Methodology for Integrated Risk Management and Proactive Scheduling of Construction Projects

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Abstract: An integrated methodology is developed for planning construction projects under uncertainty. The methodology relies on a computer supported risk management system that allows for the identification, analysis, and quantification of the major risk factors and the derivation of their probability of occurrence and their impact on the duration of the project activities. Using project management estimates of the marginal cost of activity starting time disruptions, a heuristic procedure is used to develop a stable proactive baseline schedule that is sufficiently protected against the anticipated disruptions that may occur during project execution and that exhibits acceptable makespan performance. We illustrate the application of the methodology on a real life construction project and demonstrate that our proactive scheduler generates baseline schedules that outperform the schedules generated by commercial software packages in terms of robustness and timely project completion probability.

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Introduction

Construction projects have to be performed in complex dynamic environments that are often characterized by uncertainty and risk. The literature contains ample evidence that many construction projects fail to achieve their time, budget, and quality goals (Al-Bahar and Crandall 1990; Assaf and Al-Hejji 2006; Mulholland and Christian 1999). Ineffective planning and scheduling have been recognized as major causes of project delay (Assaf and Al-Hejji 2006; Mulholland and Christian 1999). A study by Maes et al. (2006) revealed that the absence of an effective uncertainty management system and inferior planning was the third major cause of company bankruptcies in the Belgian construction industry.

The objective of this paper is to describe a methodology that integrates risk management with proactive/reactive construction project scheduling. Risk management in the construction industry has mostly been used for measuring the impact of potential *risks*—uncertain events or conditions that, if they occur, have a positive or negative effect on the global project parameters such as time and costs. The literature provides both fuzzy approaches and mixed quantitative/qualitative assessment and risk response methods (Mulholland and Christian 1999; Ben-David and Raz 2001; Carr and Tah 2001; Jannadi and Almishari 2003; Choi et al. 2004; Warszawski and Sacks 2004). Unlike these approaches, our contribution lies in the development of an integrated uncertainty management methodology that not only allows for the identification and quantification of uncertainties at the level of the individual project activities, but uses this input in a proactive scheduling system to generate a robust baseline schedule that is sufficiently protected against anticipated disruptions that may occur during project execution while still guaranteeing a satisfactory project makespan performance.

The methodology relies on a computer supported risk management system that uses a graphical user interface to support project management in the identification, analysis, and quantification of the major project risk factors and to derive the probability of their occurrence as well as their impact on the duration of the project activities. Using estimates on the marginal cost of activity starting time disruptions provided by project management, a heuristic buffer insertion algorithm is used to generate a proactive baseline schedule that is sufficiently protected against anticipated disruptions that may occur during project execution without compromising on due date performance.

The organization of this paper is as follows. In "Integrated Risk Management Framework" we describe the computer supported risk management framework and proactive schedule generation system. We illustrate the working principles of the methodology on a real-life project in "Risk Management Framework" and demonstrate that our proactive scheduling algorithm outperforms the built-in schedulers of the commercial software packages MSProject and ProChain. "Conclusions" provides overall conclusions.

Integrated Risk Management Framework

The literature provides a number of risk assessment procedures, but few of them manage to produce quantitative data (Lyons and

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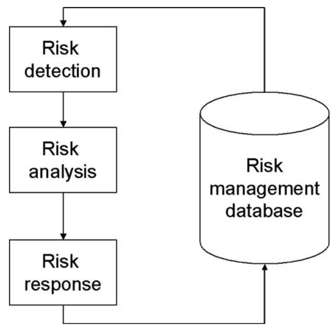

Fig. 1. Risk management process

Skitmore 2004). We offer a computer integrated approach that integrates the effective identification, analysis, and quantification of the major risk factors with a proactive project scheduling procedure that generates baseline schedules that are sufficiently protected against the disruptions they may cause during project execution. The system relies on a user friendly graphical user interface that prompts the project management team to provide the necessary data which allow for the identification of the impact of the risk factors at the level of the individual project activities.

The system maintains a risk management database that is updated with new risk information generated by the project management teams of ongoing projects and as such can serve as input for a proactive scheduling system. The system allows for the computation of the probability of occurrence of the risk factors shared by groups of activities and allows for the estimation of their impact on the duration of the individual project activities. Using project management estimates of the marginal cost of activity starting time disruptions, a robust scheduling system is used to derive proactive baseline schedules that are sufficiently protected against the anticipated disruptions without compromising the project makespan performance.

The integrated system has been developed as the major project result of a joint project executed over the past 2 years by the Belgian Building Research Institute (BBRI) and the Research Center for Operations Management of K.U. Leuven (Belgium) under a grant offered by the Institute for the Promotion of Innovation by Science and Technology in Flanders (IWT). It has been field tested at some 20 real life construction project sites (involving asbestos removal, and the construction of bridges, schools, apartments, hotels, and office buildings) and has been fine tuned in cooperation with the project management teams of the involved construction companies operating in different sectors of the Belgian construction industry.

