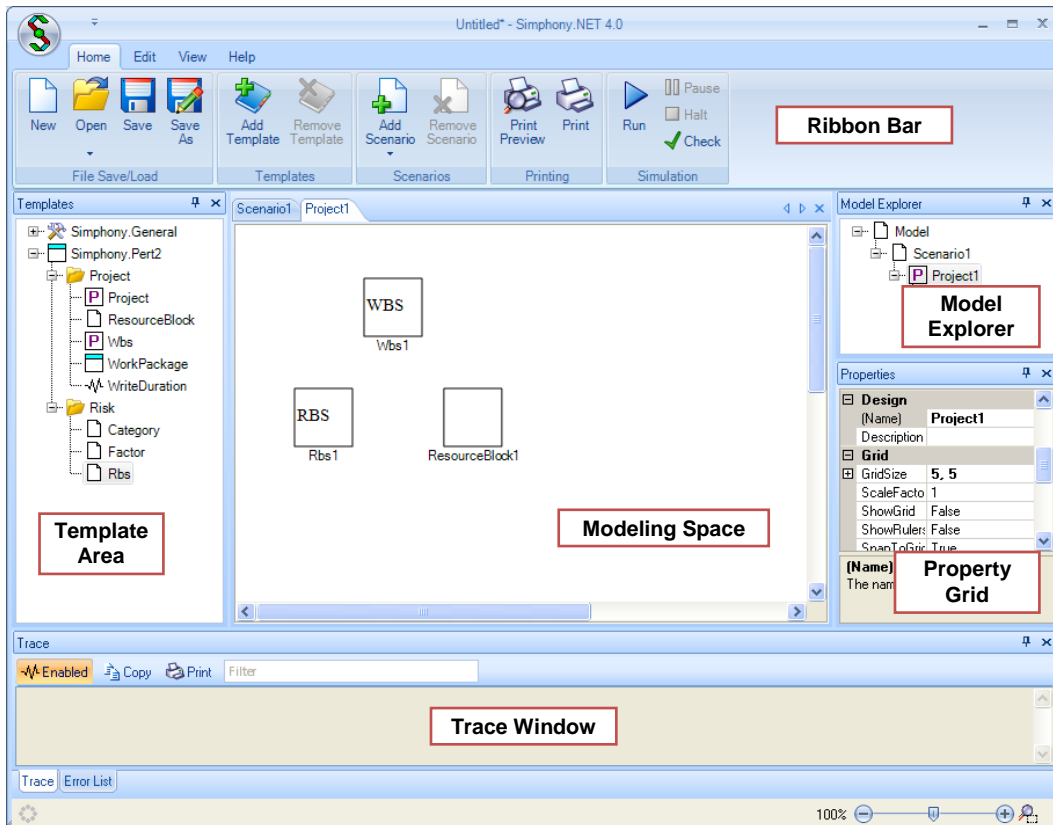
Figure 4-2 The main interface of Simphony.NET

AbouRizk and Hajjar (1998) define SPS as "a computer-based environment built to enable a practitioner who is knowledgeable in a given domain, but not

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necessarily in simulation, 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." The ISP concept has been implemented into an SPS tool in which the environment for project scope, time, cost, and risk management is provided through work breakdown structure (WBS), risk breakdown structure (RBS), range estimating and simulation-based network scheduling.

Simphony was chosen for the appropriate development environment because it supports the development and use of different SPS tools. This feature provides a more flexible development environment over other simulation software packages as a research tool; therefore, the ISP concepts are integrated together into one program package.

4.2   The Modeling Elements of the ISP Tool

The ISP tool's elements are linked to each other through composite-child relationships as shown in Figure 4-3. In Simphony.NET, the Composite Element is the basic element which enables the use of a hierarchical structure. It contains other composite elements and/or non-composite (ordinary) elements. The first element created in the ISP tool is the Project Element, whose properties are the general information of the project under consideration. The analysis result, such as cash flow graphs, and resource and WBS reports for duration and cost can be accessed through the element.

The Project Element contains several child elements, each of which contains the information necessary to characterize the project. These elements are the WBS Element, RBS Element, and Resource Block Element.
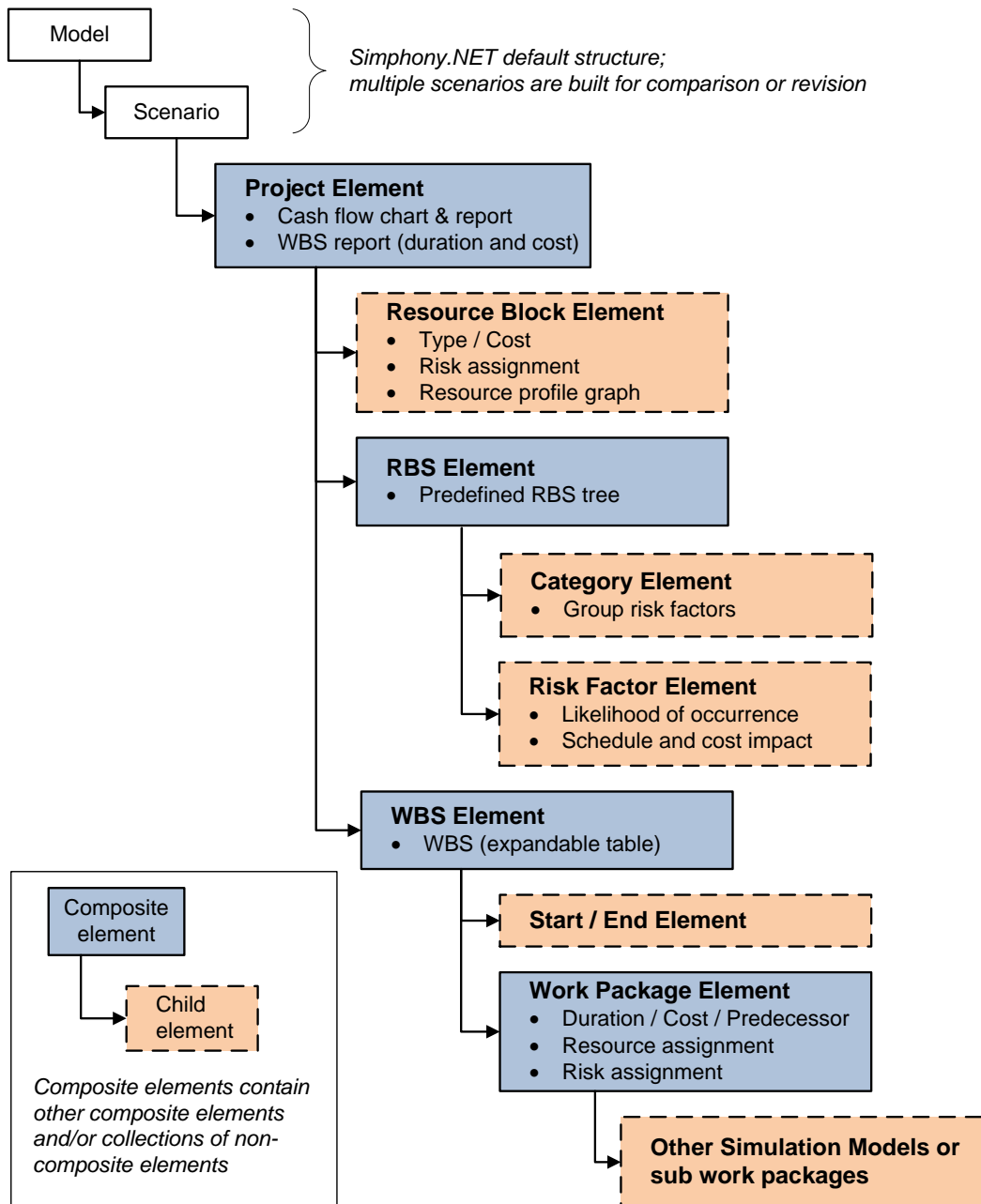
Figure 4-3 The ISP tool's elements and their relationships in Simphony.NET environment

The WBS element contains a WBS and information about the project's network scheduling. An expandable table form was adapted in the ISP tool to represent WBS rather than a tree structure since the table form is easier to accommodate in a computer screen.

WPs defined in WBS are the main objects to be analyzed in simulation-based network scheduling; therefore, WPs have properties such as duration, given in days; and predecessors. Each WP can have resources and risk factors assigned in the schedule network view. Resources are applied to WPs in order to perform resource-driven cost analysis. Risk factors affect the WPs' duration if they are assigned to WPs with sensitivity ratios.

Figure 4-4 shows WP Elements used in the ISP tool's schedule network. It was designed to show the WP name, duration, ES, EF, LS, LF, and criticality index (CI) on one diagram. If a WP is interruptible, the color of the diamond in the middle is set to cyan. In the case of uninterruptible WPs, the color beige is used. The precedence relationships of WPs other than FS(0) are shown on the arrow. In the figure, FF(3) means that WP2 can finish 3 days (lag time) after the WP1 is completed.
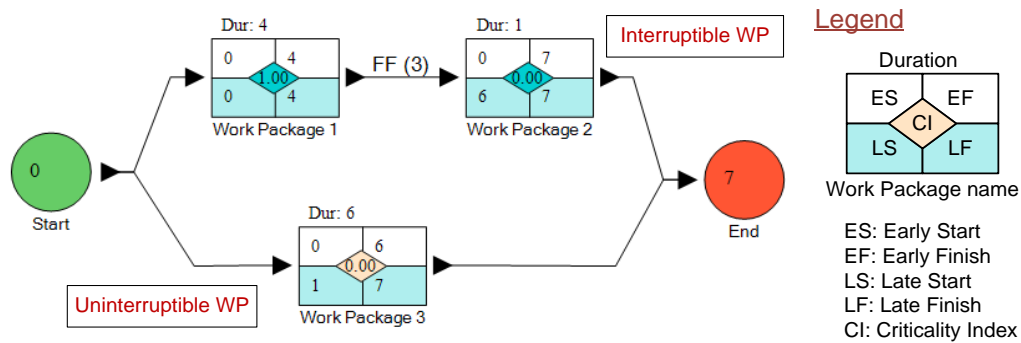
Figure 4-4 The symbols used in the ISP tool's schedule network

The Resource Block Element states the project's resources. Resources are assigned to WPs on the schedule network view created through the WBS Element, where the required quantities of the resources for each WP are specified. The element generates a graph displaying the quantity of resources during the project time span after the simulation has completed. Risk factors can

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be assigned to resources with a certain degree of sensitivity. Note that only the cost impact (either overrun or underrun) of the risk factor is effective in this case.

The RBS Element provides an RBS for risk identification, and defines the project's risk factors. The RBS Element consists of the Risk Category Element which is the intermediate level of the RBS and Risk Factor Element. The Risk Factor Element is a representation of a risk factor, and is defined at the lowest level of the RBS with a likelihood of occurrence and schedule and/or cost impacts. The risk factor might materialize depending on the start time of WPs with which the risk factor is directly or indirectly associated through resources.

A risk factor has an independent impact; therefore impacts overlap each other. This means a WP has a cumulative impact when multiple risk factors materialize at the same time. The impact can be defined as harm or opportunity to specified resources' or WPs' schedules and/or costs. The impact is entered either deterministically or probabilistically. It can also be represented as a percentage of the initially assigned value on resources or work packages. For instance, if the interference from underground utilities during a tunnel construction is defined as one risk factor under the site investigation node in the RBS, the impact can be expressed as a 10 percent delay to the tunnel construction's original schedule. Appendix A contains each element's property and simulation behaviour.

4.3   Data Processing in the ISP tool

The main interests in the simulation results are the statistics of the project's cost and duration. They are calculated with an assumption of a minimum time interval equal to one hour. This section discusses the procedure of processing

the input data before simulation, along with generating graphs and reports after simulation.

4.3.1 Input data pre-processing

Once all the required input data are entered in by users, the simulation can be fired, but some input data should be modified before the simulation begins. This modification takes into account risk allocation to WPs and resources, and resource allocation to WPs. Please note that the risk impacts are assumed to be given as a percentage of the original user input in the equations below. To consider the assigned risk factors' impact on the resources, the resources' cost information should be updated based on the equation (1) to (4).

