

COMPARING A RESOURCE LEVEL AND ACTIVITY LEVEL CONTROL APPROACH: MODELLING AND SIMULATING CORRECTIVE ACTIONS FOR RESOURCE UNCERTAINTY

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Abstract

Comparing a resource level and activity level control approach: modelling and simulating corrective actions for resource uncertainty

by Jonas VERSPEELT

Activity level control methods like CPM, CC/BM and ESM have proven to be reliable tools for project control. More precisely, during project execution, the presence of variability and uncertainty will inevitably cause deviations from your baseline schedule. Therefore, accurate tracking of the project performance and taking corrective actions to bring the project back on track are essential tools in assuring a successful project completion. Until now, all control approaches and corresponding corrective action types are focussed on the project's activities. Reducing an activity's duration or its variability will be effective upon decreasing a project's duration, especially when those activities are not constrained by any resource constraints. However, when resources come into play, the traditional activity level control approaches may lose some of their efficacy.

Therefore, in this Master's dissertation, a new tool for controlling projects including one or more resources will be constructed. More precisely, this new control approach and its corrective action types will be focussed on the resources of a project instead of its activities. The efficacy of this new resource level control approach will be compared to the efficacy of the traditional activity level control approach ESM for a diverse set of projects with varying characteristics.

After extensive research, the resource level control approach demonstrated significant potential for controlling projects with specific characteristics. However, additional future research is required to further test and improve this approach.

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Abstract

Comparing a resource level and activity level control approach: modelling and simulating corrective actions for resource uncertainty

by Jonas VERSPEELT

Os métodos de controlo do nível de atividade, como o CPM (Critical Path Method), CC/BM (Critical Chain/ Buffer Management) e ESM (Earns Schedule Management) , provaram ser ferramentas fiáveis para o controlo de projectos. Mais precisamente, durante a execução do projeto, a presença de variabilidade e incerteza causará inevitavelmente desvios em relação ao calendário de base. Por conseguinte, um acompanhamento exato do desempenho do projeto e a tomada de medidas correctivas para o repor no bom caminho são ferramentas essenciais para garantir uma conclusão bem sucedida do projeto. Até agora, todas as abordagens de controlo e os tipos de acções correctivas correspondentes estão centrados nas actividades do projeto. A redução da duração de uma atividade ou da sua variabilidade será eficaz para diminuir a duração de um projeto, especialmente quando essas actividades não estão limitadas por quaisquer restrições de recursos. No entanto, quando os recursos entram em jogo, as abordagens tradicionais de controlo do nível de atividade podem perder alguma da sua eficácia.

Assim, nesta dissertação de mestrado, será construída uma nova ferramenta para controlar projectos que incluam um ou mais recursos será construída. Mais precisamente, esta nova abordagem de controlo e os seus tipos de acções correctivas serão centrados nos recursos de um projeto e não nas suas actividades. A eficácia desta nova abordagem de controlo A eficácia desta nova abordagem de controlo ao nível dos recursos será comparada com a eficácia da abordagem tradicional de controlo ao nível das actividades para um conjunto diversificado de projectos com características variadas.

Após uma investigação aprofundada, a abordagem de controlo a nível dos recursos demonstrou um potencial significativo para controlar projectos com características específicas. No entanto, é necessária mais investigação futura para testar e melhorar esta abordagem.

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Foreword

I wrote this Master's dissertation upon completing my five-year educational program in Business Engineering at Ghent University and my one-year program in Service Engineering at the University of Porto. Writing this dissertation was a real personal challenge and a highly enriching experience. It seems only appropriate to thank the people that supported me during this two-year trajectory of completing this dissertation.

First of all, I would like to thank Prof Dr Mario Vanhoucke for granting me the opportunity to conclude my academic trajectory by delving into a subject that truly sparked my interest, namely project management. His igniting enthusiasm regarding this topic was a big motivator for choosing this dissertation's topic.

Further on I would like to thank my co-promotor João Claro, my supervisor Forough Vaseghi and my ex-supervisor Annelies Martens for their feedback, suggestions and advice over the entire duration of my thesis.

Thereafter I would also like to thank my parents and sister for giving me the opportunity to continue my studies at the University of Ghent, for allowing me to take part in the wonderful experience of following a Double Degree program at the University of Porto and for supporting me throughout my whole educational career.

Last but not least I want to thank my lovely girlfriend Victoria for supporting me in writing this dissertation, especially at the moments I needed it the most.

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List of Abbreviations

AC	Actual Cost
AD	Actual Duration
AWC	Actual Work Content
BAC	Budget At Completion
CC/BM	Critical Chain /Buffer Management
CPI	Cost Performance Index
CPI_{EVWC}	Cost Performance Index with Earned Value Work Content
CPM	Critical Path Method
CV	Cost Variance
CV_{ESWC}	Cost Variance with Earned Schedule Work Content
ES	Earned Schedule
EST	Earliest Starting Time
ESWC	Earned Schedule Work Content
EV	Earned Value
EVM	Earned Value Management
EVWC	Earned Value Work Content
EWC	Earned Work Content
GRWC	Greatest Resource Work Content
LST	Latest Start Time
MIS	Most Immediate Successors
MOI 2	Management Oriented Index 2
NPV	Net Present Value
PC	Percentage Completion
PD	Planned Duration
PERT	Program Evaluation and Review Technique
PV	Planned Value
PWC	Planned Work Content
RAC	Real At Completion
RC	Resource Constrainedness
RD	Real Duration
RLU	Reduced Level of Uncertainty
RR	Road Runner policy
RS	Resource Scarceness
RU	Resource Usage
RW	Rail Way policy
RWCAC	Real Work Content At Completion
S/P	Serial / Parallel value
SPI(t)	Schedule Performance Index with Earned Schedule

$SPI_{ESWC}(t)$	Schedule Performance Index with Earned Schedule Work Content
SPT	Shortest Processing Time
SV	Schedule Variance
SV(t)	Schedule Variance with Earned Schedule
SV(t)	Schedule Variance with Earned Schedule
$SV_{ESWC}(t)$	Schedule Variance with Earned Schedule Work Content
TF	Total Float
WC	Work Continuity
WCAC	Work Content At Completion

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1 Problem Description

1.1 Project management framework

The life cycle of a project usually consists of three main stages: the scheduling stage, the execution stage and the evaluation stage. An appropriate implementation of those 3 stages allows a project manager to accurately schedule a project, track its behaviour while it is running and evaluate the project's performance after its completion.

The goal of the first stage, *the scheduling stage*, is to generate a baseline schedule that complies with both the activity precedence relations and the resource constraints. This schedule is based on activity duration, cost and resource demand estimates and will serve as a guideline for executing the project during the next stage.

During the *execution phase* of a project, the project's activities are typically executed according to the baseline schedule. However, during this phase, it is very likely certain activities of your project will not be executed according to schedule. More precisely, it is conceivable the execution of a certain activity will be subject to a cost and/or time over- or underrun. Cost and time overruns entail that the activity's initially estimated costs and duration have been exceeded during its execution. Cost and time underruns on the other hand encompass an execution of the activity resulting in lower costs and a shorter duration than initially expected.

The occurrence of these unexpected events will significantly influence the project's performance, impacting various aspects such as time, costs and specifications. When your project appears to perform better than you expected in advance, there is no need to intervene. But when those unexpected events have a disadvantageous effect on your project and its performance, which will most likely be the case, corrective actions might be required to bring your project back on track to reach its objectives. This process of monitoring your project during its execution and taking corrective actions when necessary is called project control.

In the current project management framework, a variety of control approaches can be used to control a project on the activity level. These approaches range from having a top-down (corrective actions based on general aggregated performance metrics which need to be further investigated to detect problems at the activity level) to a bottom-up (corrective actions based on constantly available detailed information on the activity level) control approach and are summarized in Figure 1.1

(Colin & Vanhoucke, 2015).