Risk Management Framework

We follow the widely accepted view that risk management is an iterative process (see, e.g., Al-Bahar and Crandall 1990; Chapman and Ward 2000; PMI 2000) involving risk identification, risk analysis, and evaluation, risk response management, and the system administration supported by a risk management database (Fig. 1).

Risk Identification

During the project initiation phase, project management must decide on the major performance objectives (Demeulemeester and Herroelen 2002). The objectives of a project refer to the end state that project management is trying to achieve and which can be used to monitor progress and to identify when a project is successfully completed. Among the traditional objectives of time, cost, and quality, this paper will mainly focus on the delivery of the project result within a satisfactory project makespan (due date performance) relying on a stable project baseline schedule that helps to reduce the nervousness within the project supply chain.

The risk identification process involves the identification of the major potential sources of risk associated with the project objectives. Based on checklists of potential risks available in the open literature and maintained at the BBRI, a workable list of general risk factor classes has been established (a snapshot of some of the risk factor classes is shown in Table 1).

This list, which may also be applicable to construction projects outside Belgium, allows for the generation of sector and specialization specific risk profiles of the construction industry. The database can be consulted by the BBRI member project management teams and as such serves as a continuously updated source of information for the risk identification and risk analysis process. The identification of the relevant risk factors for an individual project then relies on both the input of the project management team and the BBRI database.

Based on existing tender lists, project activities are grouped into a limited number of *activity groups*, containing activities with similar risk structure. Such activity grouping should not be confused with the aggregation of activities into work packages. In a work breakdown structure, the activities "painting the bedroom ceiling" and "tiling the bedroom," for example, can be aggregated into the activity "bedroom finalization," while we are interested in grouping all painting activities that may suffer from similar potential risks together in a single activity group, regardless of where and when the individual group activities are executed. Grouping the activities that share common risks into activity groups, simplifies the subsequent risk analysis process, which can now be performed at the activity group level rather than at the level of each individual project activity.

Risk Analysis

Risk analysis involves the qualitative and quantitative assessment of the identified risk factors. Project management has to estimate the probability of occurrence of the risk factors as well as their potential impact. The risk management database can then be updated with the new information.

It is not possible to anticipate for all potential risks. Some risks may have such a rare occurrence and/or such big impact on the project that they can be classified as unpredictable special events. It is crucial, however, that the major predictable risk factors are effectively analyzed and quantified. Some of the possible risk impacts may be an activity duration increase (in time units), a productivity decrease (in percentage of the required time) caused, for example, by bad weather conditions, a delay in the planned starting time of an activity, an increase in the cost of an activity, an increase in the required amount of renewable resources, etc.

Because resources are often shared among different projects, disruptions in one project can cause delays in other projects. Also the subcontractors may generate delays. When appointments with subcontractors cannot be met because of delays in predecessor tasks, it may be difficult to fix new appointments on short notice. Ineffective planning and scheduling are important delay causes (Assaf and Al-Hejji 2006).

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Table 1. Risk Checklist (Source: BBRI Database, Reprinted with Permission)

Mark the relevant risks that could affect the activity:		
Environment	*Third party*	Damage to surrounding elements
		Obstruction to surrounding business or others
		Other claims
		Violation of legal requirements
		Provisions
	Accessibility of the construction site	Accidents
		Vandalism
		Weather delay
		Risks related to the accessibility
	Soil	Pollution
		Archeological finds
		Soil quality
Organization	*Plan*	Supply of plan
		Changes in plan
		Change of requirements
		Claims related to not keeping to promises
	Task	Extra work
		Errors in execution
		Inaccurate estimation of duration
		Indistinctness on who will perform the task
	Permits	Lack of formalities/documents/permits
Consumer goods	*General*	Price increase/decrease
		Material supply
		Availability
		Theft
Workforce	*Expertise*	Lack of expertise
		Absence of key persons
	Social	Difficulties within teams
	Availability	Absenteeism
Machines	*Availability*	Machine breakdown
		Supply of plan
		Availability
		Damage to surrounding elements
		Theft
Subcontractor	*General*	Price increase/decrease
		Failure of company
		Respected lead time
		Errors in execution

Estimating Project Activity Data

For each activity in the various activity groups, project management has to estimate the time, resource, and cost data that will be used in the baseline schedule generation process.

In no way should time contingency be included in the individual *activity duration estimates*. Contrary to project evaluation and review technique (PERT) which uses an optimistic, pessimistic, and most likely activity duration estimate, we want activity durations to be derived using aggressive time estimates d_j^*, without including any safety whatsoever. This means that we advocate the aggressive activity duration estimate to be based on the (unrealistic) best case activity duration, rather than on the mean or median duration as suggested by the critical chain approach of Goldratt (1997).

For each activity group, the project manager must also specify the *activity weight* w_j to be assigned to each activity in the group. This weight represents a marginal disruption cost of starting the activity during project execution earlier or later than planned in the baseline schedule. The weights reflect the scheduling flexibility of the activities in the groups and will be used by the robust project scheduling procedures described in the next section.