- Fixed direct unit cost of resources ($/unit)

$$RDC_i^F = \overline{RDC_i^F} + \sum_{m=1} B(1, P_m) \times \overline{RDC_i^F} \times CI_m \times RDCS_{i,m}^F \tag{1}$$

- Fixed indirect unit cost of resources ($/unit)

$$RIDC_i^F = \overline{RIDC_i^F} + \sum_{m=1} B(1, P_m) \times \overline{RIDC_i^F} \times CI_m \times RIDCS_{i,m}^F \tag{2}$$

- Variable direct unit cost of resources ($/unit/hr)

$$RDC_i^V = \overline{RDC_i^V} + \sum_{m=1} B(1, P_m) \times \overline{RDC_i^V} \times CI_m \times RDCS_{i,m}^V \tag{3}$$

- Variable indirect unit cost of resources ($/unit/hr)

$$RIDC_i^V = \overline{RIDC_i^V} + \sum_{m=1} B(1, P_m) \times \overline{RIDC_i^V} \times CI_m \times RIDCS_{i,m}^V \tag{4}$$

In Equation (1), RDC_i^F is the fixed direct unit cost of resource i which will be used in one particular run of the schedule network analysis; $\overline{RDC_i^F}$ is the original fixed direct unit cost value entered deterministically or sampled from a

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given distribution by users; $B(1, P_m)$ is the binomial distribution with P_m, as the probability of success of one draw; CI_m is the cost impact of risk factor m which is assigned to resource i; and $RDCS_{i,m}^F$ is the fixed direct unit cost sensitivity of resource i against risk factor m. The equation used for RDC_i^F means that the original fixed direct unit cost value that users entered for resource i is modified based on the probability of occurrence, cost impact, and sensitivity against the fixed direct unit cost value of all the risk factors assigned on it. The modification is the cost impact of the risk factors on the resource. All the impacts from the risk factors are independently summed up and added to the original fixed direct unit cost value. Note that the impacts of risk factors and sensitivities are entered as percentages of the original values in the equations shown in the section. If the impact of risk factor m is entered as a fixed dollar amount in Equation (1), for example, the term $\overline{RDC_i^F} \times CI_m$ should be replaced by CI_m. The symbols used in a fixed indirect, variable direct, and variable indirect unit cost equation (Equation (2) to (4)) can be interpreted in a similar way.

$$D_j = \text{Int}\left[\left(\overline{D_j} + \sum_{k=1} B(1, P_k) \times \overline{D_j} \times SI_k \times SS_{j,k}\right) \times 8 \text{ hrs/day}\right] \tag{5}$$

The original duration of a WP is also modified based on the risk factors assigned on it as Equation (5). D_j is the duration of a WP j in an integer for hours which will be used in one particular run of the schedule network analysis; $\overline{D_j}$ is the original duration value entered in days for a WP j by users; SI_k is the schedule impact of risk factor k which is assigned to a WP j; and $SS_{j,k}$ is schedule sensitivity of WP j against risk factor k. This equation is similar to

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Equation (1), except it changes time units from days to hours. Note that an eight-hour workday is assumed.

The WP's cost is affected by the directly assigned risk factors, which can be understood in the same way as in Equation (1) to (4). When resources are allocated to the WP with a certain number of quantities, the resources' costs are added to the WP's cost. Therefore, the impacts of the resource's risk factors indirectly affect the WP's cost.

- Fixed direct cost of WPs ($)

$$DC_j^F = \overline{DC_j^F} + \sum_{k=1} B(1, P_k) \times \overline{DC_j^F} \times CI_k \times DCS_{j,k}^F + \sum_{n=1} RDC_n^F \times R_{n,j} \tag{6}$$

- Fixed indirect cost of WPs ($)

$$IDC_j^F = \overline{IDC_j^F} + \sum_{k=1} B(1, P_k) \times \overline{IDC_j^F} \times CI_k \times IDCS_{j,k}^F + \sum_{n=1} RIDC_n^F \times R_{n,j} \tag{7}$$

- Variable direct cost of WPs ($/hr)

$$DC_j^V = \overline{DC_j^V} + \sum_{k=1} B(1, P_k) \times \overline{DC_j^V} \times CI_k \times DCS_{j,k}^V + \sum_{n=1} RDC_n^V \times R_{n,j} \tag{8}$$

- Variable indirect cost of WPs ($/hr)

$$IDC_j^V = \overline{IDC_j^V} + \sum_{k=1} B(1, P_k) \times \overline{IDC_j^V} \times CI_k \times IDCS_{j,k}^V + \sum_{n=1} RIDC_n^V \times R_{n,j} \tag{9}$$

In Equation (6), DC_j^F is the fixed direct cost of WP j which will be used in one particular run of schedule network analysis; $\overline{IDC_j^F}$ is the original fixed direct cost value entered for WP j entered deterministically or sampled from a given distribution by users; CI_k is the cost impact of risk factor k, which is assigned to WP j; $DCS_{j,k}^F$ is the fixed direct cost sensitivity of WP j against risk factor k; $RIDC_n^F$ is the fixed direct unit cost of resource n; $R_{n,j}$ is the quantity of resource n used in

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WP j. The equations (7) to (9) are used to calculate the fixed indirect, variable direct, and variable indirect costs of a WP and can be interpreted in a similar way.

4.3.2 Output data post-processing

The WPs' outputs are shown in each WP Element in the ISP tool's schedule network view. By implementing a Monte Carlo simulation technique in scheduling, the ranges of possible WP durations and costs are calculated based on the impacts of associated risk factors. The results are the WPs' duration, early start (ES), early finish (EF), late start (LS), late finish (LF), direct cost, indirect cost, and total cost of the last run. The criticality index (CI), which is the probability of a WP being on the critical path, is also calculated and displayed. The WPs' outputs also include various statistics, (mean, variance, standard deviation, kurtosis, and skewness), histograms, cumulative distribution function (CDF) graph of the duration, ES, EF, LS, LF, direct cost, indirect cost, and total cost.

The ISP tool's overall results are displayed in the form of graphs and reports, and can be viewed under the Project Element and Resource Block Element. The Project Element's output properties are cash flow graphs, cumulative cash flow graphs, WBS duration report, WBS cost report, and resource cost report. The Resource Block Element displays a resource profile graph for each resource.

The cash flow graph is a line chart showing the costs incurred each hour. The minimum, maximum, average, and percentile value of the direct, indirect, and total costs are plotted. The graph can be drawn based on either the early or late start date. For each period, when a WP time span coincides with the current period, its cost information is collected and added. It is assumed that the cost is evenly spread out over the WP's time span. The equations (10) to (15) are used to calculate the cost spent over a certain period.

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- Direct cost (\$/hr) spent for period P_t based on early start date, ES_j

$$DC^E(P_t)=\sum_{j=1}\left(DC_j^F+DC_j^V\times D_j\right)\div D_j \ , \qquad \text{where } ES_j\leq P_t<ES_j+D_j \qquad (10)$$

- Indirect cost (\$/hr) spent for period P_t based on early start date, ES_j

$$IDC^E(P_t)=\sum_{j=1}\left(IDC_j^F+IDC_j^V\times D_j\right)\div D_j \ , \qquad \text{where } ES_j\leq P_t<ES_j+D_j \qquad (11)$$

- Total cost (\$/hr) spent for period P_t based on early start date, ES_j

$$C^E(P_t)=DC^E(P_t)+IDC^E(P_t) \qquad (12)$$

- Direct cost (\$/hr)spent for period P_t based on late start date, LS_j

$$DC^L(P_t)=\sum_{j=1}\left(DC_j^F+DC_j^V\times D_j\right)\div D_j \ , \qquad \text{where } LS_j\leq P_t<LS_j+D_j \qquad (13)$$

- Indirect cost (\$/hr) spent for period P_t based on late start date, LS_j

$$IDC^L(P_t)=\sum_{j=1}\left(IDC_j^F+IDC_j^V\times D_j\right)\div D_j \ , \qquad \text{where } LS_j\leq P_t<LS_j+D_j \qquad (14)$$

- Total cost (\$/hr) spent for period P_t based on late start date, LS_j

$$C^L(P_t)=DC^L(P_t)+IDC^L(P_t) \qquad (15)$$

The cumulative cash flow graph shows cost values summed up over the project period based on either the early or late start date. The plots are the minimum, maximum, average, and percentile value of the direct, indirect, and total costs.

The resource profile graph is shown for each resource defined in the Resource Block Element. The graph displays the number of resources used in each period based on either the early or late start date. For each period, when a WP time span coincides with the current period, the number of a particular resource used for the WP is collected and added. The equations (16) and (17)

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are used to calculate the quantity of a resource used during a certain period, where $R_{n,j}$ is the quantity of resource n used in WP j.

- Quantity of resource n during period P_t based on early start date, ES_j

$$R_n^E(P_t)=\sum_{j=1} R_{n,j} \ , \qquad \text{where } ES_j \leq P_t < ES_j + D_j \qquad (13)$$

- Quantity of resource n during period P_t based on late start date, LS_j

$$R_n^L(P_t)=\sum_{j=1} R_{n,j} \ , \qquad \text{where } LS_j \leq P_t < LS_j + D_j \qquad (14)$$

The WBS duration report displays the information about the duration of each WBS level in days and calendar date. The minimum, mean, maximum, and percentile value of the range of the WBS duration from the Monte Carlo simulation are shown in days. A calendar date is used to display the percentile values of ES, EF, LS, and LF. The WBS cost report and the resource cost report summarize the statistics of direct, indirect, and total costs of each WBS level and resource respectively.

Chapter 5 is a case study that displays the ISP tool's outputs.

5 CASE STUDY

This chapter presents a hypothetical road construction case study as an example of ISP applications. The case study was used by Hong and AbouRizk (2011). Section 5.1 describes the input data. Section 5.2 depicts the procedure for building a model using the ISP tool and the analysis result. Section 5.3 explains how the ISP model was modified with an earth moving process interaction model. This demonstrates the hierarchical modeling feature adapted in the ISP tool. Section 5.4 presents the verification of the ISP tool.

5.1 Problem Description
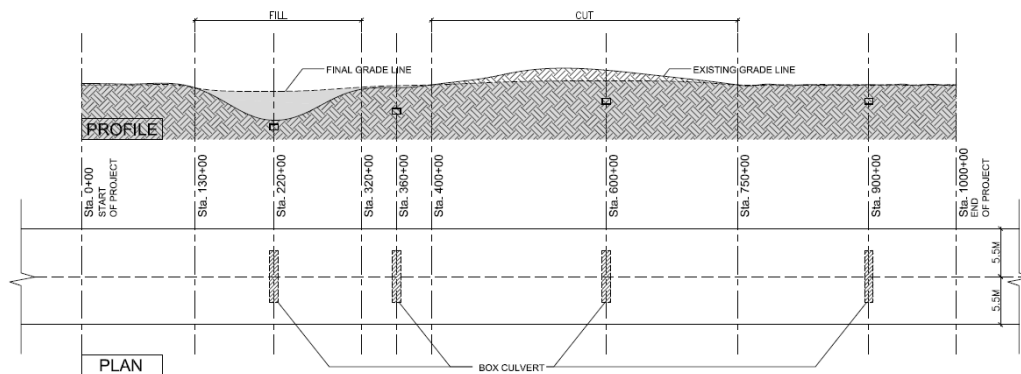
Figure 5-1 The illustration of a hypothetical road construction project (Hong and AbouRizk, 2011)

Figure 5-1 shows the profile of the country road to be constructed. The construction location is a rural area in Edmonton, AB, Canada, and it is assumed that the construction begins during spring (May, 7th, 2012). The road is 1 km long, one-way, and has two lanes. Table 5-1 shows a possible WBS for the given project which encompasses 19 WPs, including mobilization, site clearing, cut-and-fill earth moving, culvert installation, base layers, paving layers, concrete curbs, storm sewer manholes, strip painting, sign installation, landscaping, and demobilization.

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Table 5-1 The WBS of the hypothetical road construction

Code	Description	ID
1	Country road construction	0
1.1	Mobilization	1
1.2	Preparation	2
1.2.1	Site clearing and grubbing	3
1.2.1.1	Sta. 130 to 750	4
1.2.1.2	Sta. 750 to 1,000 and Sta. 0 to 130	5
1.2.2	Earth cut (Sta. 400 to 750) and fill (Sta. 130 to 320)	6
1.2.3	Drainages	7
1.2.3.1	Storm Sewer manhole connected to curbs	8
1.2.3.2	Culvert installation	9
1.2.3.2.1	Culvert at Sta. 220	10
1.2.3.2.2	Culvert at Sta. 360	11
1.2.3.2.3	Culvert at Sta. 600	12
1.2.3.2.4	Culvert at Sta. 900	13
1.3	Road work	14
1.3.1	Base layers	15
1.3.1.1	250mm deep lime-stabilized layer	16
1.3.1.2	150mm deep crushed 20mm gravel layer	17
1.3.2	Asphalt paving layers	18
1.3.2.1	110mm deep first asphalt layer	19
1.3.2.2	60mm deep second asphalt layer	20
1.3.3	Curbs	21
1.3.3.1	Cast-in place concrete curbs	22
1.3.3.2	Saw-cut at 20 meter intervals	23
1.4	Finishing work	24
1.4.1	Painting stripes	25
1.4.2	Sign installation	26
1.4.3	Fine grading and seeding work	27
1.5	Demobilization	28

It is assumed that moderate earth cut-and-fill is required between stations 130 and 750 using scrapers. Four box culverts are to be located at stations 220, 360, 600 and 900. Installing these culverts is an uninterruptable activity. Two asphalt layers are to be laid out after two base layers are completed. Installing the two asphalt layers is assumed to be uninterruptable along with the

construction of cast-in-place concrete curbs. Storm sewer manholes are to be installed at approximately 125 meter intervals and connected to the storm sewer openings located on the curbs (Hong and AbouRizk, 2011).