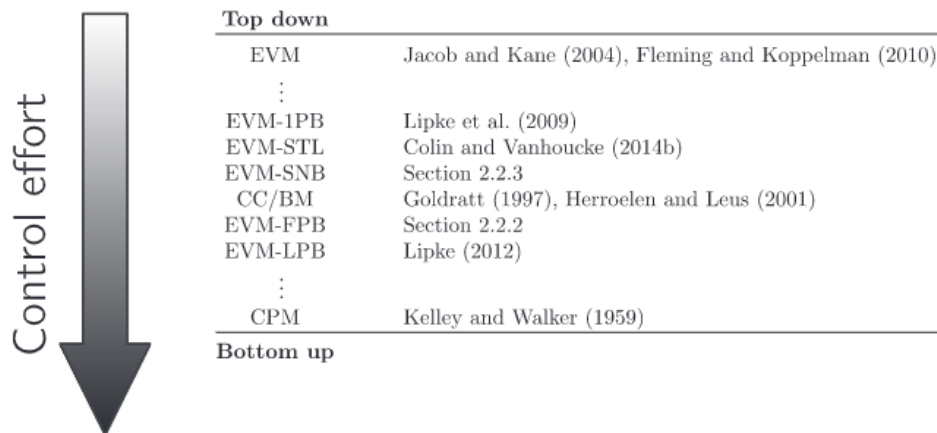


FIGURE 1.1: Activity Level Control Approaches

All these control approaches start from the assumption that project cost overruns and/or delays are caused by the variability in the actual activity duration and therefore the corrective actions are focused on the activity level.

However, variability on the activity level is not the only source of variability that should be taken into account while controlling a project. There is also a second source of variability, resource variability, that can cause your project to be executed differently than expected.

The current literature regarding control approaches at the resource level however is very limited and no clear resource level control approach has been developed yet. Therefore the major challenge of this Master's dissertation will be to create a model/heuristic that will enable us to model the resource uncertainty and will allow us to control a project and take appropriate corrective actions on the resource level. How this heuristic will look will be described in this dissertation.

Designing this heuristic for a resource level control approach will be the first major step in this research. Thereafter the performance of that heuristic will have to be validated and compared with the effectiveness of activity level control approaches by making use of a simulation experiment. More precisely, I chose to compare my heuristic with the Earned Schedule control approach developed by Lipke (2014).

In the last stage, *the evaluation stage*, the project's actual performance in terms of cost and duration (or any other objective) will be compared to its planned performance according to the baseline schedule. If a project has been executed at a lower cost than planned and/or has finished within its scheduled deadline, the project execution is regarded as being successful. However, when your actual costs/duration exceed their foreseen estimates, the project can be classified as underperforming.

As explained earlier, it is the project manager's task to control a project during its execution and to take corrective actions when the project is failing to meet its targets. The effectiveness of project control will depend on both the project characteristics and the choice of the control method and its related corrective actions. Identifying optimal combinations of certain project characteristics and the most suited control approach/corrective action will be a major goal of this dissertation.

The outline of this paper is as follows. Section 2 presents an extensive literature review providing insights into the different determinants of activity and resource level variability and covers the existing Earned Schedule activity level control approach. Further on this section elaborates on the constructed resource level control approach and identifies appropriate corrective actions that can be taken to rectify any deviations and bring the project back on track. This section concludes with a short representation of the organizational practicalities regarding the implementation of a resource level control policy. In Section 3, a classification tool for distinguishing between critical and less critical resources and activities will be explained. Further, a more detailed description of the corrective actions that will be utilized in my experiments, at both the activity and resource level control approach, will be provided. The main components of the simulation model will be covered in Section 4. More precisely, the different project characteristics that can potentially influence the effectiveness of a specific control approach will be identified, the different steps of the simulation procedure are deployed and a set of initial hypotheses regarding the performance of both control approaches will be given. The results of the computational experiments are presented in Section 5 and Section 6 provides some (intermediate) conclusions and identifies potential areas for future research.

2 Literature Review

This section will be subdivided into three subsections. The first subsection, subsection 2.1, starts with summarizing and quantifying the primary sources of variability on the activity and resource level. Those variability sources will be derived from both the current literature and some own findings. Subsection 2.2 provides a summary of the control methods for controlling a project at both the activity and resource levels. Especially the resource level control method, developed specifically for this study, will appear to be a critical element for this research. In subsection 2.3 some corrective actions related to the variability sources for both activities and resources will be discussed together with their hypothesized impact on the project objectives.

The first two subsections also include a brief and clear summary as they will be the main input for my experimental design. As you will be able to read, the main focus of my literature study was to identify the major sources of variability and the related possible corrective actions on the resource level as this topic is much less known and covered in the current project management framework.

2.1 Sources of variability

A project activity is characterized by at least its activity duration, resource consumption and precedence relationships. For each of those three characteristics, estimates will have to be made before the project is executed. In the best case, these estimates are a good representation of the actual value for those activity characteristics. Due to a project's uniqueness and unpredictability, it will be very rare that actual values for the activity duration and resource consumption (and to a less extent the precedence relationships) equal the scheduled value of those characteristics. This is because those activity characteristics are inherent to multiple sources of variability, which will impact the actual values associated with those three parameters.

In the next two parts, the main sources of variability for both the activities and resources are discussed based on a rather narrow literature study complemented by some own intermediate findings. The sources related to variability in the precedence relationships will not be covered in this paper as this source of variability is often rather small and depends on activities that were not planned before project execution and/or activities delivering low-quality performances and so require rework and or additional activities.

In the last part, many of those sources will be combined into different categories depending on their hypothesized impact on a project and its objectives.

2.1.1 Activity variability

The main sources of activity variability can be categorized into three main categories (Atkinson et al., 2006):

1. Variability related to **activity duration**
2. Variability related to **activity costs**
3. Variability related to **activity quality**

The first category will be of main interest to my research as managing this source of variability is the main tool for a project manager to control a project. Moreover, costs and the related cost variability of a certain activity are often closely interconnected with the activity duration. This interdependency will be explained further on in this report in the light of the corrective action of activity crashing.

The variability related to **activity durations** can be explained by multiple factors (Vanhoucke, 2013, pp. 189–193), :

- *Bad estimates*: assuming that activity durations are deterministic will typically have a detrimental effect on your project objectives. As explained earlier, your activity durations will be subject to a lot of variability sources and so it is more appropriate to use stochastic activity duration estimates to schedule and track your project.

One way to extend this deterministic approach and to incorporate the uncertainty regarding the activity durations is the Program Evaluation and Review Technique (PERT) method (Roman, 1962). PERT assumes that 3 estimates regarding a project duration should be made by someone familiar with the corresponding activity. The three duration estimates that should be made are:

1. Optimistic time estimate: assuming optimal conditions and that everything goes perfectly, what is the shortest possible duration in which the activity can be executed? (a)
2. Realistic time estimate: assuming normal conditions, what is the most likely time in which the activity can be executed? (m)
3. Pessimistic time estimate: assuming a worst-case scenario, what is the longest possible activity duration? (b)

PERT then assumes your actual activity duration will follow a beta probability distribution and will lie in between the extreme points a and b. However, to capture the fact that the realistic activity duration will have a higher probability to occur than the other two estimates,

the following formulas are used to capture the expected time duration t and the standard deviation of the activity duration σ :

$$t = \frac{a + 4m + b}{6} \quad \text{and} \quad \sigma = \frac{b - a}{6}$$

However, the big problem with this approach is that it still largely depends on making time estimates by a single person. Even if that person would be willing to make an appropriate estimate, it is almost impossible to incorporate every source of variability into your estimates. Therefore people often tend to make over-optimistic or -pessimistic activity duration estimates and this tendency can even be reinforced when people have the incentive to make either more optimistic or more pessimistic estimates. Some of those incentives are explained in the subsequent activity duration variability sources.

- *Parkinson's law*: a frequently occurring problem when estimating activity durations is the Parkinson's law problem. This problem is caused by an incentive mismatch between the executors and the owners of a project. In many projects, the project owners will set a certain due date or milestone regarding the finish times of individual activities and/or the project. This entails that early finishes of activities will not be rewarded, but a late finish will be highly undesirable. This will in its turn cause the activity executors to not pass their work on to a successor activity when they finished the activity before its deadline. Instead, they will add some unnecessary features to the activity that they would not have performed if they managed to only finish the execution of their activity close to or on the due date. They will do this because they are not rewarded for early finishes, but when they would pass their activity earlier than the due date, they risk having narrower deadlines for their future activity executions and/or they will be assigned new work immediately. This process of *expanding your work to fill the allocated time* is called the *Parkinson's law*.
- *Student syndrome*: a third possible undesirable trend in the estimation of activity durations is called the student syndrome. The term comes from the well-known student behaviour of postponing their work until its deadline approaches. So we can describe the *Student syndrome* as *waiting to perform activities until they get really urgent*.

Both Parkinson's law and the student syndrome will mostly occur in projects that include deterministic schedules with some in-built safety time buffers and milestones to evaluate the performance of the project workers. Those two laws will cause your project workers to deliberately over-estimate the activity durations while knowing those activities could hypothetically be performed more rapidly. Especially the student syndrome will regularly cause delays in your project as workers will use all the safety time included in the activity duration estimates by delaying their work. So when an unexpected problem occurs while performing an activity, this will directly cause delays in your activity, its successor activities and the final project completion as no positive schedule variations will probably compensate for this. In

the end, the project workers will include even more safety time in their future time estimates causing your estimates to be even more unreliable and uncertain.