A small activity weight reflects high scheduling flexibility or low instability cost: it does not "cost" that much if the actually realized activity starting time during schedule execution differs from the planned starting time in the baseline schedule. Activities that depend on resources with ample availability, for example, will be given a small weight. Their rescheduling cost is small.

A heavy weight reflects small scheduling flexibility: deviations between actual and planned starting times are deemed very costly for the organization (e.g., high penalties that are incurred when individual milestones or the project due date are not met). Activities that use scarce resources or use subcontractors that are in a strong bargaining position will receive a heavy weight, since it is preferable that the starting time of these activities (or correspond-

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ing milestones) will be kept fixed in time as much as possible. Rescheduling these activities would create additional delays or cost increases.

The activity weights can be entered as a percentage or by moving a slider bar shown to the project manager by the graphical user interface (GUI). In the latter case, the GUI software translates the slider bar value into a numerical activity weight $0 \leq w_j \leq 100$.

Constructing Project Network

The project scheduling procedure described in the next section assumes that the project is represented by an activity-on-the-node network $G(N,A)$, in which the node set N denotes the set of activities, and A specifies the precedence relations.

Generating Risk Profiles

The risk quantification procedure should be workable for the project management team. Our approach is somewhat similar to the minimalist first pass approach of Chapman and Ward (2000). Similar to theirs, our approach expects project management to provide the probability of occurrence and the impact of the risk factors on the activities of an activity group under a best case scenario and a worst case scenario.

The GUI prompts the project manager to answer a list of scenario based questions aimed at the quantification of a risk and its impact on the duration increase of the activities of a certain activity group. Upon validation, the answers provided by the project managers are directly entered into the GUI and provide the following input: the overall occurrence frequency q of the risk, an estimate b of the time (in days) by which the duration of an affected activity is extended in the worst case scenario, the frequency of appearance $\zeta(b)$ of the worst case scenario in similar previously executed projects, the estimated duration prolongation a of an affected activity (in days) in the best case scenario, and the frequency of appearance $\zeta(a)$ of the best case scenario.

The frequencies $\zeta(a)$, $\zeta(b)$, and q can be larger than one if the project manager expects several occurrences of the risk during the project. The data are entered into the GUI after passing a validation test checking whether $q \geq \zeta(a)+\zeta(b)$. If the data entered do not pass this test, they must be revised by the project manager.

From the two extreme case point estimates (a and b), a triangular probability density function $f(\mathbf{x})$ and its cumulative distribution function $F(\mathbf{x})$ for the impact $\mathbf{x}$ are generated. A triangular distribution is completely defined by three parameters: the lower limit, the mode, and the upper limit.

The first step to generate $f(\mathbf{x})$ is the determination of c, the most likely estimate for the impact. Asking the project manager for an estimate of c has been shown to be difficult because of the fuzziness inherent to the "most likely" concept. For the time being, we assume that the best case scenario a, and the worst case scenario b, are the lower and upper limit of $f(\mathbf{x})$, respectively, and calculate c as

$$c = (a\zeta(a) + b\zeta(b))/(\zeta(a) + \zeta(b)) \tag{1}$$

The reasoning behind this formula starts from the idea that project managers never think in terms of point estimates $f(x)$ for a continuous distribution. We do, however, assume that the fraction $\zeta(a)/\zeta(b)$ is a correct estimate of $P(a)/P(b)$, where

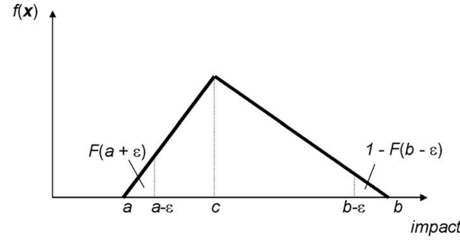

Fig. 2. Triangular probability density function $f(x)$

$$P(a) = \int_{x=a}^{x=a+\varepsilon} f(x)dx = F(a+\varepsilon) \tag{2}$$

and

$$P(b) = \int_{x=b-\varepsilon}^{x=b} f(x)dx = 1 - F(b-\varepsilon) \tag{3}$$

$P(a)$ and $P(b)$ must be interpreted as being the discrete probabilities that if the risk occurs, its impact lies within a certain scenario interval with width ε. ε reflects to what extent the project manager thinks in terms of scenarios and is highly dependent on the individual. $\zeta(a)/\zeta(b)$ is thus regarded as the ratio that the best case scenario is thought to be more likely to occur than the worst case scenario.