Table 5-2 The WP's duration in days and quantity takeoff

ID	Description	Duration (days)	Predecessor	Quantity	Unit
1	Mobilization	3	-	-	-
4	Site clearing phase 1	7.5	1	3.1	Hec
5	Site clearing phase 2	5	4	1.9	Hec
6	Earth work	16	4	17,500	Bm^3
8	Storm sewer manhole	3.5	4, 6FF	16	ea
10	Culvert at Sta. 220	1	4	20	m
11	Culvert at Sta. 360	1	5,10	20	m
12	Culvert at Sta. 600	1.5	11	20	m
13	Culvert at Sta. 900	1.5	6,12	20	m
16	Lime-stabilized layer	13	13SS	17,273	m^2
17	Crushed gravel layer	3.5	16FF+1,16SS+1	2,212	m^3
19	First asphalt layer	4.5	22FS+2	13,545	m^2
20	Second asphalt layer	3	19FF+1	12,153	m^2
22	Concrete curbs	8	8,17SS+1, 7FF+1	2,000	m
23	Saw-cut of the curbs	1	22FS+2	47	m
25	Painting stripes	2	27	2,500	m
26	Sign installation	3	27	10	ea
27	Grading and seeding	9	20FS+1, 22	8,040	m^2
28	Demobilization	4	26, 27	-	-

Table 5-2 provides the most likely duration and predecessors of each WP and its associated quantity. The unit of the duration is in days, and the working hour is assumed to be five days per week and eight hours per day. Note that the durations might be presented as a bounded form of probability distribution if the most likely duration is unknown.

Table 5-3 The cost information directly entered into the WPs

ID	Description	Material Cost ($/unit)	Unit	Variable Cost ($/hr)	
				Direct	**Indirect**
1	Mobilization	-	-	-	-
4	Site clearing phase 1	-	Hec	41.45	4.15
5	Site clearing phase 2	-	Hec	41.45	1.15
6	Earth work	-	Bm^3	382.15	73.33
8	Storm Sewer manhole	800.00	ea	-	-
10	Culvert at Sta. 220	98.00	m	-	-
11	Culvert at Sta. 360	98.00	m	-	-
12	Culvert at Sta. 600	98.00	m	-	-
13	Culvert at Sta. 900	98.00	m	-	-
16	Lime-stabilized layer	6.12	m^2	485.65	82.58
17	Crushed gravel layer	122.00	m^3	17.45	1.75
19	First asphalt layer	35.55	m^2	-	-
20	Second asphalt layer	22.25	m^2	-	-
22	Concrete curbs	21.00	m	185.78	49.91
23	Saw-cut of the curbs	-	m	63.78	22.80
25	Painting stripes	1.76	m	56.08	5.61
26	Sign installation	180.00	ea	97.55	26.01
27	Grading and seeding	0.16	m^2	-	-
28	Demobilization	-	-	-	-

Table 5-3 shows the cost information directly entered into the WPs. Although information about the materials is integrated into the relevant WPs in this example, users can define materials as resources, especially if the same materials are used in many WPs simultaneously. The value from the quantity given in Table 5-2 multiplied by the material cost ($/unit) in Table 5-3 will be entered as a fixed direct cost in each relevant WP, and 10 percent of the value is regarded as a fixed indirect cost. The variable cost includes the cost of the equipment (with operators' wage) which is small or used in a single WP such as a chainsaw required for the site clearing. The resources shared with multiple WPs are defined separately in Table 5-4.

Table 5-4 Cost information for the resources

Resource Type	Resources	Quantity	Variable cost ($/hr/ea)	
			Direct	**Indirect**
Labour	Labourer	Infinity	33.50	18.50
Equipment	Loader	Infinity	177.58	34.83
Equipment	Grader	Infinity	120.73	29.13
Equipment	Vibration roller	Infinity	122.10	29.26
Equipment	Dozer	Infinity	241.95	41.23
Equipment	Truck	Infinity	70.15	21.10
Equipment	Paver	Infinity	292.20	46.28
Equipment	Pneumatic roller	Infinity	85.10	25.56
Equipment	Tandem roller	Infinity	72.35	24.59
Equipment	Crane	Infinity	78.93	25.50

Table 5-5 The resource quantity to be used in the WPs

ID	Description	Labourer	Equipment								
			Loader	Grader	Dozer	Truck	Vibration Roller	Paver	Pneumatic Roller	Tandem Roller	Crane
1	Mobilization	3									
4	Site clearing phase 1	5	1								
5	Site clearing phase 2	5	1								
6	Earth work	2			1		1				
8	Storm sewer manhole	2	1								1
10	Culvert at Sta. 220	3	1		1		1				1
11	Culvert at Sta. 360	3	1		1		1				1
12	Culvert at Sta. 600	3	1		1		1				1
13	Culvert at Sta. 900	3	1		1		1				1
16	Lime-stabilized layer	2		1		2	1				
17	Crushed gravel layer	3	1	1	1	1	1				
19	First asphalt layer	8						1	1	1	
20	Second asphalt layer	8						1	1	2	
22	Concrete curbs	4									
23	Saw-cut of the curbs					1					
25	Painting stripes	5				1					
26	Sign installation	2				1					
27	Grading and seeding	5	1								
28	Demobilization	3									

Table 5-4 shows the resources used in the example, along with their cost information and Table 5-5 shows the number used in a certain WP.

Please note that the resources are in unlimited supply for resource-driven cost estimating and resource unavailability is considered a risk event.

Table 5-6 Risk factor identification and assessment

Code	Risk Factor	Likeli-hood	Impact (%)	
			Schedule	Cost
1	Project risk	-	-	-
1.1	Internal risk	-	-	-
1.1.1	Job condition	-	-	-
1.1.1.1	Weather & climate condition	-	-	-
1.1.1.1.1	Heavy rainfall	0.250	+T(17,25,28)	+B(2,3,4,10)
1.1.1.1.2	Extreme temperature	0.030	+B(2,5,4,8)	+U(4,8)
1.1.1.2	Interference with underground facility	0.005	+T(17,25,28)	+B(3,2,3,10)
1.1.2	Difficulties with access to the site	0.100	+B(1.5,4,6,9)	+T(4,5,8)
1.1.3	Resource	-	-	-
1.1.3.1	Unavailability of resource	0.250	+U(13,17)	+T(9,12,15)
1.1.3.2	Labour	-	-	-
1.1.3.2.1	Low skill level	0.100	+U(10,15)	+T(8,10,12)
1.1.3.2.2	Labour injury	0.100	+B(2,5,4,8)	+U(10,15)
1.1.3.3	Equipment breakdown	0.500	+B(5,2,15,50)	+B(5,2,15,30)
1.1.4	Organization	-	-	-
1.1.4.1	Conflict between parties	0.003	+U(15,25)	+T(8,10,12)
1.1.4.2	Changes in engineering & design	0.250	+B(3,2,9,15)	+B(3,2,9,13)
1.2	Unfavourable market condition	0.005	+U(15,20)	+B(3,2,20,35)

*Note
U : Uniform distribution (lower value, upper value)
T : Triangular distribution (lower value, mode, upper value)
B : Beta distribution (alpha, beta, lower value, upper value)

Table 5-6 displays the identified risk factors with the likelihood of occurrence (See Table 3-1) and the impact on schedule and cost. Note that the risk identification session was set at project's initial planning stage; therefore the assessment of the risk factors will evolve or even more risk factors might be added as the project progresses. Because only the threats to the project are considered, the impacts are schedule delay and cost overrun, which are depicted in the table with a plus sign before the percentage.

Table 5-7 A matrix for risk allocation to WPs and Resources

Sensitivity Assignment (%) Work Packages (schedule & fixed indirect cost impact)	Heavy rainfall	Extreme temperature	Interference with facility	Difficulties with access to site	Unavailability of resource	Low skill level	Labour injury	Equipment breakdown	Conflict between parties	Inadequate specification	Unfavourable market condition
1 Mobilization	50	25		100		25	25		50		100
4 Site clearing phase 1	100	75			25	75	75	25	50		100
5 Site clearing phase 2	100	75			25	75	75	25	50		100
6 Earth work	125	25	100		100	25	25	100	100	25	100
8 Storm Sewer manhole	50	25	25		25	25	25	50	25	50	100
10 Culvert at Sta. 220	50	50	50		25	25	25	50	25	50	100
11 Culvert at Sta. 360	50	50	50		25	25	25	50	25	50	100
12 Culvert at Sta. 600	50	50	50		25	25	25	50	25	50	100
13 Culvert at Sta. 900	50	50	50		25	25	25	50	25	50	100
16 Lime-stabilized layer	125	25		50	100	25	25	100	75	75	100
17 Crushed gravel layer	75	25		50	100	25	25	100	75	75	100
19 First asphalt layer	150	100		125	100	100	100	125	75	100	100
20 Second asphalt layer	150	100		125	100	100	100	125	75	100	100
22 Concrete curbs	150	100		150	50	100	100		75	100	100
23 Saw-cut of the curbs	50				25				25	75	100
25 Painting stripes	150	50			25	50	50	25	25	25	100
26 Sign installation	50	25			25	25	25	25	25		100
27 Grading and seeding	100	50			25	50	50	25	25		100
28 Demobilization	50	25		100		25	25		50		100

Resources (Variable cost)

	Heavy rainfall	Extreme temperature	Interference with facility	Difficulties with access to site	Unavailability of resource	Low skill level	Labour injury	Equipment breakdown	Conflict between parties	Inadequate specification	Unfavourable market condition
Labourer		100			50	100	100				100
Loader		50			100			100			100
Grader		50			75			100			100
Vibration Roller		50			75			100			100
Dozer		50			75			100			100
Truck		50			75			100			100
Paver		50			100			100			100
Pneumatic Roller		50			100			100			100
Tandem Roller		50			100			100			100
Crane		50			75			100			100

The RBS in Figure 3-3 was used during the risk identification session, and the structure was modified based on the project characteristics as shown in Figure 5-4. Table 5-7 shows the risk factors assigned to the WPs and/or resources with sensitivity ratios. Although a different sensitivity ratio for each piece of cost information can be specified, for simplicity's sake the cost impacts of the risk factors assigned to WPs are only applied to the WPs' fixed and variable indirect cost. The risk factors assigned to the resources are assumed to affect the variable cost of the resources with the specified sensitivity ratio in the table. The WP without sensitivity value in the table does not have a direct associated risk factor but other risk factors might affect it indirectly. The saw-cut of curbs (ID 23), for instance, is indirectly affected by the equipment breakdown factor, although it does not have the sensitivity value in the relevant cell. The saw-cut WP requires a truck whose sensitivity against the equipment breakdown risk factor is 100 percent; therefore, the truck breakdown will indirectly affect the WP's cost.

5.2 Procedure of Modeling and Analysis Result

The procedure of building a model in the ISP tool for the case study is explained as follows;

(1) Create a Project Element and enter the project name, description, and start date of the project in the property grid. The Project Element contains a WBS Element as a default.

(2) Enter the WBS information (name, duration, cost, predecessors and interruptibility) from Table 5-1 to 5-3 in the WBS Element spreadsheet as shown in Figure 5-2. The start and finish date in the spreadsheet do not

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account for WP interruption. WP interruptibility is utilized during simulation resulting in changes in the total project duration.