- *Multiple parallel paths*: when you combine a project network consisting out of multiple parallel paths of activities (that diverge and join at different places) and your activities have predominantly finish-start precedence relations (i.e. the next activity can only start when the latest of its predecessor activities has been finished), a delay in one single activity will directly cause your project to finish late.
- *Multitasking*: this is the concept of performing multiple project activities at the same time. Multitasking is often considered a good method of improving your efficiency as it ensures that everyone is busy at all times. However, this can also have detrimental effects on activity durations in two different ways. First of all, working partly on two different activities will cause at least one of your activities to be finished much later than when you would finish the two activities sequentially. As you can see in Figure 2.1, the total duration of activity 1 (and also 2) is much longer when you multitask between the two activities compared to executing both activities after one another.

A second drawback of multitasking is the fact that by repeatedly alternating between two or more activities, you will always have to incorporate some set-up time in the activity duration as the worker will need some time for physical transportation, adjusting machines, . . . This will again cause your activity durations and uncertainty to increase unnecessarily.

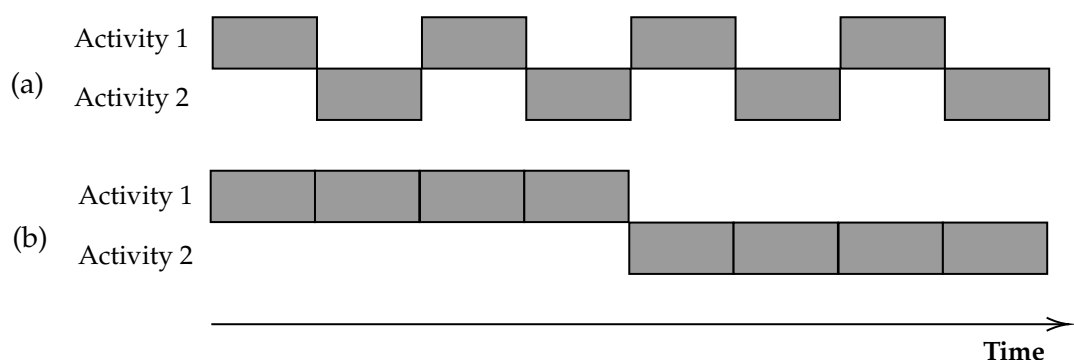


FIGURE 2.1: Execution of 2 activities with (a) and without (b) multitasking

For the remainder of my thesis I will make an abstraction of these factors and just generalise them all together as 'activity duration variability' to be able to focus on the main goal of my research.

The third source of variability, variability related to **activity quality**, is probably less controllable by the project manager and depends on the characteristics of the manual operator and/or the production machine performing a certain activity and therefore being responsible for the delivered

quality. Investigating this source of variability in this research would lead us too far from the main objective but this could certainly be a starting point for future research.

Activity's riskiness

When one wants to assess the riskiness of an activity, one cannot only rely upon its variability. Activities with a lot of variability but with a rather small possible impact on a project objective will not be regarded as a critical activity (i.e. an activity with a high risk). According to Madadi & Iranmanesh (2012), the riskiness of an activity depends both on its likelihood of exceeding its expected duration and its possible impact on the project objective.

We will have to understand and model those two dimensions to assess the risk of an activity.

- *The likelihood of exceeding the expected duration* can be characterized by probability density functions that represent the probability an activity will be executed in less than a predetermined amount of days/weeks.... I will further discuss the different possible probability functions in Section 3.1.1.
- *The impact* an activity can have on the project duration can be measured by its total expected float together with a parameter that represents the morphological structure of an activity in a project network. How I will do this is again further explained in Section 3.1.1.

Next to the information I found in the current literature, I also came up with some other sources of activity variability:

- Adding activities to the project network during the execution phase
- Rework
- Positive bias towards the mean activity duration
- Machine failures/ operators absenteeism
- Learning effects
- Machine performance degradation

This list of other possible activity variability sources is neither exhaustive nor mutually exclusive. For the remainder of this paper, I will again make an abstraction of all these different sources.

2.1.2 Resource variability

Resources are defined by Sheppard (1995) as “anything the firm receives in an exchange and uses as inducements to influence those with whom the firm has a relationship”. Vanhoucke (2013, p. 110) identifies three types of resources:

1. **Renewable resources:** resources that are constrained at each time period
2. **Non-renewable resources:** resources that are constrained over the project duration
3. **Doubly-constrained resources:** resources that are constrained both at each period and over the project duration

In my research, I will focus on renewable resources as those are the resources that have to be allocated over the different activities each time period and this allocation will have an impact on the project complexity and the final project objective. The major significant factors impacting the resource variability according to Sheppard (1995) are shown in Table A.1 in Appendix A.

All those factors do not seem very relevant for this research at first sight but they are still included as they explain for a large part how easily certain firms can get access to new resources if needed and at which cost.

Using all those factors would be impracticable and this is why I decided to first combine these factors in more broad resource uncertainty classes. Thereafter I will merge those uncertainty classes into one or more constructs which will determine a firm's ability to deal with resource variability. This approach will be explained in the next section.

2.1.3 Summary

In this summary section, I will combine all the different sources of variability on both the activity and resource level into more broad constructs based upon their hypothesized impact on the different project objectives (+ = positive effect, 0 = neutral effect, - = negative effect). In Tables 2.1 and 2.2 and you can find the hypothesized impact of the activity and resource variability on the minimised project time objective. Some of these hypotheses will be tested during the simulation experiments.

Minimizing the total project duration is probably the most important objective during the scheduling phase but multiple other project objectives can be followed. A list of the most widely used project objectives together with a short description is given below (Vanhoucke, 2013, pp. 111–124):

- **Time Minimization:** the objective of minimizing total project duration is by far the most widely used objective in reality and does not need a lot of further explanation. It just entails that, during the scheduling phase, you will try to schedule your project activities such that the total expected project duration is minimized while also satisfying the precedence relation constraints and avoiding any resource conflicts (i.e. the total resource use at a certain point in time is never higher than the resource's actual availability). This scheduling approach is known as the *Resource-Constrained Project Scheduling Problem*
- **Cost Minimization:** a second possible objective a project manager can pursue is minimizing the total cost related to the project's execution. These costs include both the activity and

Variability source	Variability class	Project mean duration	Project duration variability
The use of estimations for the activity durations	Activity duration (natural) variability	0	-
Positive bias towards the mean activity duration			
Unexpected and unplanned activities showing up	Project network variability	-	-
Rework			
Machine failures/ operator absenteeism			
Learning effects	Activity duration improvements	+	0
Multiple operators working parallel on the same activity			
Machine performance degradation	Activity duration increases	-	0
Fatigue among operators			

TABLE 2.1: Hypothesized impact of activity variability factors on minimize time objective

Variability source	Variability class	Project mean duration	Project duration variability
Late delivery of a resource	Resource scarcity/ unavailability	-	0
Stock-out of a resource			
Industry profitability			
Industry growth rate			
Industry instability			
Number of director interlocks	Influence by resource providers	-	0
Percentage of outside directors			
Joint ventures			
Firm size			
Diversification	Environmental buffering	+	+

TABLE 2.2: Hypothesized impact of resource variability factors on minimize time objective

resource costs. The activity costs in their turn exist of a fixed cost (a cost that will be included regardless of its duration and use of resources) and a variable cost (a variable amount of money that depends on the activity duration). The resource costs on the other hand include both a cost per use (a one-time cost that is incurred every time the resource is being used by an activity) and a cost per unit (a cost that will depend upon the amount of the resource

used by the activity). Minimizing all those costs typically boils down to a trade-off between time and cost. This time/cost relation can be both linear (Figure 2.2a) or discrete (Figure 2.2b) but always entails that shorter activity durations correspond with higher related costs. This trade-off will typically result in an increased project duration when following a cost