From Eqs. (2) and (3) we may conclude that

$$\zeta(a)/\zeta(b) = P(a)/P(b) = F(a+\varepsilon)/(1 - F(b-\varepsilon)) \tag{4}$$

Next, the distribution function $F(x)$ of a triangular distribution is known and defined by

$$F(x) = \begin{cases} (x-a)^2/(b-a)(c-a) & \text{for } a \leq x \leq c \\ 1 - ((b-x)^2/(b-a)(b-c)) & \text{for } c < x \leq b \end{cases} \tag{5}$$

Substituting Eq. (5) into Eq. (4) gives

$$\zeta(a)/\zeta(b) = (\varepsilon^2/(b-a)(c-a))/(\varepsilon^2/(b-a)(b-c)) = (b-c)/(c-a) \tag{6}$$

Because $b-c=(b-a)-(c-a)$, we find that

$$c = a + (b-a)/(1 + \zeta(a)/\zeta(b)) \tag{7}$$

Reformulating Eq. (7) yields Eq. (1). This formula is independent of the actual values of ε, $\zeta(a)$, and $\zeta(b)$. Fig. 2 shows a triangular density function $f(\mathbf{x})$ constructed on the basis of the input parameters a, b, and c. Note that $\zeta(a)/\zeta(b)=3$ in this figure. The cumulative distribution function $F(\mathbf{x})$ of $f(\mathbf{x})$ is shown in Fig. 3.

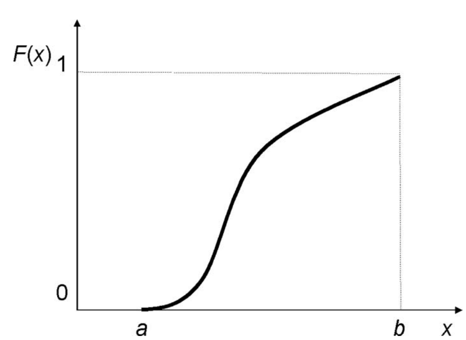

Fig. 3. Cumulative distribution function $F(x)$

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Deriving Individual Activity Risk Profiles

The probability density functions $f(\mathbf{x})$ of the impacts for all detected risks derived at the level of the activity groups have to be projected on the individual project activities. This projection is the key to the reusability of the risk assessments at the level of the activity groups. Using the characteristics of the risk impact densities and probability, risk assessments, and/or risk data coming from project records, distributions for project activities can be calculated and entered in the risk management database.

In the previous section we explained how the GUI was used to prompt the project manager to specify the average occurrence rate q of any risk in activity group AG. To obtain the probability density function $f(\mathbf{x})$, we rather need the occurrence rate of the risk at the level of a single project activity j.

We assume that the number k of risk occurrences is Poisson distributed

$$f(k;\lambda_j) = e^{-\lambda_j}\lambda_j^k/k! \tag{8}$$

and that the rate λ_j at which the risk occurs for activity j can be calculated as

$$\lambda_j = v_j q \Bigg/ \sum_{\forall i \in AG} v_i \tag{9}$$

The weights v_i depend on the characteristics of the risk. If the risk occurrence rate is independent of the activity duration d_i (e.g., a license delay), we set $v_i = u_i$, where u_i is a binary variable that equals 1 if the risk affects activity i and equals 0 otherwise. When the risk occurrence depends on d_i, we set $v_i = d_i^* \times u_i$, where d_i^* is the aggressive duration estimate of activity i.

Simulation can then be used to obtain a probability density function $f(\mathbf{d}_j)$ for the activity duration $\mathbf{d}_j$. We start by simulating the number of occurrences k which follows the distribution of Eq. (8). Then, for each occurrence $l, l = 1, \ldots, k$, the inverse distribution function $\mathbf{x} = F^{-1}(\mathbf{y})$ can be used to generate random values x_l for the risk impact, with $\mathbf{y}$ drawn from a uniform distribution between 0 and 1.

Subsequently, the simulated activity duration d_j is calculated as a function of the aggressive activity duration d_j^* and the simulated impacts x_l for each l. How this is done depends on the characteristics of the risk impact. For example, for risk factors that may lead to an activity duration increase—our major concern in this paper—we obtain the expected activity duration as

$$d_j = d_j^* + \sum_{l=1}^{k} x_l \tag{10}$$

A sufficient number of simulation runs allow the generation of the distribution functions $f(\mathbf{d}_j)$. These simulated distribution functions are then fit into known distribution functions f^*. A triangular distribution, for example, is completely characterized by its lower limit a_j, its upper limit b_j, and its mode c_j. a_j and b_j are directly distilled from the simulated f and c_j is calculated as

$$c_j = 3 \times E(\mathbf{d}_j) - a_j - b_j \tag{11}$$

where $E(\mathbf{d}_j)$ = mathematical expectation of $\mathbf{d}_j$.

Visibility for project managers is the main advantage of this approach. a_j, b_j, and c_j refer to an optimistic, a pessimistic, and a most likely estimate of $\mathbf{d}_j$.

Validating Estimates

The estimates a_j, b_j, and c_j are the result of subjective parameter estimates and need to be handled with care. The project manager who detected and analyzed the risks should validate the resulting parameters by consulting the historical data in the risk management database and/or gathering expert opinion.

It should be clear that, when the risk analysis procedure described above is deemed too extensive, the three point estimates of $\mathbf{d}_j$ may be directly determined on the basis of past experience or historical data.

Applying a sensitivity analysis of the risk parameter estimates might provide additional insight into the robustness of the estimates. A project manager could overestimate the worst case impact of a risk, just to make a statement. Showing him the impact of this overestimation could change his mind.