ID	Parent ID	Name	Duration	Start	Finish	Predecessors	Interrupti...	Fixed Dire...	Fixed Indi...	Var Direct ...	Var Indire...
0	-1	Road Construction	80.1	07/05/2012	13/08/2012		☑	1197630	11978	1371.34	267.29
1	0	Mobilization	3	07/05/2012	09/05/2012		☑	0	0	0	0
2	0	Preparation	26.6	10/05/2012	13/06/2012		☑	20640	208	465.05	78.63
3	2	Site Clearing	12.5	10/05/2012	28/05/2012		☑	0	0	82.9	5.3
4	3	Clearing 1	7.5	10/05/2012	21/05/2012	1FS	☑	0	0	41.45	4.15
5	3	Clearing 2	5	21/05/2012	28/05/2012	4FS	☑	0	0	41.45	1.15
6	2	Earth Work	16	21/05/2012	12/06/2012	4FS	☑	0	0	382.15	73.33
7	2	Drainages	19.1	21/05/2012	13/06/2012		☑	20640	208	0	0
8	7	Storm Sewer Manhole	3.5	07/06/2012	12/06/2012	4FS,6FF	☑	12800	128	0	0
9	7	Culvert Installation	17.5	21/05/2012	13/06/2012		☐	7840	80	0	0
10	9	Culvert Sta.220	1	21/05/2012	22/05/2012	4FS	☐	1960	20	0	0
11	9	Culvert Sta.360	1	28/05/2012	29/05/2012	5FS,10FS	☐	1960	20	0	0
12	9	Culvert Sta.600	1.5	29/05/2012	30/05/2012	11FS	☐	1960	20	0	0
13	9	Culvert Sta.900	1.5	12/06/2012	13/06/2012	12FS,6FS	☐	1960	20	0	0
14	0	Road Work	36.6	12/06/2012	19/07/2012		☑	1169504	11695	752.66	157.04
15	14	Base Layers	17.1	12/06/2012	02/07/2012		☑	375575	3756	503.1	84.33
16	15	Lime Layer	13	12/06/2012	29/06/2012	13SS	☑	105711	1057	485.65	82.58
17	15	Gravel Layer	3.5	27/06/2012	02/07/2012	16FF+1,16SS+1	☑	269864	2699	17.45	1.75
18	14	Paving Layer	8.1	12/07/2012	19/07/2012		☐	751929	7519	0	0
19	18	First Asphalt	4.5	12/07/2012	18/07/2012	22FS+2	☐	481525	4815	0	0
20	18	Second Asphalt	3	16/07/2012	19/07/2012	19FF+1	☐	270404	2704	0	0
21	14	Curbs	12.4	28/06/2012	12/07/2012		☑	42000	420	249.56	72.71
22	21	Concrete Curbs	8	28/06/2012	09/07/2012	17SS+1,17FF+1,8FS	☐	42000	420	185.78	49.91
23	21	Curb Saw-cut	1	12/07/2012	12/07/2012	22FS+2	☑	0	0	63.78	22.8
24	0	Finishing Work	12	20/07/2012	07/08/2012		☑	7486	75	153.63	31.62
25	24	Painting Strips	2	02/08/2012	06/08/2012	27FS	☑	4400	44	56.08	5.61
26	24	Sign Installation	3	02/08/2012	07/08/2012	27FS	☑	1800	18	97.55	26.01
27	24	Fine Grading	9	20/07/2012	02/08/2012	22FS,20FS+1	☑	1286	13	0	0
28	0	Demobilization	4	07/08/2012	13/08/2012	27FS,26FS	☑	0	0	0	0

Figure 5-2 A WBS Spreadsheet used for the case study

Resources

Members:

0 Labourer
1 Loader
2 Grader
3 Vibration Roller
4 Dozer
5 Truck
6 Paver
7 Pneumatic Roller
8 Tandem Roller
9 Crane

Add | Remove

Labourer properties:

Inputs
FixedDirectCost	**Constant(0)**
FixedIndirectCost	**Constant(0)**
RiskAssignment	**(Collection)**
VariableDirectCost	**Constant(33.5)**
VariableIndirectCost	**Constant(18.5)**

Misc
(Name)	**Labourer**
Generic Scenario	Scenario1
Type	LabourResource

(Name)
The name of the object.

OK | Cancel

Figure 5-3 A screenshot of resource definition for the case study

(3) Create a Resource Block Element inside the Project Element and define resources based on Table 5-4. Figure 5-3 shows a resource definition form used in the ISP tool.

(4) Create a RBS Element inside the Project Element and double-click the element to access the default RBS. Modify the default RBS as Table 5-6 using the Risk Category Element and Risk Factor Element, and enter the likelihoods of occurrence and impacts in each Risk Factor Element. Figure 5-4 shows the RBS screenshot for the case study.
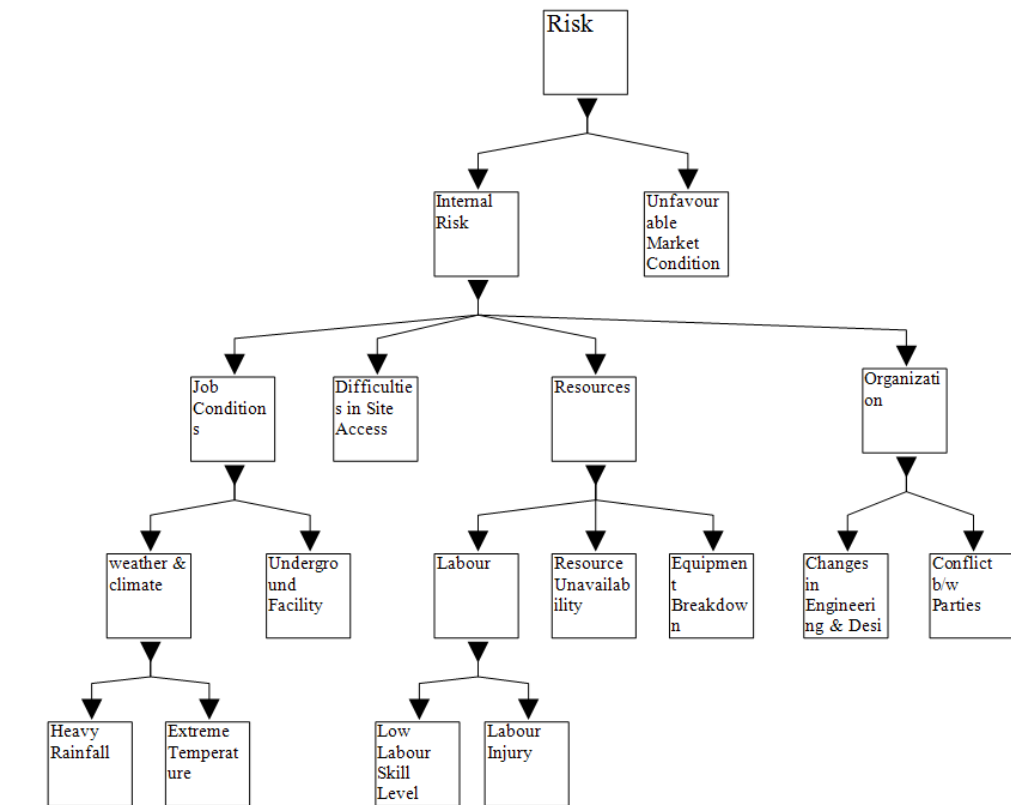
Figure 5-4 The screenshot of an RBS used for the case study

(5) Assign risk factors on the resources with the specified sensitivity ratio between them, based on Table 5-7. Figure 5-5 shows the risk factor allocation form used in ISP.

(6) Open the schedule network view by double-clicking the WBS Element and assign resources to the WPs as defined in Table 5-5. Figure 5-6 shows the resource allocation form used in ISP. The risk factors are also assigned to the relevant WPs with the sensitivity ratio shown in Table 5-7.
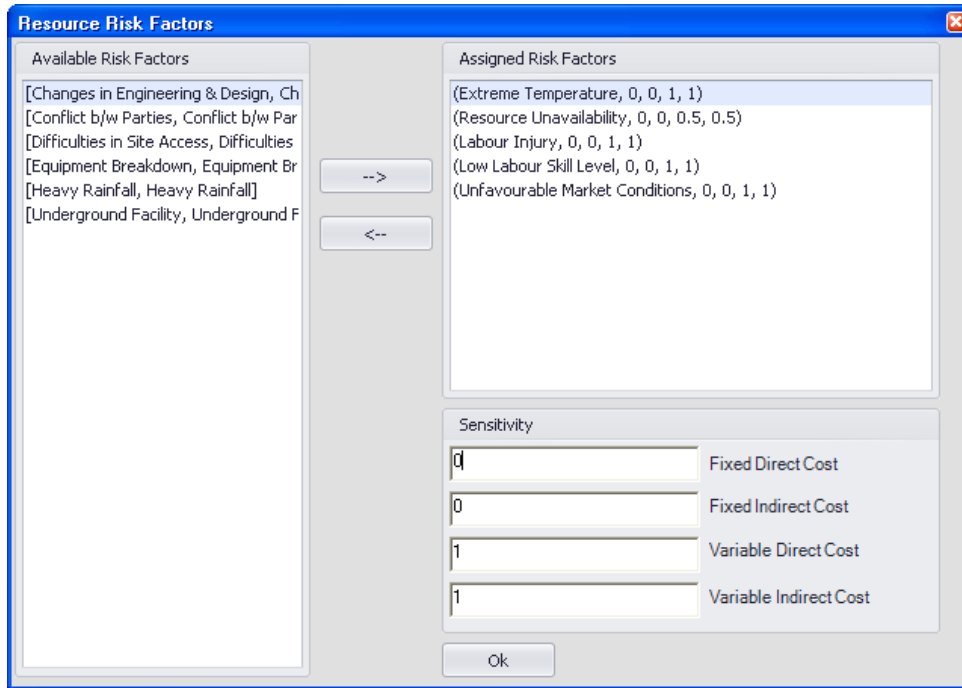
Figure 5-5 The screenshot of the risk factor assignment on the resources
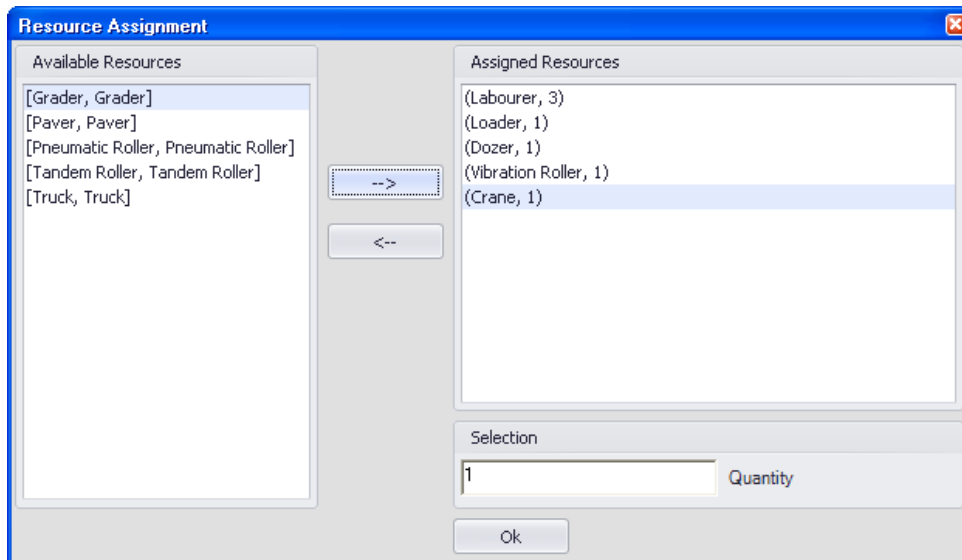
Figure 5-6 The screenshot of resource allocation to the WPs

(7) Specify the desired number of iterations for the Monte Carlo simulation and
    execute the simulation. Figure 5-7 displays the schedule network model
    created for the case study.
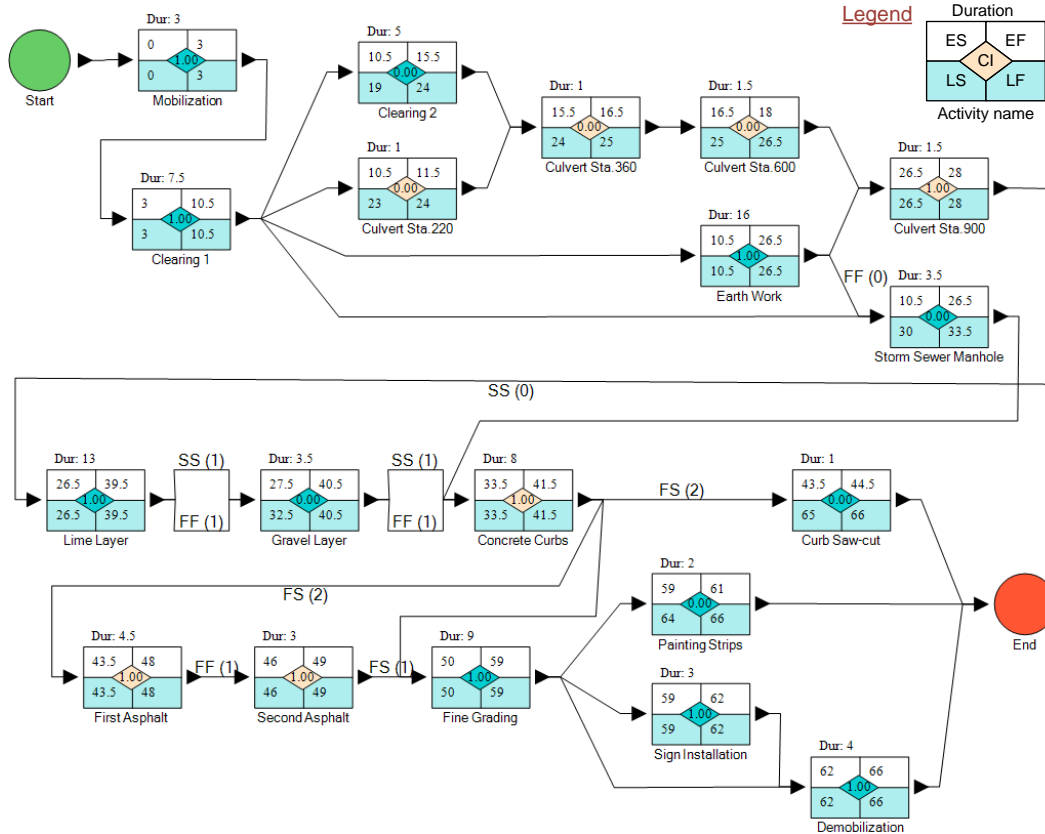
Figure 5-7 The screenshot of the schedule network model