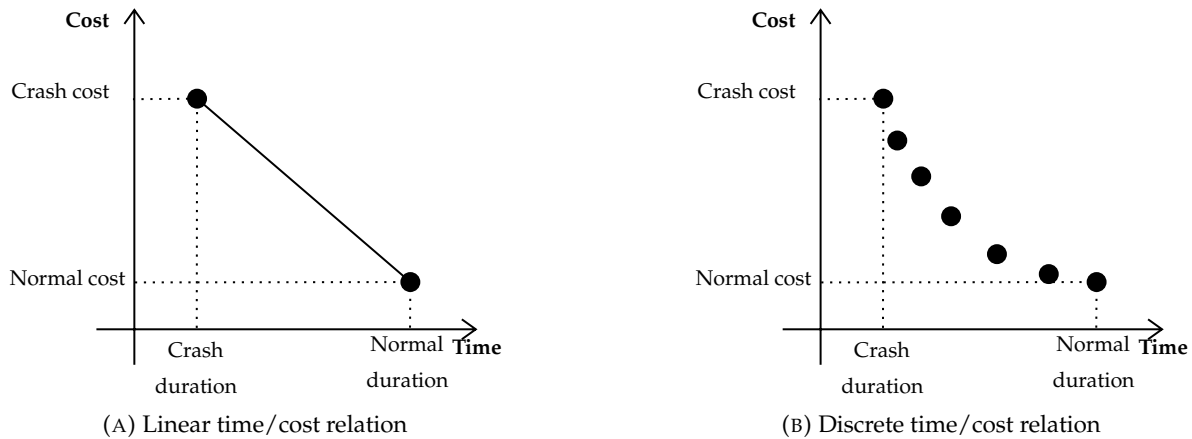


FIGURE 2.2: Time/cost relations

minimization objective than when your objective is to minimize time. This is closely related to the corrective action of activity crashing: performing an activity more quickly is often accompanied by higher costs. As you can see in Figure 2.2, there are different activity modes ranging from the crash mode (with the shortest duration but the highest cost) to the normal mode (lowest cost but longest duration). So when your objective is to minimize costs this will typically cause your project duration to increase. For the hypothesized impact of the different activity and resource variability sources on the minimizing cost objective, I refer to Tables B.1 and B.2 in Appendix B.

- **Maximize Net Present Value:** this third objective will allow a project manager to take into consideration the financial aspects of the project. The principle behind this objective is very simple: reject the project if the NPV is smaller than zero and accept the project if the NPV is larger than or equal to zero. The scheduling approach of maximizing your NPV without violating any of the precedence and resource constraints is called *Resource-Constrained Project Scheduling Problem with Discounted Cash Flows*. Providing formulas on how to calculate the NPV of a project would be out of this dissertation's scope.

Maximizing your project's NPV actually corresponds with scheduling activities with positive cash flows (i.e. incoming cash flows) as early as possible and delaying activities with negative cash flows (i.e. outgoing cash flows) as much as possible. For the hypotheses regarding the impact of the activity and resource variability factors, I refer to Tables B.3 and B.4 in Appendix B.

- **Resource levelling:** this fourth objective differs from the three previous ones by the fact that the three previous objectives do not take into account the pattern of total resource use over time. This often results in very irregular patterns of resource use with alternating peaks and lows. In reality, however, it can sometimes be infeasible, impracticable or very time-inefficient to constantly hire and fire resources during the project's execution. This is why this fourth scheduling approach, called the *Resource-Levelling Project Scheduling Problem*, aims to construct a schedule that is both precedence- and resource feasible, takes into account a predefined deadline and balances the use of all resource types over the total schedule horizon. Often this scheduling approach is also constrained by a maximum resource availability for each resource type. The hypothesized impact of all the variability factors are displayed in Tables B.5 and B.6 in Appendix B. To measure the performance of a resource levelling schedule, the sum over all periods of the (squared) differences between the mean resource use and the actual resource use is used.
- **Optimize work continuity:** all previously discussed project scheduling objectives resolved resource conflicts by shifting activities in time. This results in a schedule that will comply with the resource availability constraints. However, they do not try to schedule activities that use the same resource type together resulting in certain resources that will have a high amount of idle time. When you want to minimize the idle time of resources, the optimizing work continuity objective comes into play. Some situations in which this objective is appropriate are when your project makes use of spatial resources (i.e. a resource type that is required by a group of activities and not by a single activity) and/or time-dependent cost resources (i.e. the project cost increases significantly with the duration of usage of a resource type). The scheduling approach that aims to optimize the work continuity is called the *Resource-Constrained Project Scheduling Problem with Work Continuity Constraints* and the hypothesized impact of the activity and resource variability factors on this objective are summarized in Tables B.7 and B.8 in Appendix B. The performance of a schedule aiming to optimize work continuity is measured by the total amount of resource idle time.

2.2 Control Methods

Project control can be described as the process of continuously (or at least at regular time intervals) monitoring your project during its execution and taking corrective actions when necessary. Corrective actions are certain measures you can take in case your project does not perform as you expected it to perform, mostly leading to time- and/or budget overruns. The different types of corrective actions and their corresponding (hypothesised) impact on the project objectives will be discussed in the next section.

In this section, I will mainly discuss which specific performance measures, both on the activity and resource level, you should keep track of to assess the performance of your project relative to its objectives. Selecting the right measures to monitor and setting appropriate thresholds for those measures will be critical for the results of my research.

2.2.1 Activity level

To control my project on the activity level I will make use of the Earned Schedule method created by Lipke (2014). This control method has appeared to be effective and efficient in controlling projects and will serve as a good reference point to compare the resource level control method.

The Earned Schedule control method is based upon Earned Value Management methodology described by Fleming & Koppelman (2016). This EVM methodology has appeared to be very practical in measuring and communicating the real physical progress of a project and integrating the three major elements of managing a project (scope, time and cost management). However, this methodology also suffers from one major drawback: its quirky behaviour towards the end of a project. The performance measure Schedule Variance (SV) is calculated in such a way that at the end of the project, it always indicates your project has been finished on time regardless of the real time performance of your project. This will, first of all, cause your final assessment to be over-optimistic, but secondly, it will also cause your variance performance metric SV to tend to zero towards the end of the project (it will start when more or less 50% of your project has been executed) resulting in a very unreliable metric.

This unreliability in the EVM performance measure is the reason why I will opt for the Earned Schedule control method designed by Lipke (2014). This method keeps track of a set of parameters calculated before and during the project execution.

The following parameters will be calculated before project execution:

- *Planned Duration (PD)*: the expected total project duration calculated based upon the constructed baseline schedule.
- *Budget At Completion (BAC)*: this is the sum of the budgeted costs for all individual activities. In my research, this BAC will be calculated by summing the fixed activity costs of all

activities and the cost related to the available resources. This second type of cost will be determined by the available quantity of each resource and not by the actual consumed quantity. I decided to also include unused resources in the BAC calculation to provide a more comprehensive and accurate estimation of the total project costs. This decision was based on the fact that various resource types, such as manpower, leased machines, borrowed funds, ... still incorporate a cost for the company irrespective of whether they are used in the project execution or not. In this way, it is acknowledged that certain resources may stay unused but still contribute to the resource's and project's total cost.

So the total cost of a specific resource i is calculated by multiplying the sum of the resource's availability in each time period and the resource's unit cost, as shown in Equation 2.1.

$$BAC_i = c_i \times \sum_{t=1}^{PD} a_{i,t} \quad (2.1)$$

with $a_{i,t}$ = total amount of resource type i available in time period t

c_i = cost of using 1 unit of resource type i for 1 period of time

The BAC of the project can then easily be calculated by taking the sum of each resource's budget at completion and adding the activity's fixed costs.

Parameters that will be calculated and tracked during project execution:

- *Actual Duration (AD)*: the number of time periods the project has been running at the current time instance.
- *Planned Value (PV)*: the budgeted cost of work scheduled. This is just taking the sum of the scheduled costs related to each activity that should have been executed according to your baseline schedule.
- *Actual Cost (AC)*: the real cost of the activities that have been executed at the current time instance.
- *Earned Value (EV)*: budgeted cost of the work performed. This is just the sum of the budgeted cost of the activities already executed at the current time instance and can be calculated using the formula:

$$EV = PC * BAC \quad (2.2)$$

with PC being the percentage activity or project completion. Note that this EV parameter will not be used directly to control projects because of its quirky behaviour, but it will be necessary for calculating the Earned Schedule parameter and some performance measures as will be shown in the remainder of this section.