Risk Responses

Having identified the risk exposure and having quantified its potential impact, it is time to deploy well-known suitable risk treatment strategies such as risk avoidance (performing an alternative approach that does not contain the risk), risk probability reduction (taking actions to reduce the probability of the risk), risk impact reduction (taking actions to reduce the severity of the risk, e.g., by switching to a different activity execution mode, adding additional workforce, . . .), risk transfers ("selling" the risk to a third party, e.g., by outsourcing an activity or activity group), taking a risk insurance, or generating a baseline schedule that anticipates identified risks. It is the latter response strategy that calls for a robust project scheduling system discussed in the next section.

Robust Project Scheduling System

The robust project scheduling system we propose relies on the generation of a robust project baseline schedule that anticipates identified risks and that is sufficiently protected against distortions that may occur during actual project execution. The system takes as input the data generated during the risk identification and risk analysis process described in the previous sections: the activity duration distribution yielding the expected activity durations d_j and activity duration variance σ_j^2, and the activity weights w_j representing the marginal activity starting time disruption cost.

The robust baseline schedule is generated by introducing time buffers in a precedence and resource feasible project schedule. *Time buffering* is one of the possible techniques for generating proactive project schedules (Herroelen 2005; Herroelen and Leus 2004; Van de Vonder 2006; Van de Vonder et al. 2006b).

The *critical chain methodology* introduced by Goldratt (1997), uses aggressive mean or median activity duration estimates and computes the so-called critical chain in a precedence and resource feasible input schedule. The *critical chain* (CC) is defined as the chain of precedence and/or resource dependent activities that determines the project duration. If there is more than one candidate critical chain, an arbitrary one is chosen. A *project buffer* is inserted at the end of the CC to protect the project due date against variation in the CC. *Feeding buffers* are inserted wherever noncritical chains meet the CC in order to prevent distortions in the noncritical chains from propagating throughout the CC. The default buffer size is 50% of the length of the chain feeding the buffer. Alternative buffer sizing procedures have been presented in the literature (Newbold 1998; Tukel et al. 2006). A *resource buffer*, usually in the form of an advance warning, is placed whenever a resource has to perform an activity on the critical

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chain, and the previous critical chain activity has to be done by a different resource.

The potentials and pitfalls of the CC methodology have been extensively discussed by Herroelen and Leus (2001) and Elmaghraby et al. (2003). The main conclusion that can be drawn from these studies is that the project buffer may overprotect the project makespan and may lead to unnecessarily high project due dates, and that the procedure may generate unstable schedules caused by the fact that the feeding buffers mostly fail to prevent propagation of schedule disruptions throughout the baseline schedule.

Van de Vonder (2006) and Van de Vonder et al. (2005b) have evaluated the critical chain methodology using a computational experiment on an extensive set of test instances, reaching the paradoxical conclusion that the CC scheduling procedure—being essentially a scheduling procedure that tries to protect the project makespan—is hard to defend, especially for those projects where due date performance is deemed important. The feeding buffers may fail to act as a proactive protection mechanism against schedule disruptions and cannot prevent the propagation of activity distortions throughout the schedule.

The proactive project scheduling system that we advocate in this paper tries to generate a robust baseline schedule that is sufficiently protected against the anticipated risk factors identified through the risk identification and analysis process described earlier. We distinguish between two types of schedule robustness: quality robustness and solution robustness or stability.

Quality robustness refers to the insensitivity of the solution value of the baseline schedule to distortions. The ultimate objective of a proactive scheduling procedure is to construct a baseline schedule for which the solution value does not deteriorate when disruptions occur. The quality robustness is measured in terms of the value of the objective function z. In a project setting, commonly used objective functions are project duration (makespan), project earliness and tardiness, project cost, net present value, etc. It is logical to use the service level as a quality robustness measure, i.e., to maximize $P(z \leqslant z)$, the probability that the solution value (i.e., the makespan) of the realized schedule stays within a certain threshold. As a result, we want to maximize the probability that the project completion time does not exceed the project due date δ_n, i.e., $P(s_n \leqslant \delta_n)$, where s_n denotes the starting time of the dummy end activity. Van de Vonder (2006) refers to this measure as the *timely project completion probability* (TPCP).

Solution robustness or *schedule stability* refers to the difference between the baseline schedule and the realized schedule upon actual project completion. We measure the difference by the weighted sum of the absolute difference between the planned and realized activity start times, i.e., $\Delta(S,S)=\Sigma_j w_j|\mathbf{s}_j-s_j|$, where s_j denotes the planned starting time of activity j in the baseline schedule, $\mathbf{s}_j$ is a random variable denoting the actual starting time of activity j in the realized schedule, and the weights w_j represent the activity disruption costs per time unit, i.e., the non-negative cost per unit time overrun or underrun on the start time of activity j.