After simulating the model 100 times, a range of possible project duration
and cost was generated. Table 5-8 and Table 5-9 display the statistic of WBS
duration and cost respectively. The range of the project completion time is [68, 97]
days, and the mean completion time is 82 days. Figure 5-8 shows the CDF graph,
where users approximate any percentile of the project completion time. The 85th
percentile, for example, is about 88 days, meaning that the probability of the
project being completed in 88 days or less is 85 percent.
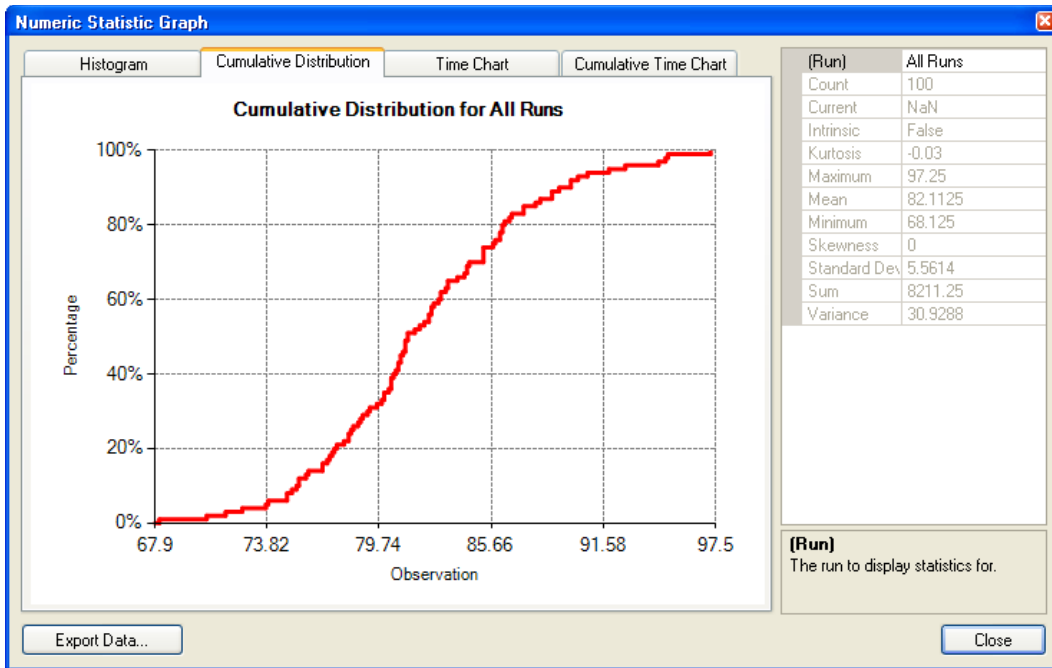
Figure 5-8 The CDF graph of the project completion time
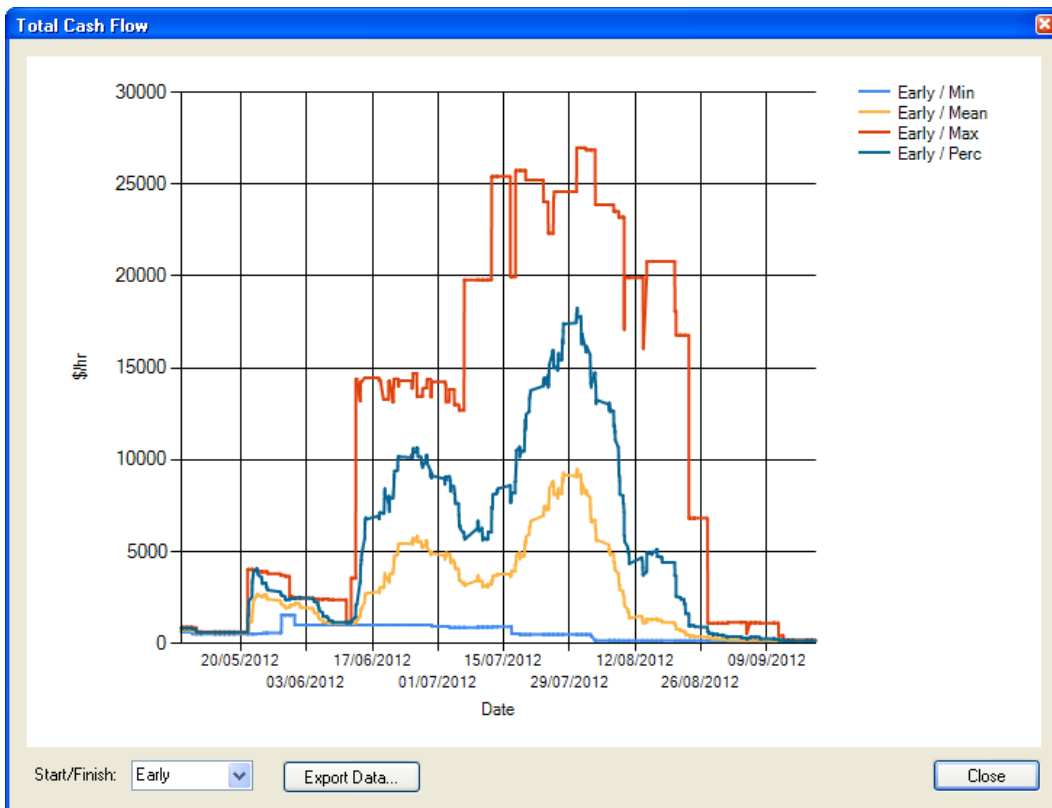
Figure 5-9 The total cash flow graph of the project based on early start time

A possible range of the project completion cost is [1,840,117, 2,130,670] dollars. The 85th percentile is 2,028,473 dollars. Figure 5-9 displays the total cash flow graph of the project. The graph shows how much money was spent each hour and helps project managers maintain control of project budgets.

Table 5-10 displays statistics about the cost of resources during project execution. Figure 5-10 shows how many labourers were used each hour. Through the resource profile graphs, project managers can figure out the maximum quantity of each resource and perform resource levelling.

Figure 5-10 The resource profile graph of the labourer

Table 5-8 The WBS duration report of the road construction example

Code	WBS	CI	Duration (days)				Calendar (percentile)			
			Min.	Mean	Max.	Percentile	ES	EF	LS	LF
1	Country road construction	N/A	69.25	82.53	95	88.73	05/07/2012	09/06/2012	05/07/2012	09/06/2012
1.1	Mobilization	1	3	3.22	3.88	3.49	05/07/2012	05/10/2012	05/07/2012	05/10/2012
1.2	Preparation	N/A	25	32.76	42.5	37.31	05/10/2012	07/02/2012	05/10/2012	7/16/2012
1.2.1	Site clearing and grubbing	N/A	12.5	14.84	19	16.12	05/10/2012	06/01/2012	05/10/2012	6/25/2012
1.2.1.1	Sta. 130 to 750	1	7.5	8.94	11.63	10	05/10/2012	5/24/2012	05/10/2012	5/24/2012
1.2.1.2	Sta. 750 to 1,000 and Sta. 0 to 130	0	5	5.9	7.63	6.59	5/24/2012	06/01/2012	6/15/2012	6/25/2012
1.2.2	Earth cut and fill	1	16	22.06	31	26.45	5/24/2012	6/28/2012	5/24/2012	6/28/2012
1.2.3	Drainages	N/A	17.5	23.83	32.88	28.21	5/24/2012	07/02/2012	6/22/2012	7/16/2012
1.2.3.1	Storm Sewer manhole connected to curbs	0	3.5	4.14	5.75	4.61	5/24/2012	6/28/2012	07/10/2012	7/16/2012
1.2.3.2	Culvert installation	N/A	17.5	23.83	32.88	28.21	5/24/2012	07/02/2012	6/22/2012	07/02/2012
1.2.3.2.1	Culvert at Sta. 220	0	1	1.21	1.38	1.34	5/24/2012	5/25/2012	6/22/2012	6/25/2012
1.2.3.2.2	Culvert at Sta. 360	0	1	1.36	2	1.62	06/01/2012	06/04/2012	6/25/2012	6/26/2012
1.2.3.2.3	Culvert at Sta. 600	0	1.5	1.8	2.25	2	06/04/2012	06/06/2012	6/26/2012	6/28/2012
1.2.3.2.4	Culvert at Sta. 900	1	1.5	1.76	2.13	1.97	6/28/2012	07/02/2012	6/28/2012	07/02/2012
1.3	Road work	N/A	22.5	29.31	38.5	33.18	6/28/2012	08/10/2012	6/28/2012	09/06/2012
1.3.1	Base layers	N/A	14	18.63	25.88	21.93	6/28/2012	7/26/2012	6/28/2012	7/26/2012
1.3.1.1	250mm deep lime-stabilized layer	1	13	17.63	24.88	20.93	6/28/2012	7/25/2012	6/28/2012	7/25/2012
1.3.1.2	50mm deep crushed 20mm gravel layer	0	3.5	4.7	6.75	5.57	6/29/2012	7/26/2012	7/13/2012	7/26/2012

1.3.2	Asphalt paving layers	N/A	5.5	7.67	11.63	9.19	7/31/2012	08/10/2012	7/31/2012	08/10/2012
1.3.2.1	110mm deep first asphalt layer	1	4.5	6.67	10.63	8.19	7/31/2012	08/09/2012	7/31/2012	08/09/2012
1.3.2.2	60mm deep second asphalt layer	1	3	4.39	6.25	5.28	08/06/2012	08/10/2012	08/06/2012	08/10/2012
1.3.3	Curbs	N/A	11	12.7	15.75	14.2	7/16/2012	08/01/2012	7/16/2012	09/06/2012
1.3.3.1	Cast-in place concrete curbs	1	8	9.61	12.75	11.1	7/16/2012	7/27/2012	7/16/2012	7/27/2012
1.3.3.2	Saw-cut at 20 meter intervals	0	1	1.09	1.38	1.18	7/31/2012	08/01/2012	09/05/2012	09/06/2012
1.4	Finishing work	N/A	12	13.7	16.5	14.83	8/13/2012	8/31/2012	8/13/2012	09/06/2012
1.4.1	Painting stripes	0	2	2.39	3.38	2.76	8/28/2012	8/30/2012	09/04/2012	09/06/2012
1.4.2	Sign installation	1	3	3.34	4.13	3.61	8/28/2012	8/31/2012	8/28/2012	8/31/2012
1.4.3	Fine grading and seeding work	1	9	10.36	13	11.45	8/13/2012	8/28/2012	8/13/2012	8/28/2012
1.5	Demobilization	1	4	4.31	5.75	4.68	8/31/2012	09/06/2012	8/31/2012	09/06/2012

Table 5-9 The WBS cost report of the road construction example

Code	WBS	Direct Cost				Indirect Cost				Total Cost			
		Min.	Mean	Max.	Percentile	Min.	Mean	Max.	Percentile	Min.	Mean	Max.	Percentile
1	Country road construction	1,690,764	1,791,565	1,932,106	1,839,306	149,353	179,118	213,676	190,893	1,840,117	1,970,683	2,130,670	2,028,473
1.1	Mobilization	12,786	16,295	21,947	18,642	2,508	3,177	4,396	3,661	15,294	19,472	25,869	21,961
1.2	Preparation	221,350	278,669	373,229	312,605	52,000	67,051	94,842	75,103	274,874	345,720	468,072	386,962
1.2.1	Site clearing and grubbing	40,972	49,779	71,174	55,408	13,609	16,344	20,846	17,907	54,817	66,123	92,021	72,918
1.2.1.1	Sta. 130 to 750	23,192	29,674	47,249	33,875	8,113	9,838	13,643	11,115	31,333	39,512	60,892	44,796
1.2.1.2	Sta. 750 to 1,000 and Sta. 0 to 130	15,461	20,105	33,062	23,135	5,142	6,506	9,560	7,372	20,606	26,611	42,621	30,393
1.2.2	Earth cut and fill	104,090	155,029	244,873	187,250	23,689	36,600	62,517	44,191	130,427	191,628	307,389	231,018