- *Earned Schedule (ES)*: the PV and EV are used to keep track of the cost performance of the project while the ES is the EV equivalent for measuring a project's time performance. Calculating the ES can be done by finding a t such that $EV \geq PV_t$ and $EV < PV_{t+1}$. Based on this value for t the ES parameter is calculated by interpolating between PV_t and PV_{t+1} using the formula:

$$ES = t + \frac{EV - PV_t}{PV_{t+1} - PV_t} \quad (2.3)$$

A set of performance measures will be calculated using the three key parameters PV, AC and EV/ES:

- **Variances**: both the project time and cost performance measures will be determined by comparing the three key parameters in absolute terms.
 - *Schedule Variance with Earned Schedule (SV(t))*: this performance measure measures the project time performance in absolute terms and is calculated using Equation 2.4 :

$$SV(t) = ES - AD \quad (2.4)$$

If this parameter is greater than, equal to or smaller than zero, the project is ahead of, on, or behind schedule respectively.

- *Cost Variance (CV)*: this measure is used to measure the project cost performance and is calculated similarly to the SV(t) performance measure:

$$CV = EV - AC \quad (2.5)$$

A project has a budget underrun and overrun when the CV is greater than and smaller than zero respectively. When the CV is equal to zero, the project is right on budget.

- **Indicators**: because the variances are measured in absolute terms and their values depend upon the measurement units, it is often difficult to compare the performance of two different projects. This is why the indicators measure a project's time and cost performance in relative terms (which are both unitless).
 - *Schedule Performance Index with Earned Schedule (SPI(t))*: the SPI(t) measures the project time performance in relative terms and is calculated using Equation 2.6.

$$SPI(t) = \frac{ES}{AD} \quad (2.6)$$

An SPI(t) greater than one indicates a project ahead of schedule, smaller than zero indicates a project delay and a value equal to zero entails a project on schedule.

- *Cost Performance Index (CPI)*: the CPI is similar to the SPI(t) but it measures the relative cost performance of a project. The formula to calculate the CPI is displayed in Equation

2.7.

$$CPI = \frac{EV}{AC} \quad (2.7)$$

A CPI greater than, equal to and smaller than 1 indicates a budget underrun, a project on budget and a budget overrun respectively.

Parameters calculated after the project completion:

- *Real Duration (RD)*: the effective real duration of the project.
- *Real At Completion (RAC)*: the effective real project costs.

To track the behaviour of a project and to take corrective actions when necessary, all the parameters and performance indicators will be calculated and evaluated during each time period over the entire time horizon. Based upon the performance measures SV(t), CV and mainly the SPI(t) and CPI and based upon the activity criticality (see Chapter 3), the project manager will be able to decide whether or not to take any corrective actions on the activity level and if so, which activity will be suitable for corrective actions taking.

2.2.2 Resource level

A method to control a project on the resource level has not been discovered in previous research papers and will surely be the most challenging and innovative part of this Master's Dissertation. Based upon an extended literature review in which I compared a lot of different control approaches, although they were all designed to control a project on the activity level, I came up with the following model.

The resource control method I designed is to a large extent based on the Earned Schedule method as this method is currently the most effective control method available in the project management framework. I adapted this Earned Schedule method using some insights from the SPIwc performance measurement indicator (Martens & Vanhoucke, 2017). This new performance measurement indicator was constructed to integrate constrained resources into top-down project control and was a major source of information for constructing a resource level control method.

The following parameters will be calculated before project execution:

- *Planned Duration (PD)*: the expected total project duration calculated based upon the constructed baseline schedule (same as on the activity level).
- *Budget At Completion (BAC)*: summing the fixed activity costs of all activities and the cost related to all resources involved in the project (same as on the activity level).

- *Work Content At Completion (WCAC)*: summing the total planned work content related to each resource involved in the project.

The work content of resource type i can be calculated using Equation 2.8.

$$WCAC_i = \sum_{j=1}^J D_{j,i} \times d_j \quad (2.8)$$

with $D_{j,i}$ = resource demand of activity j for resource i
 d_j = planned duration of activity j

Again the project's WCAC can be calculated by taking the sum of each resource's WCAC

Parameters that will be calculated and tracked during project execution:

- *Actual Duration (AD)*: the number of time periods the project has been running at the current time instance.
- *Planned Work Content_i (PWC_i)*: planned consumed work content of resource type i at the current time instance.

This can easily be calculated by taking the sum of the work content of the activities that were planned to be (partly) executed at the current time instance. If the activity is only partly executed at the current time instance, only the corresponding fraction of its work content should be added to the resource's planned work content.

To calculate the project's planned work content at a certain time instance, just take the sum of the work content of all resources utilized in the project.

- *Actual Work Content_i (AWC_i)*: total consumed work content of resource type i at the current time instance. Again the project's total actual work content is equal to the sum of the actual work content of all resources involved in the project.
- *Earned Work Content_i (EWC_i)*: budgeted work content of resource i of the work performed. This EWC parameter is very closely related to the EV parameter used in the activity control approach and measures the work content that should have been earned at the current time instance based on the work that was performed.

The formula to calculate the EWC of resource type i is shown in Equation 2.9.

$$EWC_i = PC_i \times WCAC_i \quad (2.9)$$

The project's EWC is just equal to the sum of each resource's EWC.

As in the case of the EV parameter, this EWC parameter will also show some quirky behaviour towards the end of the project and will always equal the (project's) WCAC upon the project's finish. This is why I will not directly use this EWC parameter in my resource level control approach, but it will be needed for calculating some other (performance) measures

- *Percentage Completion (PC)*: measures the project's progress expressed as a percentage of the work that has been executed compared to the total planned project's work.

More precisely, I will calculate the project's PC as follows:

$$PC = \frac{EWC_t}{WCAC} \quad (2.10)$$

with EWC_t = project EWC at time instance t

Based on this formula, you can see that the project's PC can only be calculated when the EWC has been calculated for each resource.

- *Earned Schedule Work Content (ESWC)*: the ES equivalent of the resource control approach. While the EWC keeps track of the project performance in terms of work content completed, the ESWC will keep track of the project's time performance. The ESWC can be calculated after finding a t such that $EWC_t \geq PWC_t$ and $EWC_t < PWC_{t+1}$ and then interpolating between PWC_t and PWC_{t+1} using the Equation 2.11.

$$ESWC_t = t + \frac{EWC_t - PWC_t}{PWC_{t+1} - PWC_t} \quad (2.11)$$

As can be derived from this set of parameters, my main focus during project execution will be on parameters related to the resource work content. Those who are more interested in parameters related to the project's cost performance can convert the work content-related parameters to cost performance parameters by multiplying the work content related to each resource by the resource cost per unit. This generates the same performance assessment as using the work content performance measures as I will assume the resource unit costs to be fixed over the project horizon. However, it enables project managers to evaluate a project's performance in terms of cost rather than work content. The conversion of work content-related measures to cost-related measures only increases effort without gaining new insights. Therefore, I will only perform this transition while calculating the variances and indicators.

Variances and indicators: these parameters can be calculated in a very similar way to those in the EV control approach.

- **Variances:** To assess a project's time and cost performance, the three key parameters PWC, AC and EWC/ESWC will be compared in absolute terms.
 - *Schedule Variance with Earned Schedule Work Content $SV_{ESWC}(t)$* : this performance measure measures the project time performance in absolute terms and is calculated using the Equation 2.12.

$$SV_{ESWC}(t) = ESWC - AD \quad (2.12)$$

If this parameter is greater than, equal to or smaller than zero, the project is ahead of, on, or behind schedule respectively.

- *Cost Variance with Earned Value Work Content* CV_{ESWC} : this measure is used to measure the project cost performance and is calculated similarly to the $SV(t)$ performance measure. However, one additional step is needed to convert EWC into an Earned Value measure. This can be done in the following way:

$$EVWC_i = EWC_i \times c_i \quad (2.13)$$

with $EVWC_i = \text{Earned Value Work Content of resource } i$
 $c_i = \text{unit cost of resource } i$

The project's Earned Value Work Content can again be found by just taking the sum of each resource's EVWC.

After this intermediate step, the following formula provides the Cost Variance:

$$CV_{EVWC} = EVWC - AC \quad (2.14)$$

A project has a budget underrun and overrun when the CV_{EVWC} is greater than and smaller than zero respectively. When the CV_{EVWC} is equal to zero, the project is right on budget.

- **Indicators:** again the variances are measured in absolute terms and so are difficult to compare over different projects. Therefore the unitless indicators will be preferred to measure project time and cost performance.

- *Schedule Performance Index with Earned Schedule Work Content* ($SPI_{ESWC}(t)$): the $SPI_{ESWC}(t)$ measures the project time performance in relative terms and is calculated using Equation 2.15.

$$SPI_{ESWC}(t) = \frac{ESWC}{AD} \quad (2.15)$$

The $SPI_{ESWC}(t)$ will differentiate between projects being finished on time or over time by having a value greater than or smaller than one respectively.