We use the bicriteria objective $F(P(\mathbf{s}_n \leqslant \delta_n), \Sigma_j w_j|\mathbf{s}_j-s_j|)$ of maximizing the timely project completion probability and minimizing the weighted sum of the expected absolute deviation in activity starting times. We hereby assume that the composite objective function $F(.,.)$ is not known a priori and that the relative importance of the two criteria is not known from the outset and no clear linear combination is known that would reflect the preference of the decision maker.

Van de Vonder (2006) has extensively evaluated a number of exact and heuristic proactive scheduling procedures. The writers are currently experimenting with these procedures on a number of real life construction projects.

Excellent results have been obtained by the so-called *starting time criticality* (STC) heuristic that exploits the information generated by the risk assessment procedure described earlier. The basic idea is to start from an unprotected input schedule that is generated using any procedure for generating a precedence and resource feasible solution to the well-known *resource-constrained project scheduling problem* (RCPSP): schedule the activities subject to the precedence and resource constraints under the objective of minimizing the project duration. In practice, the feasible schedule generated by any of the existing commercial software packages such as MS Project can be used as the input schedule. We then iteratively create intermediate schedules by inserting a one-time period buffer in front of the activity that is the most starting time critical in the current intermediate schedule, until adding more safety would no longer improve stability. The starting time criticality of an activity j is defined as $\text{stc}_j = P(\mathbf{s}_j > s_j) \times w_j = \gamma_j \times w_j$, where γ_j denotes the probability that activity j cannot be started at its scheduled starting time.

The iterative procedure runs as follows. At each iteration step the buffer sizes of the current intermediate schedule are updated as follows. The activities are listed in decreasing order of the stc_j. The list is scanned and the size of the buffer to be placed in front of the currently selected activity from the list is augmented by one time period and the starting times of the direct and transitive successors of the activity are updated. If this new schedule has a feasible project completion ($s_n \leqslant \delta_n$) and results in a lower estimated stability cost ($\Sigma_{j \in N} \text{stc}_j$), the schedule serves as the input schedule for the next iteration step. If not, the next activity in the list is considered. Whenever we reach an activity j for which $\text{stc}_j=0$ (all activities j with $s_j=0$ are by definition in this case) and no feasible improvement is found, a local optimum is obtained and the procedure terminates.

Applying Framework to Real-Life Project

In this section, we document the application of our risk management and proactive/reactive scheduling framework to a real-life project in the Belgian construction industry selected among the more than 20 construction projects (with a number of activities ranging from 200 to 2,000) to which the methodology has currently been applied. The housing project involved the construction of a five-story apartment building in Brussels, Belgium. The project required both structural and finishing works.

We used the initial project network developed by the project team and their activity time estimates as input. During the risk assessment procedure, use could be made of the risk management database maintained at the BBRI, which contained risk data obtained on a similar construction project. During the execution of the project, the project team systematically updated the risk database by the registered disruptions.

Project Network and Activity Groups

The real-life project comprised 234 activities. The activities were grouped in 20 activity groups. A total of 103 of the 234 activities were identified as inflexible activities, mostly because they had to be subcontracted or were identified as crucial milestones. As the

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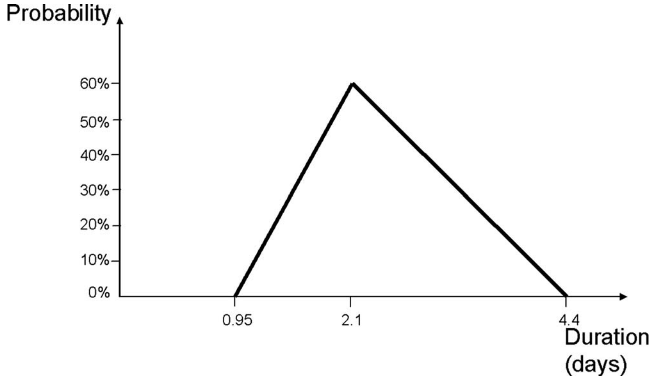

Fig. 4. Impact of bad weather as triangular distribution

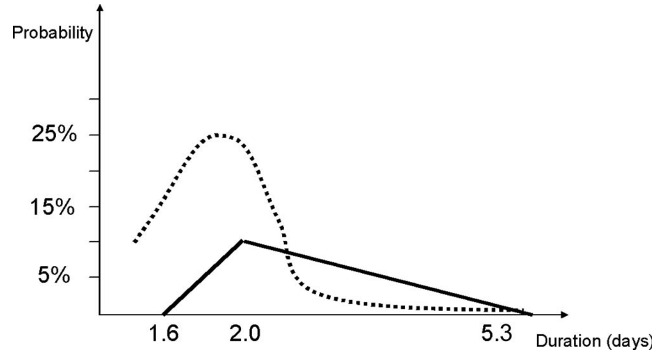

Fig. 5. Triangular distribution function for $\mathbf{d}_{10}$

contract gave high importance to meeting the planned due date of the project, a large weight had to be given to the activity marking the project completion.