1.2.3	Drainages	65,892	73,861	85,630	78,267	11,694	14,108	16,338	15,170	78,124	87,969	101,621	93,028
1.2.3.1	Storm Sewer manhole connected to curbs	21,858	25,084	30,515	26,709	2,853	3,738	4,823	4,157	25,190	28,823	35,338	30,749
1.2.3.2	Culvert installation	42,789	48,777	58,025	52,536	8,762	10,370	12,124	11,265	51,817	59,146	69,708	63,524
1.2.3.2.1	Culvert at Sta. 220	7,877	10,100	12,353	11,109	1,511	2,067	2,674	2,316	9,569	12,166	14,824	13,388
1.2.3.2.2	Culvert at Sta. 360	7,909	10,858	13,822	12,493	1,534	2,259	3,127	2,671	9,726	13,116	16,589	15,135
1.2.3.2.3	Culvert at Sta. 600	11,143	13,774	17,472	15,464	2,258	2,984	3,699	3,354	13,777	16,757	21,113	18,772
1.2.3.2.4	Culvert at Sta. 900	11,329	14,046	16,783	15,555	2,362	3,061	4,233	3,465	13,789	17,107	20,462	18,956
1.3	Road work	1,374,577	1,441,859	1,502,055	1,473,136	71,392	90,976	111,459	99,289	1,450,103	1,532,835	1,604,563	1,571,720
1.3.1	Base layers	500,039	553,441	616,174	582,497	34,951	49,372	65,022	56,706	538,397	602,813	676,899	638,759
1.3.1.1	250mm deep lime-stabilized layer	203,032	247,275	299,374	275,371	25,199	37,304	52,876	44,520	228,231	284,579	348,755	319,549
1.3.1.2	50mm deep crushed 20mm gravel layer	295,324	306,166	321,788	313,147	9,088	12,068	14,731	13,696	304,702	318,234	336,471	326,708
1.3.2	Asphalt paving layers	796,223	820,734	850,109	832,224	23,132	30,970	40,249	34,840	819,661	851,704	889,181	866,659
1.3.2.1	110mm deep first asphalt layer	508,205	523,478	543,322	532,449	13,918	19,841	29,280	23,099	522,124	543,319	572,175	555,322
1.3.2.2	60mm deep second asphalt layer	286,148	297,256	312,929	303,711	7,630	11,130	15,571	13,016	294,915	308,386	327,448	316,583
1.3.3	Curbs	63,537	67,684	81,950	71,685	8,755	10,634	16,514	12,197	72,430	78,318	98,465	83,845
1.3.3.1	Cast-in place concrete curbs	62,466	66,409	80,693	70,405	8,350	10,216	16,115	11,778	70,816	76,625	96,809	82,146
1.3.3.2	Saw-cut at 20 meter intervals	1,071	1,276	1,680	1,409	351	418	597	463	1,423	1,693	2,276	1,861
1.4	Finishing work	44,031	51,122	62,536	55,138	13,853	15,931	19,634	17,203	58,596	67,053	82,134	72,039
1.4.1	Painting stripes	9,100	10,452	12,896	11,489	1,960	2,489	3,557	2,907	11,060	12,941	16,453	14,377
1.4.2	Sign installation	7,433	8,472	10,215	9,051	2,065	2,432	2,791	2,622	9,498	10,905	12,894	11,648
1.4.3	Fine grading and seeding work	26,132	32,198	44,052	36,008	9,181	11,010	14,072	12,179	35,314	43,208	57,685	47,923
1.5	Demobilization	1,690,764	1,791,565	1,932,106	1,839,306	149,353	179,118	213,676	190,893	1,840,117	1,970,683	2,130,670	2,028,473

Table 5-10 The resource cost report of the road construction example

Code	Resource	Direct Cost				Indirect Cost				Total Cost			
		Min.	Mean	Max.	Percentile	Min.	Mean	Max.	Percentile	Min.	Mean	Max.	Percentile
Labour	Labourer	92,058	105,894	127,019	113,014	50,246	58,722	75,433	63,324	142,896	164,617	197,540	174,968
Labour	**Subtotal**	92,058	105,894	127,019	113,014	50,246	58,722	75,433	63,324	142,896	164,617	197,540	174,968
Equipment	Loader	64,639	82,541	109,410	94,497	12,678	16,107	20,190	18,291	77,317	98,649	128,871	111,199
Equipment	Grader	15,936	25,043	36,715	29,840	3,874	5,888	8,827	7,009	19,931	30,931	43,299	36,430
Equipment	Vibration Roller	37,363	54,502	79,732	65,135	8,954	13,370	17,611	15,687	46,316	67,872	96,097	79,995
Equipment	Dozer	50,568	71,168	104,963	84,792	8,535	12,133	19,097	14,448	60,601	83,301	121,827	98,425
Equipment	Truck	20,203	29,680	42,079	35,328	6,161	9,027	13,142	10,701	26,645	38,706	54,164	45,497
Equipment	Paver	19,577	29,158	44,140	34,644	3,084	4,758	7,392	5,716	23,017	33,916	51,461	40,048
Equipment	Pneumatic Roller	5,532	8,730	13,821	10,614	1,661	2,608	3,827	3,144	7,193	11,338	16,786	13,605
Equipment	Tandem Roller	6,077	10,488	15,321	12,523	2,066	3,501	5,325	4,205	8,143	13,989	20,402	16,543
Equipment	Crane	5,683	7,468	9,413	8,511	1,836	2,389	3,094	2,725	7,519	9,856	12,166	10,986
Equipment	**Subtotal**	225,578	318,778	455,594	375,881	48,849	69,781	98,504	81,924	276,682	388,559	545,072	452,728
Total		317,636	424,672	582,613	488,895	99,095	128,503	173,937	145,248	419,578	553,176	742,612	627,696

5.3 Application of Hierarchical Modeling

In order to demonstrate the hierarchical modeling feature in the ISP tool, a Simphony.NET general purpose template model was created inside the cut-and-fill earth moving work package as shown in Figure 5-11. The resources used in the model are two scrapers, a dozer, and a roller. The entity represents approximately 15 Bm^3, which is the scrapers' loading capacity. The scrapers' loading, hauling, dumping, and return times are 0.8, 3, 0.5 and 2.5 minutes. It is assumed that the dozer starts spreading after the scraper delivers the dirt, which takes 3 minutes each time. The compaction begins with every 150 Bm^3 soil and takes 30 minutes. Interested users should refer to the Simphony.NET General Guide to understand the simulation behaviour and properties of the elements used in the model.
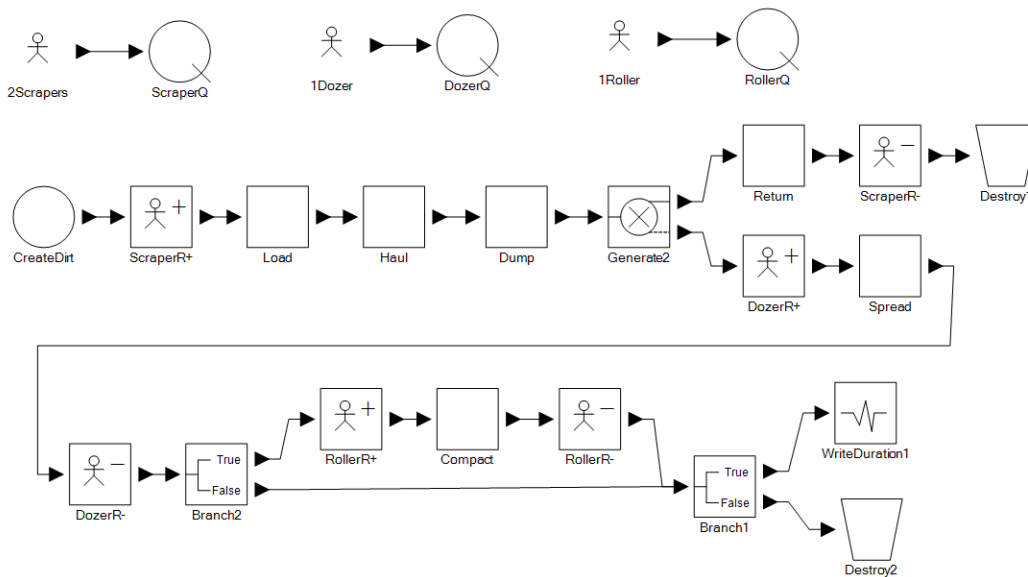
Figure 5-11 A sub-model depicting the earth cut-and-fill operation

The model generated 16.3 days as the duration of the cut-and-fill earth moving work package. The value is transferred to the schedule network model

and used in the analysis instead of the user-input in Table 5-2. The results of the model are similar to the original model and therefore are not explained in this section.

5.4   Verification

The developed ISP tool was verified to ensure that the tool generates accurate results as intended. Due to the ISP's unique framework, most of the results were verified by hand calculation with simple examples. Amongst these is the verification of cash flow graphs. Figure 5-12 displays the case study's cash flow graph based on an early start date. Figure 5-12 (a) was drawn using MS Excel based on the cost information given in Table 5-3 in order to ensure the accuracy of the ISP tool's cash flow graph shown in Figure 5-12 (b). Both graphs show a similar trend. The difference comes from the amount of data used in the graphs. The excel graph shows cost information every 4 hours while the ISP graphs displays it every hour.

The verification of the ISP's network scheduling module was performed by comparison with Oracle Primavera P6 using the case study example. Microsoft Project was not used for this purpose since the software only allows setting up one relationship between two activities and the example includes repeating activities (i.e., two activities have both SS and FF relationships). Figure 5-13 shows the scheduling information of the road construction example created in P6. The date and duration information in Figure 5-13 was compared with the ISP's scheduling information shown in Figure 5-2. The ISP tool generates accurate results as intended.

Note that for simplicity's sake, the verification examples explained above did not account for the ISP's resource and risk assignment features.
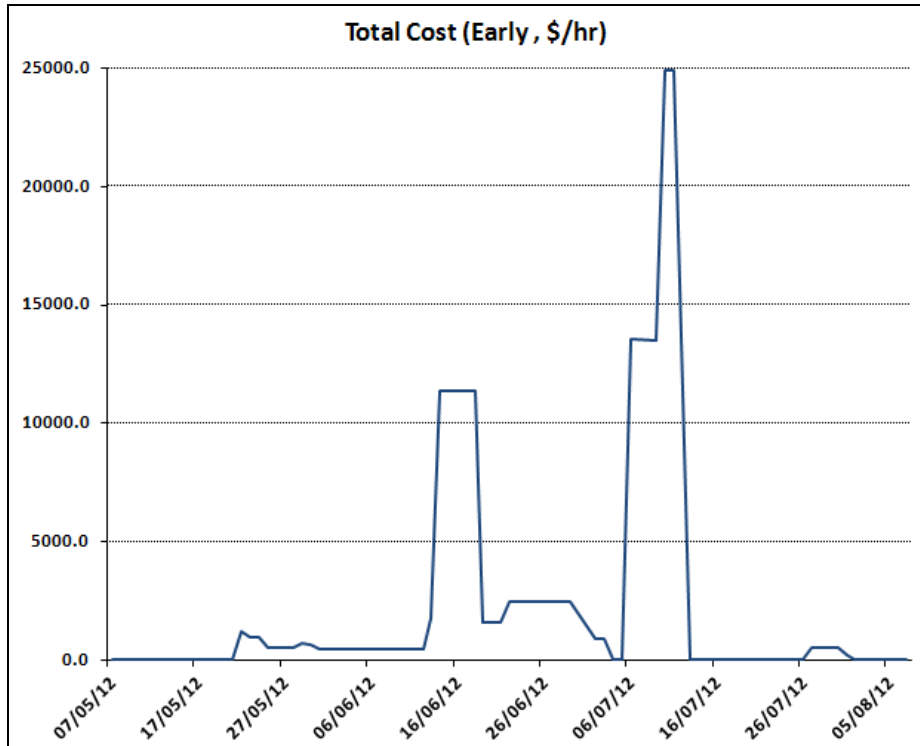
(a) Drawn by hand calculation
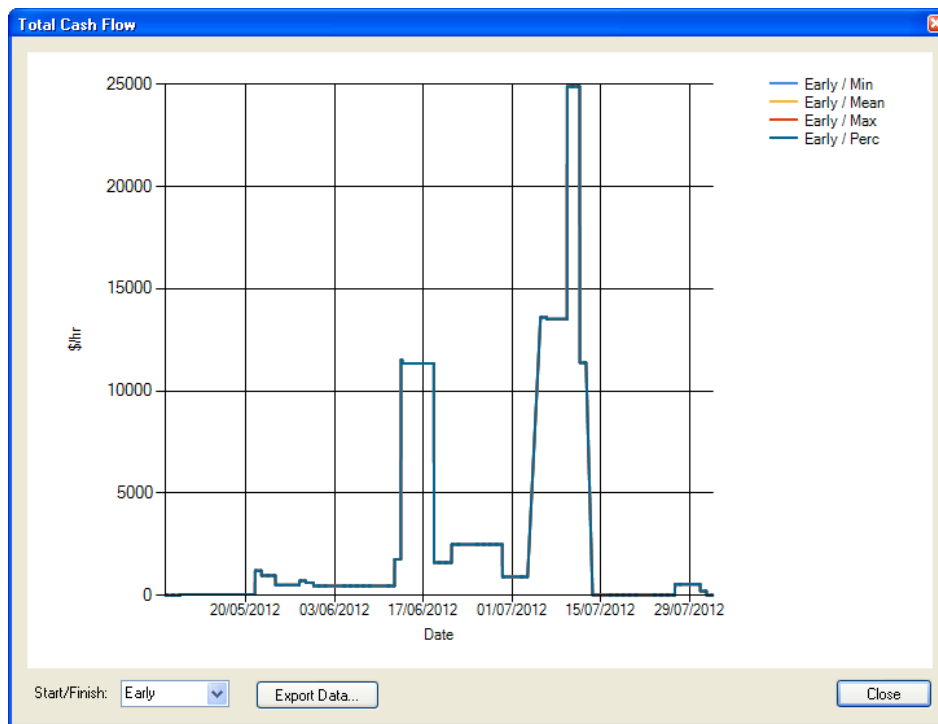
(a) Drawn by the ISP tool