- *Cost Performance Index with Earned Value Work Content* (CPI_{EVWC}): the CPI_{EVWC} measures the relative cost performance of a project and is calculated using Equation 2.16:

$$CPI_{EVWC} = \frac{EVWC}{AC} \quad (2.16)$$

A cost overrun is indicated by a CPI_{EVWC} smaller than 1 and a cost underrun by a CPI_{EVWC} greater than 1.

Further, these indicators, together with the resource risks will allow me to execute corrective actions for the appropriate resource types when necessary.

Parameters calculated after the project completion:

- *Real Duration (RD)*: the effective real duration of the project.
- *Real At Completion (RAC)*: the effective real total cost of the project. The RAC of resource i can be calculated using Equation 2.17.

$$RAC_i = RWCAC_i \times c_i \quad (2.17)$$

Afterwards, the project's RAC follows from taking the sum over all resources' RAC and adding the fixed activity costs of the activities performed.

- *Real Work Content At Completion_i (RWCAC_i)*: the work content of resource type i used at completion. This measure can again be translated into a cost-related measure by multiplying the $RWCAC_i$ with the unit cost of resource i .

To generate the project's total RWCAC, just take the sum of each resource's RWCAC.

2.2.3 Summary

Table 2.3 represents a summary of the project parameters that will be tracked and calculated before, during and after the project execution.

	Activity level control	Resource level control
Before project execution		
Planned Duration (PD)	Expected total project duration ~calculated based upon baseline schedule	
Budget At Completion (BAC)	Sum of budgeted costs for all activities	Sum of budgeted costs for all resources
WC At Completion (WCAC)	/	Sum of budgeted work contents for all resources
During project execution		
Actual Duration (AD)	Number of time periods the project has been running	
Planned Value (PV)/ Planned Work Content (PWC)	Budgeted cost of performing scheduled activities	Budgeted work content of all resources for performing scheduled activities
Actual Cost (AC)/ Actual Work Content (AWC)	Real cost of activities executed	Real work content consumed of all resources

Earned Value (EV)/ Earned Work Content (EWC)	Budgeted cost of activities performed	Budgeted work content of all resources consumed for activities performed
Earned Schedule (ES)/ Earned Schedule WC (ESWC)	$t + \frac{EV - PV_t}{PV_{t+1} - PV_t}$	$t + \frac{EWC_t - PWC_t}{PWC_{t+1} - PWC_t}$
Earned Value WC (EVWC)	/	$EVWC_i = EWC_i \times c_i$
Performance measures during project execution		
Schedule Variance with - Earned Schedule (SV(t)) - Earned Schedule WC (SPI _{ESWC} (t))	ES - AD	ESWC - AD
Cost Variance (CV / CV _{EVWC})	EV - AC	EVWC - AC
Schedule Performance Index with - Earned Schedule (SPI(t)) - Earned Schedule WC (SP _{ESWC} (t))	ES/AD	ESWC/AD
Cost Performance Index (CPI/CPI _{EVWC})	EV/AC	EVWC/AC
After project completion		
Real Duration (RD)	The effective final project duration	
Real At Completion (RAC)	The effective costs of activities executed	The effective costs of resources consumed
Real WC At Completion (RWCAC)	/	The effective amount of consumed work content for all resources

TABLE 2.3: Project control parameters

2.3 Corrective actions

Taking corrective actions during the project execution stage will be necessary to bring the project back on track and to meet its predefined objectives in case the project seems to exceed its planned duration and/or budgeted costs. Determining when to take corrective action will be done during the control phase as explained earlier. In this section, a summary of all the corrective actions that can be taken on the activity and resource level will be given. Note that these actions are closely related to the sources of variability.

2.3.1 Activity level

Corrective actions on the activity level are widely discussed in the literature and so there is no need to develop new corrective actions myself. The most important actions that can be taken are summarized below:

- **Activity crashing:** reducing the activity durations, often linked with a cost increase (Vanhoucke, 2012). This will have an impact on the mean activity and project duration, not on the related duration variability.
- **Fast tracking:** parallel execution of precedence related activities. Same effects as activity crashing.
- **Activity variability reduction:** to reduce the variability of your activities, you should first determine which activities are critical for the project and which amount of effort that should be assigned to control them, thereby completing the project successfully. By increasing your effort for a particular activity, its variability is assumed to decrease and the costs to increase (Creemers et al., 2010). Reducing the variability in the activity durations will be done in practice by adjusting one of the parameters constitution the *MOI2* (Section 3.1.1) during project execution.

2.3.2 Resource level

On the resource level, the number of corrective actions described in the literature is less numerous than for corrective actions on the activity level. This is why I mainly focused on how businesses do take corrective actions in practice and I came to the following results:

- **Increasing the availability:** enlarges the available pool of a certain resource type. This will cause some activities with resource conflicts to be executed in parallel instead of in series (if this does not violate the activity precedence relationships) and will in this way be able to reduce the expected project duration. Increasing the availability is also closely linked to the activity crashing action discussed earlier.

- **Reducing the resource risk:** to reduce the risk of your resources you should address one of the factors contributing to a resource's risk. Further details on this approach will be provided in Section 3.1.2.
- **Reducing the probability of failure:** lowering the likelihood that one of your resources will fail.
- **Resource firing:** if the total activity's resource demand for a certain resource type never exceeds or approaches the availability of that resource type, firing some of those resources could lead to a cost reduction without impacting your project objectives (Al-Jibouri, 2002). These cost savings in their turn can allow the project manager to invest in other resource types, which have a higher utilisation than the fired resource, and in this way, you can finish the project sooner without violating the budget constraints.
- **Resource reallocation:** when a critical activity requires a specific resource type that is unavailable at the planned start of this activity, the project manager can deal with this problem in two different ways. Either he can just leave that critical activity idle until the resource becomes available again or he can interrupt a non-critical activity that is utilizing the same resource type and reallocate this resource to the critical activity. Making the appropriate decision will largely depend on the criticality of the activity but also the resource's riskiness.
- **Resource boosting:** when a project is underperforming and seems to miss its intended targets, project managers can decide to apply a "whatever it takes" policy for a short duration of time. During this time frame, the project manager will make sure that the supply of each resource is set to such a high degree that the project execution will not be constrained by its resources. In this way, the project is only constrained by its activity precedence relations and so more activities can be performed than was scheduled beforehand (on the condition that a parallel execution of non-related activities was restrained by the resource availability). After this short time frame, the project is assumed to be back on track and the normal resource availabilities can be reset.
This corrective action can be observed empirically when a company decides to make its employees work one or more weekends on an exceptional basis to catch up with an elevated demand.

Determining when corrective actions should be taken both on the activity and resource level, will be done by setting a certain threshold. For the activity level, this threshold will be applied to the SPI(t) and CPI values. On the resource level, on the other hand, the thresholds will be applied on the SPI_{ESWC}(t) and CPI_{ESWC} measures. The exact values for those threshold parameters will be determined by a short simulation study which will be explained in Section 4.2.2.

2.4 Practical implementations for the organization

Implementing a resource level control approach will involve several practical implementations that differ from an activity level control implementation. Controlling a project on the resource level will require a project manager, more than in an activity level control approach, to reflect on the required resource types for executing all project's activities, the initial resource availabilities, new control mechanisms for tracking the project such as performance measurement parameters and corrective actions,...

The complexity of this task is even more increased by the wide variety of resource types. These can include physical assets (e.g. machinery, equipment), intellectual resources (e.g. patents, copyrights), human resources (e.g. labour, skills) and financial resources (bank loans, equity capital) (Daou et al., 2020). All these types of resources can be required for executing a project and therefore need to be managed carefully by a project manager. One of the key organisational requirements for a firm to be able to execute a resource level control policy is to have access to flexible resource sources.

This takes us to the concept of a supply chain which can be defined as "encompassing every effort involved in producing and delivering a final product or service, from the supplier's supplier to the customer's customer" (Lummus et al., 2003). This includes managing supply and demand, sourcing raw materials, manufacturing, assembly, warehousing, inventory tracking, order entry and management, distribution across different channels and delivery to the customer. All these functions are usually distributed across different organisations resulting in a supply chain as shown in Figure 2.3. Here we can see that each supply chain's entity performs the role

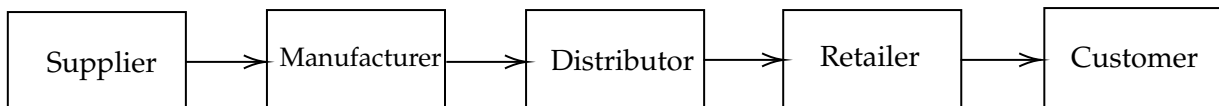


FIGURE 2.3: Supply chain

of being a customer (i.e. receiving required resources from its direct and indirect suppliers) and a supplier of its direct and indirect customers. Each entity will transform its inputs into outputs by adding customer value. This transformation will usually require many projects and activities and therefore a resource level control approach can be deployed at each entity.