Risk Detection and Risk Analysis

We illustrate the risk assessment approach on Activity 10, which belongs to the activity group "concrete pouring and polishing." A similar procedure was applied for all the activity groups. The risks that could affect the activity groups were identified, relying heavily on the risk management database. The risks could be divided into six main categories: environment, organization, consumer goods, workforce, machines, and subcontractors.

For the "Concrete pouring and polishing activity group," the project manager deemed six risks to be important: machine breakdown (machines), errors in execution (organization), material supply (consumer goods), weather delay (environment), extra work (organization), and absenteeism (work force).

For each of these six risks, our scenario-based approach for risk analysis was applied. Estimates of probability and impact of both a best and worst case scenario and the overall frequency of risk occurrence were obtained from the project management team during an interview session. The obtained data were entered into a GUI (note that this graphical user interface provides functionalities such as cost analysis tools that are not discussed in this work). The estimates were transformed into a distribution function of the impact of risks per time unit or per activity.

Fig. 4 shows the distribution function $f(x)$ of the delays on the activity group "concrete pouring and polishing" due to bad weather conditions. A similar approach supplied the distribution functions of the impact of the other risks on the activity group.

The impact of all the concerning risks were mapped on the individual project activities. By simulating a large number of project executions (1,000 iterations), a range of estimates for the realized activity duration d_{10} was obtained. The dashed line in Fig. 5 shows the simulated distribution function of these estimates. The full line represents the fitted triangular distribution $f(\mathbf{d}_{10})$. From this triangular distribution, three PERT-type estimates of $\mathbf{d}_{10}$ were distilled: an optimistic estimate $a_{10}=1.6$, a pessimistic $b_{10}=5.3$, and a most likely estimate $c_{10}=2$.

Flexibility of Activities

The project manager considered the "concrete pouring and polishing activity group" as rather flexible. This was mainly due to the fact that the activities had to be done by the company's own sufficiently available workforce. It was expected that rescheduling this activity could be easily done without causing any major problems.

Project Schedules

Multiple candidate schedules were generated for the project using the average activity durations obtained from the simulated distribution.

Four procedures were used to construct a baseline schedule: the standard resource leveling scheduling mechanism embedded in MS Project, the default ProChain scheduling mechanism that uses the critical chain approach (Goldratt 1997) relying on the above mentioned 50% rule for sizing both the feeding and project buffers. Additionally we used the ProChain scheduling mechanism that uses buffer sizing based on the sum of squares of both critical chain and feeding chains

$$\text{buffer} = \sqrt{\sum_{k=1}^{n} ((l_k - d_k)/2)^2} \qquad (12)$$

in which n=number of activities on the critical chain or feeding chain; l_k=low risk value for the duration of activity k which corresponds to the 90th percentile of its duration distribution; and d_k=average duration of activity k. Finally we use the STC procedure proposed by Van de Vonder et al. (2005a) and discussed above, based on a 99% service level, i.e., a 99% certainty that the project delivery date will be met.

In a first analysis we took the four generated baseline schedules as input and submitted them to disruptions in 100 simulation runs of the project, using the estimated activity distributions and imposing a reactive scheduling procedure at schedule breakage that applies a robust parallel generation scheme based on a priority list that orders the activities in nondecreasing order of their starting times in the baseline schedule (Van de Vonder et al. 2006a). The requested probability of meeting the due date for each of the four schedules was set to 99%, which corresponds to a requested completion within 538 working days.

The results are shown in Fig. 6. The results clearly demonstrate the superiority of the STC algorithm which convincingly reduces the stability costs, without compromising makespan performance.

A second analysis was performed upon completion of the project. At the time when the actual disturbances that occurred during the execution of the project were all known, we confronted the four baseline schedules with the actual schedule disrup-

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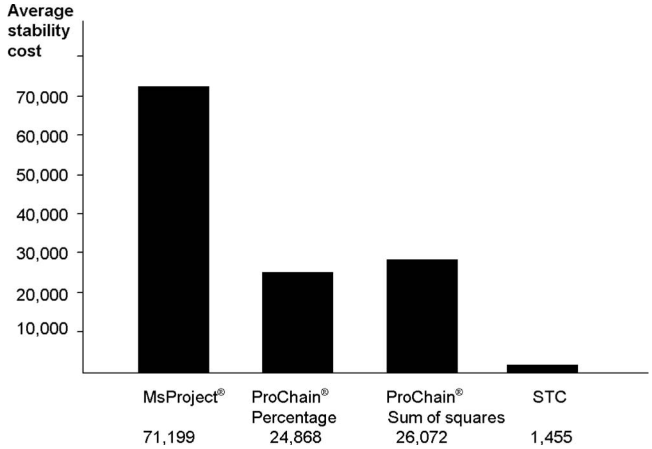

Fig. 6. Average stability cost

tions. Each time a schedule was disrupted, the same reactive procedure as used in the first analysis, was used to repair the schedule.