Figure 5-12 A cash flow graph for the total cost based on an early start date

Figure 5-13 A schedule network for the case study (Oracle Primavera P6)

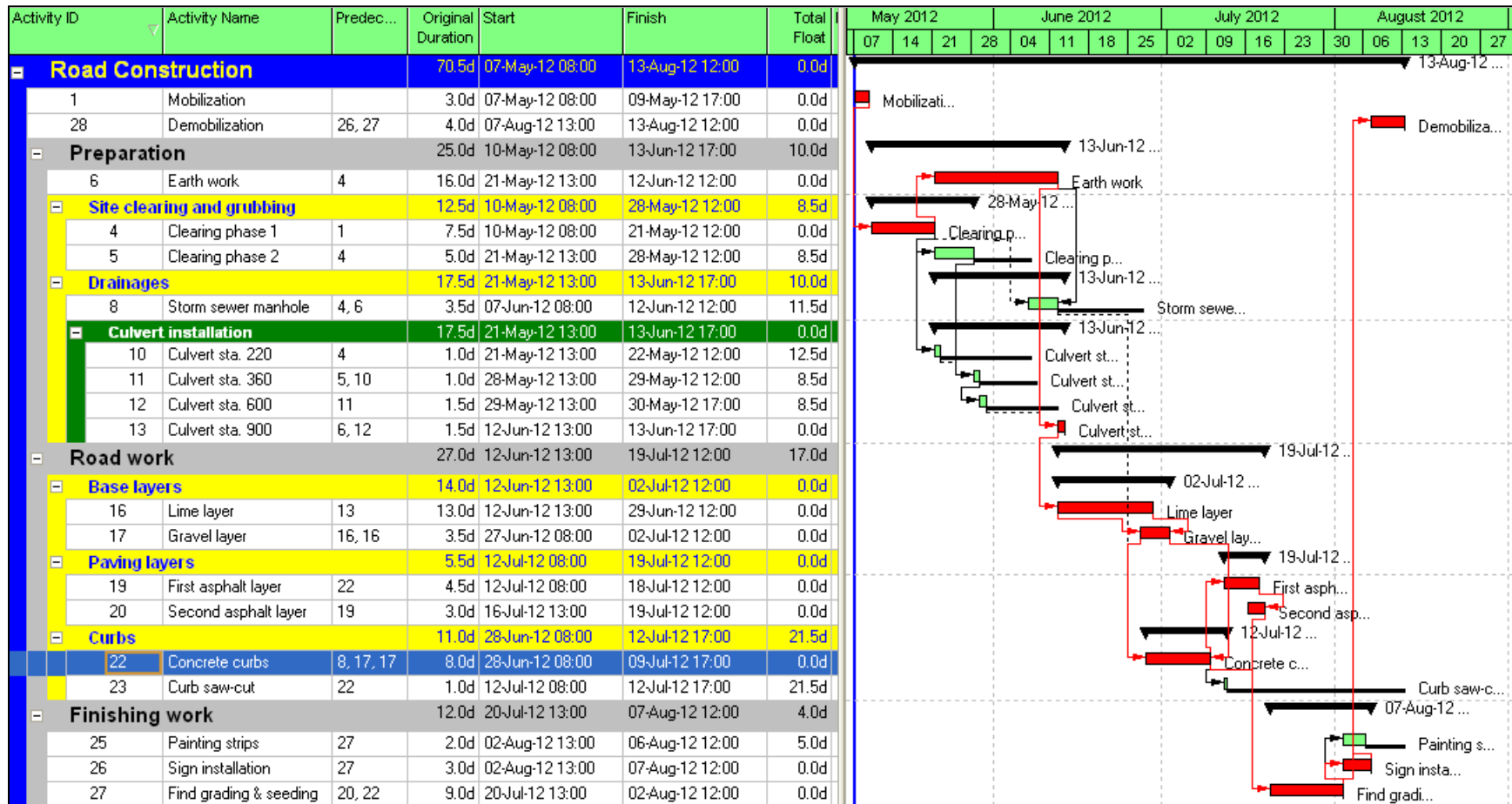In order to verify ISP's risk analysis function, a risk-enable cost estimating model was created using Palisade @Risk. The model accounted for the work packages, resources, and risk factors of the road construction example. After 1,000 iteration, a possible range of the project completion cost is [1,744,109, 2,355,220] dollars. The 85th percentile is 2,080,670 dollars. The difference of the project cost range between the ISP and @Risk results is 5 to 10 percent, and their percentile difference is less than 3 percent. This shows that the ISP tool generates accurate results as intended. Figure 5-14 shows the @Risk analysis results.

Simulation Summary Information	
Workbook Name	Case study(at risk).xlsx
Number of Simulations	1
Number of Iterations	1000
Number of Inputs	44
Number of Outputs	1
Sampling Type	Latin Hypercube
Simulation Start Time	3/2/12 12:11:09
Simulation Duration	00:00:02
Random # Generator	RAN3I
Random Seed	229072235

Summary Statistics for Total cost			
Statistics		Percentile	
Minimum	1744108.92	5%	1764208.848
Maximum	2355219.899	10%	1785624.108
Mean	1952467.207	15%	1813930.989
Std Dev	125772.9601	20%	1834234.288
Variance	15818837503	25%	1851811.612
Skewness	0.443788981	30%	1875534.56
Kurtosis	2.785049552	35%	1892994.412
Median	1942854.145	40%	1909601.317
Mode	1744108.92	45%	1925341.068
Left X	1764208.848	50%	1942854.145
Left P	5%	55%	1960425.983
Right X	2164942.579	60%	1980707.38
Right P	95%	65%	2000370.738
Diff X	400733.7302	70%	2018419.901
Diff P	90%	75%	2038124.668
#Errors	0	80%	2060079.917
Filter Min	Off	85%	2080669.913
Filter Max	Off	90%	2116383.738
#Filtered	0	95%	2164942.579

Figure 5-14 A risk analysis result of the case study (Palisade @Risk)

6 CONCLUSION

This chapter summarizes the work conducted in the research. It also outlines the limitation of the current work and recommendations for future enhancement.

6.1 Conclusion

Project planning is important to successfully deliver construction projects. In the early planning stage, the realistic predictions of project milestones, completion time, and cost estimating are necessary. However, construction projects are subject to many uncertain factors such as unfavourable market conditions, adverse weather and ground conditions, and change orders. These factors make it difficult for project managers to use deterministic and static approaches to planning and predict realistic predictions for successful project deliveries.

The objective of this research is to provide an integrated cost/schedule model, and transform the model to simulation-based planning through: (1) incorporating an explicit risk identification and assignment procedure when deriving uncertainties for a work package; (2) incorporating the details of operation into work packages to calculate more accurate activity durations and investigate production optimization; (3) incorporating explicit resources during network scheduling for resource-driven cost estimating; (4) evaluating a project schedule and cost using the Monte Carlo simulation; (5) providing an easy-to-use environment.

The main contribution of the research is the development of an integrated framework for simulation-based planning. This was achieved through incorporating the uncertainties, resources, and work packages' detailed operation

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into one integrated model. The framework combines the existing planning techniques such as range estimating, simulation-based network analysis, and risk identification and analysis resulting in one comprehensive framework.

For integrated simulation-based planning, an SPS tool called ISP has been developed using the Simphony.Net modeling environment. The ISP tool provides planning methods such as WBS, PDM, and RBS to guide project managers and increase flexibility in planning. The core of the ISP tool is simulation-based network analysis based on PDM. The feature is reinforced by the WBS for the work-packaging model, the RBS for risk identification, and resource-driven cost estimating to assist in project planning. The WBS helps define the project's scope and automates network model generation. By adapting as a network scheduling method the PDM, an advanced form of the CPM, it is possible to create various relationships between WPs. The RBS guides risk categorization and identification, helping to define which risk factors are likely to occur and what their impact will be.

As the simulation applications in the construction industry are mainly focused on the operation level, the linkage between the planning and operation level simulation is desirable to maximize the benefits of simulation. In ISP, this is achieved through a hierarchical modeling concept. By creating a sub-model inside of a WP using the Simphony.Net general template or other SPS templates, activities can be visualised on a more detailed level, and users can estimate the activities' production rate and calculate a more accurate WP duration.

As a secondary contribution, the ISP tool is expected to help students or inexperienced professionals to understand simulation fundamentals and

construction planning through WBS creation, resource allocation, risk identification and assignment, and simulation-based schedule network analysis.

6.2 Limitations and Future Work

The research is intended to provide a framework of the risk-associated cost/schedule integration model, and develop a prototype simulation tool for integrating planning tools including scheduling, cost estimating, and risk analysis into a simulation-based environment. The research has great potential to increase the application of simulation-based planning tools. This section includes a discussion of the ISP's current limitations and the direction of future work, along with additional topics which provide benefits for the ISP tool's users.

- The ISP currently assumes an unlimited supply of resources. It can be modified to consider resource-constrained scheduling by adapting an appropriate resource optimization algorithm.

- ISP offers a hard-coded example of the RBS for general construction projects, but the risk identification procedure can be improved if an RBS database is created for various types and contexts of construction projects.

- The research assumes that each risk factor has an independent impact. If the correlation between risk factors or activities affecting overall cost and duration is considered, a more realistic and accurate prediction will be possible.

- In this research, the data for risk identification and analysis are based on users' experiences. It is desirable to include features such as a risk matrix, analytical hierarchy process (AHP), and decision tree to help users make decisions.

- The current risk identification and analysis procedure can be modified using qualitative linguistic terms to provide consistency and convenience for users. Fuzzy logic, which uses possibility distribution rather than probability distribution, can be used for this purpose.

- The impacts of some risk factors keep changing. Weather is a good example of this as it changes daily. To consider this type of risk, the program could add combined discrete-event continuous simulation modeling, by which the internal simulation clock progresses in increments of fixed amounts of time (Wales, 1994)

- The suggested framework is focused on a pre-planning stage. In order to allow for the system's usability in the project control stage, it would be useful to add an automated information system to acquire, store, and present quality data.

The ISP SPS tool itself can also be embellished by adding user-friendly interface features to make the application more flexible. Some potential improvements are as follows:

- Resources and risk factors are only assigned to WPs in the current version, but to make group assignment more convenient, they could be assigned to any level of the WBS.

- It is desirable to view a cash flow graph in any level of WBS. This will assist in identifying which work groups have a major impact on the project cost.

- If an operation-level simulation model can be defined as an independent function, it can be used by multiple WPs. This feature will be useful in

projects such as bridges, roads, and multi-story buildings, which require building repeated components.

▪ The number of WPs affects the speed of the automation from the WBS spreadsheet to the schedule network view. Generating 1,000 WPs takes about 5 minutes with 2.33 GHz CPU and 3.25GB of RAM. Adding a better algorithm may boost the speed.

As computer simulation applications and techniques evolve, it is believed that the demand for integrated simulation-based planning will also increase. Therefore, integrating existing planning tools in the research is an effective contribution to the existing simulation-based research, and provides a stepping stone for future development.

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APPENDIX A: A USER MANUAL OF THE ISP

It is recommended that users read this manual in conjunction with the Simpnony.NET General Guide. The ISP elements are created using a drag-and-drop operation from the Template Area to the Modeling Space in the Simphony.Net user interface.

A.1 Project Element

The Project Element is the first element to be modeled in order to perform integrated schedule and cost analysis. It has input fields for general information for the project, and can contain several child elements, each of which represents the modules necessary to characterize the project. They are the Work Breakdown Structure (WBS) Element, the Resource Block Element, and the Risk Breakdown Structure (RBS) Element. The WBS Element is included as default upon creation of the Project Element. After the simulation is performed, users can view the project's cash flow graphs, WBS, and resource reports. Line charts show the project's cash flow and cumulative cash flow during the project period. The WBS report shows statistics for duration, direct cost, indirect cost, and total cost. The resource report contains the information about all the resources used in the project. The time unit to be used in the template is one day.