For each entity to be able to maintain a resource level control approach, a flexible resource provision from its direct supplier is required. Therefore installing a resource level control approach for one entity's processes will require effort from all its predecessors. Consequently, a flexible resource supply for one entity will require an entire flexible supply chain which extends the entity's internal flexibility. Vickery et al. (1999) defined five elements to transform a supply chain into a flexible one :

- *Product flexibility*: "the ability to handle difficult, nonstandard orders; to meet special customer specifications; and to produce products characterized by numerous features,

options, sizes or colours ". This entails that a firm should have access to very specific resources when applying a resource level control approach. Suppose for example a firm wants to reallocate its resources from a less critical to a more critical activity. In this case, its supplier should be able to provide resources that are very firm-specific as they need to be able to serve two specific activities. This will usually involve some more customization than the standard resource product.

- *Volume flexibility*: "the ability to rapidly adjust capacity to accelerate or decelerate production in response to changes in customer demand". When a firm decides to increase the availability of one of its resources, it should be able to receive the additional required amount within a relatively short time frame. This requires its supplier to be able to adapt its capacity in a flexible way to produce the new resource demand from its customer.
- *New product flexibility*: "the ability to rapidly introduce large numbers of product improvements/ variations or completely new products". A firm that wants to improve its resource quality to reduce the resource demand from its activities, will probably demand more innovative and complicated resources from its supplier. This will in its turn require the supplier to have an R&D department that can effectively revise and improve its product in a short period of time.
- *Distribution flexibility*: "the ability to effectively provide widespread and/or intensive distribution coverage". When a firm wants to execute a resource boosting action, it will require a large number of additional resources within a short time frame. So its supplier should not only be able to produce these additional amounts (*volume flexibility*), but also to deliver these newly demanded resources to its customers. For this, a flexible distribution mechanism will be required.
- *Responsiveness flexibility*: "the ability to respond to the needs and wants of the firm's target market(s)". A supplier possessing the four previous flexibility items will only end up being a flexible supplier when he can rapidly handle these items. A firm asking for an increased quantity of a certain resource type will often only need these resources if they can be supplied almost immediately, without long replenishment lead times.

Based on these flexibility types, we can conclude that transforming a supplier into a flexible supplier and therefore enabling effective use of the resource level control approach, is not an easy task and will require a firm to completely change its business model. Further on, the specific implementation of a resource level control approach will vary depending on the organization, industry, and context. Therefore the implementation should be adapted to suit the unique needs and requirements of your organization and the supply chain your organization is operating

3 Research methodology

In this chapter, I will explain the most important elements of the methodology I will apply to compare the performance of an activity level control approach with a resource level control approach. As explained earlier, the current literature and project management framework mainly focus on activity duration variability and its corresponding corrective actions. Therefore, I will make use of the currently available project control approaches and corrective actions regarding activity level control. For the resource level control, however, I use the project control approach described in the previous section.

This chapter will start by describing two classification tools, one for the activities and one for the resources, that will allow me to differentiate between activities (resources) that have a high risk for the project and activities (resources) that are less risky. Thereafter I will elaborate on the types of corrective actions I will make use of to bring a project back on track.

3.1 Classification tools

The main purpose of the classification tools I will discuss here is to allow me to differentiate between critical activities and resources (i.e. that can possibly have a huge impact on the project objective) and less critical activities and resources. Making this distinction will appear to be crucial during the project control phase to decide upon which activities/resources I should take corrective action when the project is off track.

3.1.1 Activity level

According to Madadi & Iranmanesh (2012) and the well-known Pareto principle, 80% of the effects on project completion time come from only 20% of the activities. This explains why a project manager must be able to identify those 20% critical activities and focus on them during project execution. Most traditional control approaches (CPM, CC/BM,..) use the total float of an activity to assess its riskiness because they assume those durations to be deterministic. However, when the activity duration becomes stochastic, this total float value does not completely represent the total risk related to an activity. This is why Madadi & Iranmanesh (2012) came up with a new index to determine activities which deserve special attention. I think their way of thinking was very interesting but decided to make a few adaptations to their classification tool and came up with a construct that exists out of the following parameters :

- **The activity's variability:** this is represented by the standard deviation of the corresponding probability density function of the activity divided by the maximum standard deviation over all activities. There are multiple different forms to represent an activity's duration probability density function of which I will discuss three: *the normal probability function, the lognormal probability function and the probability density functions derived from generalised beta distribution family*. A visual representation of those three probability functions can be found in Figure 3.1.

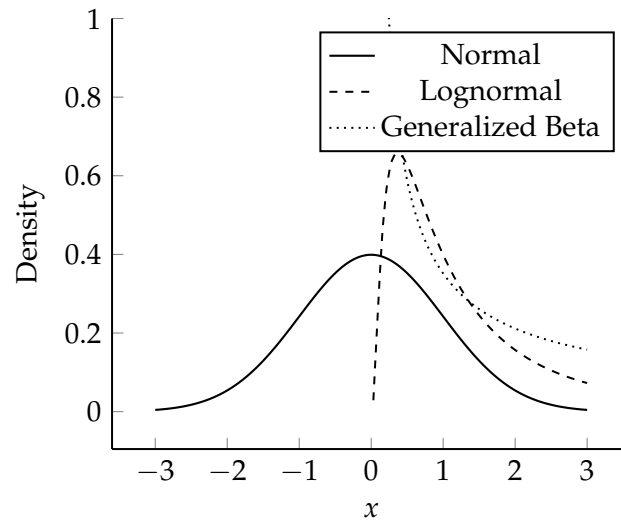


FIGURE 3.1: Probability function of Normal, Lognormal and Generalized Beta distribution

1. *Normal probability function:* this probability function is widely used in current literature to quantify stochastic activity durations (Madadi & Iranmanesh, 2012). It is a symmetrical distribution and so assumes that the probability of having a duration higher than the mean is equal to having one lower than the mean duration. This probability function is characterized using two parameters: the mean duration μ and its variance σ^2 .
A major shortcoming of this probability function is that it assumes that the probability of an activity exceeding its mean duration is equal to the probability that this activity's duration will be shorter than expected. This assumption is rather optimistic and not a good reflection of empirically found activity durations.
2. *Lognormal probability function:* to alleviate this shortcoming of the normal distribution, a skewed to the right distribution will be applied to model the activity duration distributions. As can be observed in Figure 3.1, both the lognormal and Generalized Beta distribution exhibit this characteristic of having a skewed to the right distribution. This implies that the probability of having a duration smaller than the mean duration will be lower than the probability of obtaining a duration that is higher

than the mean duration. An additional benefit of using the lognormal or Generalized Beta distribution to model activity duration uncertainty is that you can truncate the minimal duration at zero. In this way, you avoid the possibility of generating negative activity durations.

To model the lognormal distribution, I will rely on a study of Martens & Vanhoucke (2019). In their research they describe two different sets of parameters to parameterise a lognormal distribution:

- The arithmetic mean m and standard deviation s of the log-normally distributed variable
- The arithmetic mean μ and standard deviation σ of the normally distributed natural logarithms of the variable

The relation between those two sets of parameters can be modelled by Equations 3.1 and 3.2.

$$\mu = \ln \left(\frac{m}{\sqrt{1 + \frac{s^2}{m^2}}} \right) \quad \text{and} \quad \sigma = \sqrt{\ln(1 + \frac{s^2}{m^2})} \quad (3.1)$$

$$m = e^{\mu + \frac{1}{2}\sigma^2} \quad \text{and} \quad s = e^{\mu + \frac{1}{2}\sigma^2} \sqrt{e^{\sigma^2} - 1} \quad (3.2)$$

The only deficiency of using the arithmetic mean m and standard deviation s to characterize the lognormal distribution is that they are not robust parameters for skewed distributions. The arithmetic mean fails to reflect the true central tendency of the distribution since it is affected by the high values contained in the right tail of the lognormal distribution. This will cause the arithmetic standard deviation, which is a measure of the spread around the mean, to be affected as well.

Therefore it is recommended to use the robust summary statistics, the geometric mean $GM[X]$ and standard deviation $GSD[X]$ to characterize the lognormal distribution.