The unprotected schedule generated by MS Project was subject to many schedule breakages and heavy due date violation, while the STC schedule perfectly met its due date, exhibiting a striking robustness, especially for the heavy weighted inflexible project activities. Fig. 7 indeed shows that the STC algorithm efficiently protects those activities that are hard to reschedule. In other words, it perfectly meets the project due date and delivers a high solution robustness. One of the most important strengths of the STC algorithm is that it concentrates its schedule protection on those activities where stability pays off, i.e., the inflexible activities for which rescheduling is very costly. The flexible activities, where schedule stability is not that important, are scheduled in a way that balances stability with makespan performance.

Table 2 summarizes the results of the second analysis were the four scheduling procedures where confronted with the disruptions that actually occurred. The schedule generated by MS Project sets

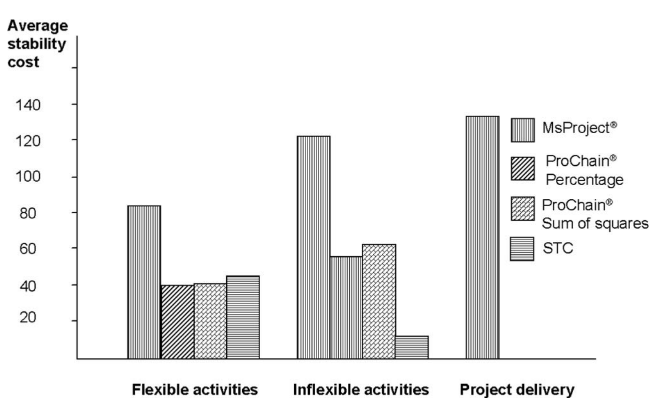

Fig. 7. Average stability delays

a completely unrealistic planned project delivery date, which was violated by more than 4 months. Moreover, it suffered from numerous schedule breakages during project execution, resulting in the highest stability cost: a highly undesirable situation.

The schedule generated by ProChain, using the 50% buffer sizing rule, included too much protection resulting in an unacceptable planned project delivery date caused by the insertion of a much too long project buffer. It is highly questionable whether such a long project buffer would be acceptable within the construction industry. Actually the project could have been completed 1 year earlier than originally planned, but the schedule was subject to numerous distortions, resulting in high stability costs.

The ProChain schedule, based on the sum of squares buffer sizing rule, does away with the unacceptable large project buffer, but still does not clearly beat the STC algorithm on makespan. It is outperformed by the STC schedule on makespan performance and stability cost.

The STC schedule finishes the project about 1 month later than the other schedules. This result should be interpreted with sufficient care. Because in our model we do not take into account the possible additional delays caused by the rescheduling of activities, the delivery dates shown are likely to suffer from an underestimation. This is why it is reasonable to suspect that the additional delay caused by rescheduling inflexible activities could argue in favor of the STC algorithm. For a similar delivery date performance, the stability costs for the ProChain and MS Project schedules are much higher.

Conclusions

The introduction of a user friendly, time saving risk assessment method and risk database can persuade the construction project teams to go for a more quantitative risk management approach. It enables them to reuse previous risk assessments and hereby avoid recurring, time consuming efforts.

The efficient risk quantification method introduced in this paper yields a duration distribution for each project activity. This information can accordingly be used by a proactive scheduling algorithm to insert time buffers in such a way that the planned starting time of the activities and the realization time of the milestones that suffer from a high disruption cost are sufficiently protected. Unlike ProChain and MS Project, the STC algorithm schedules the activities to such an extent that both solution and quality robustness are boosted, without giving in to makespan performance.

The results obtained during the implementation of the methodology on real life projects are very promising. Further research will refine the risk database and hopefully allow the construction companies to reap the benefits of increased stability and makespan performance.

Table 2. Schedule Performances

Algorithm	Kick off	Planned delivery date	Delivery date	Stability cost
MsProject	March 19, 2004	October 25, 2005	March 7, 2006	168,265
ProChain percentage	March 19, 2004	March 1, 2007	March 1, 2006	57,561
ProChain sum of squares	March 19, 2004	April 24, 2006	March 1, 2006	64,341
STC	March 19, 2004	April 12, 2006	April 5, 2006	16,749

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Notation

The following symbols are used in this paper:

A = set of arcs;
a = duration extension in best-case scenario;
b = duration extension of activity in worst-case scenario;
c = most likely duration impact;
d_j = expected duration of activity j;
d_j^* = aggressive duration estimate for activity j;
$F(\mathbf{x})$ = cumulative distribution function;
$f(k;\lambda_j)$ = Poisson distribution for number of risk occurrences;
$f(\mathbf{x})$ = triangular probability density function;
$G(N,A)$ = activity-on-node network;
l_k = low risk value for duration of activity k;
N = set of nodes;
q = overall frequency of risk;
$\mathbf{s}_j$ = actual starting time of activity j;
s_j = planned starting time of activity j;
stc_j = starting time criticality of activity j;
w_j = weight for activity j;
γ_j = probability that activity j cannot be started on its scheduled starting time;
δ_n = project due date;
λ_j = occurrence rate for risk for activity j;
$\zeta(a)$ = frequency of best-case scenario; and
$\zeta(b)$ = frequency of worst-case scenario.

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