Design	-	Name: the project name.
	-	Description: the project description.
Inputs	-	Project Start: the project start date (default: current date and time).
	-	Percentile: the percentile (from 0 to 100) to be used in the statistics of results.
Outputs	-	Cash Flow Chart: showing the costs incurred during each time unit (an hour) based on either the early or late start date. The minimum, maximum, average, and percentile value of the direct, indirect, and total cost are plotted.
	-	Cumulative Cash Flow Chart: showing the cumulative cost values

over the period of the project based on either the early or late start date. The plots are the minimum, maximum, average, and percentile value of the direct, indirect, and total cost.

- WBS Duration Report: the minimum, mean, maximum, and percentile value of WBS duration are shown in days; and the percentile values of ES, EF, LS, and LF are displayed in a calendar date.

- WBS Cost Report: summarizing the statistics of direct, indirect, and total cost of each WBS level.

- Resource Cost Report: summarizing the statistics of direct, indirect, and total cost of each resource.

A.2 WBS Element

The Work Breakdown Structure (WBS) is a hierarchical structure which breaks down the scope of work into manageable pieces. The lowest level of WBS consists of work packages, each of which has its own schedule and budget for ease of managerial control including sub-contracting and responsibility allocation. The WBS Element has a spreadsheet control in which the WBS level can be defined in each line. The spreadsheet can be accessed from the WBS Element's property grid. The element has a precedence schedule network as a child, which can be accessed by double clicking on the element. The schedule network shows the work packages (node) and their sequential relationship (arrow) explicitly based on the inputs in the WBS table. At least one WBS Element should be defined as a child of the Project Element.

Input	-	WBS (Spreadsheet): See section A.2.1.
	-	Equality Precision: the precision (number of decimal places) of the equality comparison for criticality index calculation.

A.2.1 WBS (Spreadsheet)

Users can create a project hierarchy through the spreadsheet and insert each work package's duration, sequential relationship, and cost information. The

lowest levels of the hierarchy automatically become work packages in the schedule network. The descending levels of the WBS are represented with an indent, and the identification number is automatically assigned to each node upon creation. If any WBS level has a child level, all the input fields except Parent ID and Name become disabled. The highest level with the project name entered in the Project Element appears when the table is open. The upper levels of WBS show the aggregated information from their lower level entries.

.**Fields**	-	Name: the name of a WBS level.
	-	ID: a unique integer value for identification given to each row.
	-	Parent ID: the ID of the row to which the current row belongs as a direct child.
	-	Duration: the estimated duration in days to finish the work package.
	-	Start: the estimated start of a WBS level on a calendar date.
	-	Finish: the estimated finish of a WBS level on a calendar date.
	-	Predecessor: the ID of the proceeding activities and the precedence relationship with lead/lag time in days. The format is the predecessor Id' 'relationship (FS, FF, SS, SF)' '+lead/lag time', e.g. 3FF+2.
	-	Interruptible: defining whether the work package is interruptible or not. If the field is checked, the work package's duration might be delayed with interruption due to the logical relationship to other work packages (default: checked).
	-	Fixed Direct Cost: the constant amount of money to be directly used for initiating the work package. The field might be used when resources are not driving cost estimations.
	-	Fixed Indirect Cost: the basic behaviour is the same as that of the Fixed Direct Cost but the cost is not directly related to the work package.
	-	Variable Direct Cost: an hourly cost to be directly spent as the

work package is performed. The field might be used when resources are not driving cost estimating.

- Variable Indirect Cost: basic behaviour is the same as that of the Variable Direct Cost but the cost is not directly related to the work package.

A.3 Resource Block Element

Users can define the information about resources to be used in the project if resource-driven cost estimating is used. To make categorization easier, multiple resource blocks can be used in the same project as long as the name of the resource is uniquely defined. The Resource Block Element contains a resource definition control in which the cost information and type of each resource are defined. Once resources are defined, they are assigned to work packages through the schedule network. Note that the Resource Block Element can only be created inside the Project Element.

Inputs - Resource (collection editor): see section A.3.1

A.3.1 Resource (collection editor)

A resource can be one of four types. Each resource has a direct and/or indirect cost for one resource quantity as a fixed and/or variable cost. When risk factors are associated with the resource, the risks are assigned through a Risk Assignment dialog box with a certain degree of sensitivity. Users can also view the graph displaying the quantity of the resource used during the project time span.

Inputs - Name: the resource name.

- Type: the type of resource, to be chosen from labour, material, equipment, or user-defined.

- Fixed Direct Cost: the constant amount of money to be directly used for initiating the resource in a work package. The user can set this cost to a constant or to a random value sampled from a statistical distribution. Note that the cost is for one resource

quantity.

- Fixed Indirect Cost: the basic behaviour is the same as that of the Fixed Direct Cost but the cost is not directly related to the resource.

- Variable Direct Cost: the amount of money to be spent as the resource is utilized. The user can set this cost to a constant or to a random value sampled from a statistical distribution. It is a unit cost per hour and the cost is for one resource quantity.

- Variable Indirect Cost: basic behaviour is the same as that of the Variable Direct Cost but the cost is not directly related to the resource.

- Resource Profile Chart: displaying the quantity of a resource used during the project time span.

- Risk Assignment (dialog box): see section A.3.2.

A.3.2 Risk Assignment (dialog box)

In the dialog box, the available risk factors, which have been defined in the RBS Element, are listed on the left side. Risk factors can be applied to the current resource by the clicking the '→' button, and they will appear on the right side with certain sensitivity. The sensitivity shows how effective the resource is against the risk factor. Users assign a percentage of the cost impact to be materialized when the risk occurs while the resource is being used. The default value is 1 (=100%), which means that the full impact as assigned in the RBS Element is materialized upon the risk occurrence. If the value is 0, the selected risk's cost impact is not valid for the cost item.

| **Control** | - | Fixed Direct Cost Sensitivity: the proportional adjustment of the RBS Element's original cost impact value to the fixed direct cost of a resource. |
| | - | Fixed Indirect Cost Sensitivity: the proportional adjustment of the RBS Element's original cost impact value to the fixed indirect cost |

of a resource.

- Variable Direct Cost Sensitivity: the proportional adjustment of the RBS Element's original cost impact value to the variable direct cost of a resource.

- Variable Indirect Cost Sensitivity: the proportional adjustment of the RBS Element's original cost impact value to the variable indirect cost of a resource.

A.4 RBS Element

Users can define the information related to the risks in the project if the risks or opportunities related to schedule are taken into account. The RBS (Risk Breakdown Structure) Element allows users to systematically define risk factors. Double-click on the element drills down to a tree structure which represents a pre-defined RBS. The RBS consists of two elements: the Risk Category Element and the Risk Factor Element. Users can delete any element or add more levels in the structure. Note that the RBS Element can only be created inside the Project Element.

A.4.1 Risk Category Element

This element represents the intermediate level of the RBS. It has one upper level category element or root element (top level category) and multiple risk factor elements. It has a name and description field and helps risk identification through categorizing the risk factors.

A.4.2 Risk Factor Element

The Risk Factor Elements are located on the lowest level of the RBS. The element's properties are the name, likelihood of occurrence, and schedule and cost impact. The risk factors defined here are assigned to work packages and resources through the Work Package Element in the schedule network and Resource Block Element. Note that if the impact is given as a negative value, the risk occurrence provides a positive result such as cost underrun or schedule acceleration.

Inputs	-	Name: the name of a risk factor.
	-	Description: the description of the risk factor including causes and, possibly, mitigation.
	-	Likelihood: the probability (from 0 to 1) of occurrence of the risk/opportunity during the realization of the work package or resources associated.
	-	Schedule Impact: the percentage of the schedule delay/acceleration on the work packages where the risk/opportunity is associated. The user can set this value to a constant or to a random value sampled from a statistical distribution. (default: 0%).
	-	Cost Impact: the percentage of the cost overrun/underrun on the work packages or associated resources. The user can set this value to a constant or to a random value sampled from a statistical distribution (default: 0%).

A.5 Work Package Element

The Work Package Element can only be modeled as a child of the WBS Element. The elements are automatically generated when the WBS Element is double-clicked along with the Start Element and Finish Element. The initial input data is driven from the WBS spreadsheet. Users can modify the information, delete or add elements, and the changes will be reflected on the WBS spreadsheet. Resources and risk factors can be assigned to the WBS work packages. The cost and schedule output of each work package after simulation can be checked through the Output and Statistics field of the element. The available statistics are mean, minimum, maximum, standard variation, variance, skewness and kutosis. Users can refer to the output property of the Finish Element to view the result of overall project completion time and cost.

Inputs	-	Name: the name of a WBS level.
	-	Duration: the estimated duration in days to finish the work

package.

- Requested Start: the estimated start of a WBS level on a calendar date.

- Requested Finish: the estimated finish of a WBS level on a calendar date.

- Interruptible: defining whether the work package is interruptible or not. If the field is true, the duration might be delayed with interruption due to the logical relationship to other work packages (default: true).

- Fixed Direct Cost: the constant amount of money to be directly used for initiating the work package. The field might be used when cost estimating is not driven by the resources.

- Fixed Indirect Cost: the basic behaviour is the same as that of the Fixed Direct Cost but the cost is not directly related to the work package.

- Variable Direct Cost: an hourly cost to be directly spent as the work package is performed. The field might be used when cost estimating is not driven by the resources.

- Variable Indirect Cost: basic behaviour is the same as that of the Variable Direct Cost but the cost is not directly related to the work package.

- Resource Assignment: (Dialog box)

- Risk Assignment: (Dialog box)

Outputs	- CI: criticality index, the probability (from 0 to 1) of a work package being on the critical path.
	- Duration: the duration of a work package in days from the last run.
	- ES: the early start of work package in days from the last run.
	- EF: the early finish of a work package in days from the last run.

	- LS: the late start of a work package in days from the last run.
	- LF: the late finish of a work package in days from the last run.
	- Fixed Direct Cost: the fixed direct cost of a work package from the last run.
	- Fixed Indirect Cost: the fixed indirect cost of a work package from the last run.
	- Variable Direct Cost: the variable direct cost of a work package from the last run.
	- Variable Indirect Cost: the variable indirect cost of a work package from the last run.
Calendar	- ES date: the calendar date of the work package's early start from the last run.
	- EF date: the calendar date of the work package's early finish from the last run.
	- LS date: the calendar date of the work package's late start from the last run.
	- LF date: the calendar date of the work package's late finish from the last run.
Statistics	- Duration: the statistics of the duration of a work package from multiple runs.
	- ESStat: the statistics of the early start of a work package from multiple runs.
	- EFStat: the statistics of the early finish of a work package from multiple runs.
	- LSStat: the statistics of the late start of a work package from multiple runs.
	- LFStat: the statistics of the late finish of a work package from multiple runs.
	- Direct Cost: the statistics of the direct cost of a work package

from multiple runs.

- Indirect Cost: the statistics of the indirect cost of a work package from multiple runs.

- Total Cost: the statistics of the total cost of a work package from multiple runs.

A.5.1 Resource Assignment (Dialog box)

The available resources, which have been defined in the Resource Block Element, are listed on the left side of the dialog box. Resources can be applied to a work package by the clicking the '→' button, and they will appear on the right side with quantity information.

Controls -	Quantity: the quantity of a resource to be used in the work package. The value should be a positive integer (default: 1).

A.5.2 Risk Assignment (Dialog box)

In the dialog box, the available risk factors, which have been defined in the RBS Element, are listed on the left side. Risk factors can be applied to a work package by the clicking the '→' button, and they will appear on the right side with certain sensitivity. The sensitivity shows how effective the work package is against the risk factor. Users assign a percentage of the schedule/cost impact to be materialized when the risk occurs during execution of the work package. The default value is 1 (= 100%), which means that the full impact as assigned in the RBS element is materialized upon the risk occurrence. If the value is 0, the schedule/cost impact of the selected risk is not valid for the item.

Control -	Duration Sensitivity: the proportional adjustment of the original schedule impact value defined in the RBS Element to the duration of a work package.
-	Fixed Direct Cost Sensitivity: the proportional adjustment of the original cost impact value defined in the RBS Element to the fixed direct cost of a resource.

- Fixed Indirect Cost Sensitivity: the proportional adjustment of the original cost impact value defined in the RBS Element to the fixed indirect cost of a resource.

- Variable Direct Cost Sensitivity: the proportional adjustment of the original cost impact value defined in the RBS Element to the variable direct cost of a resource.

- Variable Indirect Cost Sensitivity: the proportional adjustment of the original cost impact value defined in the RBS Element to the variable indirect cost of a resource.

A.6 Write Duration Element

The Write Duration element can only be modeled inside of a Work Package Element. The Work Package Element can contain Simphony.Net simulation models inside in order to analyze the work package's operation in detail. Users attach the Write Duration Element to the simulation model to collect the duration of the work package.

Input	-	Multiplier: the value entered is to be multiplied with the duration obtained from the simulation.
Output	-	Duration: the duration resulting from the simulation.