These statistics can be calculated using Equation 3.3.

$$GM[X] = e^{\mu} \quad \text{and} \quad GSD[X] = e^{\sigma} \quad (3.3)$$

3. *Probability density functions derived from generalised beta distribution family:* Colin & Vanhoucke (2015) modelled the activity duration variability by using these beta distributions because of their ability to accurately mimic the behaviour of the random input processes driving the system. This probability density function looks as follows:

$$\begin{aligned} f_x(x|a, b, \theta_1, \theta_2) &= \frac{\Gamma(\theta_1 + \theta_2)}{\Gamma(\theta_1) + \Gamma(\theta_2)} \times \frac{(x - a)^{\theta_1 - 1} \times (b - x)^{\theta_2 - 1}}{(b - a)^{\theta_1 + \theta_2 + 1}} & \text{if } a \leq x \leq b \\ &= 0 & \text{if } x < a \vee b < x \end{aligned} \quad (3.4)$$

with $\Gamma(\cdot)$ denoting the gamma function and θ_1 and θ_2 denoting the shape parameters.

To characterize the beta distribution for each activity duration, they make use of the following vector: $w = (a, b, m, \mu)$ with a , b , m and μ being estimates for the minimum, maximum, mode and the mean of the distribution expressed as a fraction of the baseline estimate duration d_i . For further clarification regarding to this approach, I refer to the paper of Colin & Vanhoucke (2015).

In the remainder of this paper, we will make use of the lognormal probability function to generate random activity durations. In this way, we make the reasonable assumption that people often tend to come up with rather optimistic activity duration estimates. This causes the probability of having an actual activity duration that is higher than the expected duration to be higher than having a lower activity duration. This decision is also supported by the fact that the minimal (unrealistic) actual activity duration is zero time units while the maximal possible duration can go to infinity. This again justifies the choice for a skewed to-the-right distribution over a symmetrical distribution.

The Generalized Beta distribution also possesses this property and so would also be an appropriate activity duration distribution function. However, there are two main reasons why I preferred to select the lognormal distribution over the Generalized Beta one:

- (a) Difficult to control: generating activity durations from a Generalized Beta distribution can be confusing as this type of distribution is very hard to control. Setting the distribution parameters can have a high influence on the distribution's shape and so many different shapes may result from setting the parameters to different values.
 - (b) Empirical evidence for lognormal distribution: based upon a study of Colin & Vanhoucke (2016), the lognormal distribution seems to fit the empirical activity durations the best for projects in a wide range of industries: the construction, information technology (IT) and education industry.
- **The possible effect of an activity on the project duration:** to measure this impact, I decided to use the ratio of the total expected float of an activity over the mean activity duration. Calculating these expected floats will be done by calculating the float of each activity according to the baseline schedule, which will be both resource feasible and will not violate the activity precedence relations.
- This expected total float will be calculated based on the mean activity durations and therefore the actual float (calculated based on real activity duration) can differ from the expected float. However, I decided to only calculate the activities' possible effects based upon their mean duration as the actual duration of an activity will not be available to the project manager until the activity is finished.

A critical note I wanted to add here is that in very complex project networks, it could be that the float of an activity with a high duration variability, also shows a high variability in its total float. This will make the expected total float less reliable and maybe not the perfect indicator of the activity's possible impact. Nevertheless, we will use this ratio during the simulation experiments to measure the possible effect an activity can have on the total project duration.

- **Morphologic feature of the activity in the project network:** a last factor that also needs to be taken into account to assess the risk of an activity is the morphological structure of an activity in the network. As we can see in Figure 3.2, the importance of activity i differs over those three activity-on-the-node networks. It is obvious, delaying activity 1 will have less effect on the total project duration in the first network compared to the second and third one. This is because the number of paths derived from activity i in network 1 (1) is less than in networks 2 and 3 (2 and 3 paths respectively). To measure this feature, I will use the post-density value for each activity which is defined as the total number of successors of an activity divided by the number of activities in the network (Madadi & Iranmanesh, 2012).

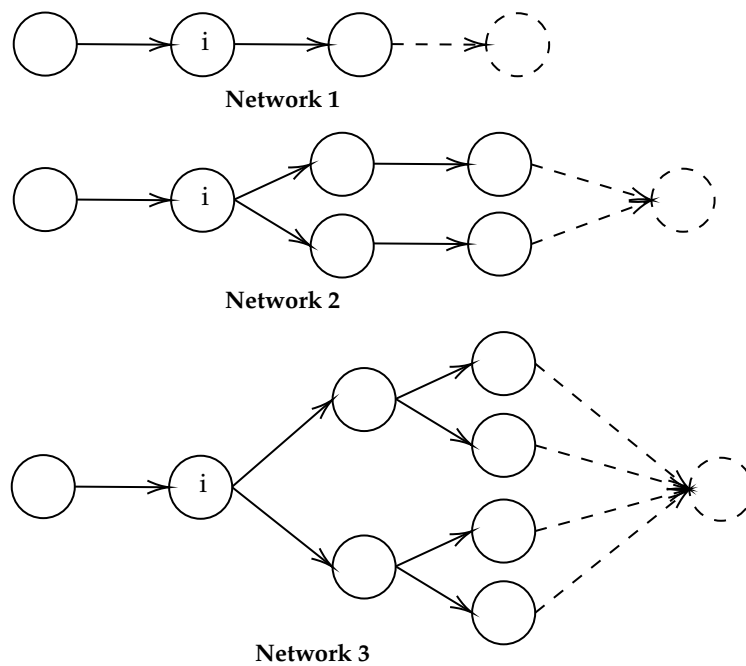


FIGURE 3.2: Morphological structures

The construct for determining the criticality of an activity will be called the MOI 2 (Management Oriented Index 2). The MOI 2 for an activity is defined as the product of an activity's variability and its possible impact on the project duration (composed of an activity's possible effect and its

morphological feature). The MOI 2 for activity i can be calculated using Equation 3.5.

$$MOI2_i = \frac{\sigma_i}{\sigma_{max}} \times \frac{1}{E(TF_i)/d_i - POST_{DENSITY_i} + 1} \quad (3.5)$$

with σ_i representing the standard deviation of the activity's duration probability function and σ_{max} the maximal standard deviation over all activity durations. The expected total float of activity i is represented as $E(TF_i)$ and d_i represents the mean activity duration. The ratio total number of successors of activity i over the number of activities in the network is represented by $POST_{DENSITY_i}$.

3.1.2 Resource level

There is very little literature available about constructing a tool that can be used to differentiate between risky and less risky resources for a project. This is why I came up with a new index myself. This index is just a very easy-to-use metric to allow me to differentiate between critical and less critical resources in my research. I acknowledge more components could and probably should have been included to improve this metric. However, this is not the main purpose of this research and can be investigated in further research.

The index is composed of two components that reflect the possible impact a resource can have on the project's time objective on the one hand and the likelihood that a resource will affect the project's duration :

- **Resource impact:** the potential impact a resource i can have on a project will be calculated using Equation 3.6.

$$Impact_i = \frac{newPD_i - originalPD}{originalPD} \quad (3.6)$$

with *originalPD* being the originally planned project duration.

The *newPD* for a certain resource will be obtained by reducing its original availability by 50% while maintaining the original availability of all other resources and recalculating the planned project duration based on this new resource availability.

- **Resource likelihood :** the likelihood that a resource and its corresponding availability will impact the final project duration.

Based upon an experimental investigation, the factor PRES seemed to reflect the degree of resource limitation very well (Davies, 1973). This ratio is equal to the available quantity of resources over the expected maximum demand for resources (= average activity demand * max. number of activities in parallel). In case the available quantity of a resource changes over the project duration, they just took the weighted average available quantity over the project horizon (with the weights equal to the number of time periods a certain quantity was available).

In my research, I decided to construct a new metric to assess a resource's likelihood of impacting the project duration that was based on this PRES factor. To calculate the numerator I will employ the resource Work Content At Completion, which can be derived from Equation 2.8. This parameter is a good estimate of the total resource demand over the project's planned duration.

In the denominator, I will use the total supply of a resource over the project's (expected) duration. When the resource availability remains constant over the entire project duration, the numerator is calculated by simply multiplying the planned project duration by the availability of that specific resource. However when the availability of the resource changes during the project execution, the numerator is constituted by the weighted sum of the products of resource availability and corresponding resource availability duration as shown in Equation 3.7.

$$Resource\ supply_i = \sum_{j=1}^J A_{i,j} \times (Dur_j) \quad (3.7)$$

with J being the number of availability modes of resource i , $A_{i,j}$ the availability for availability mode j of resource i , and Dur_j the duration of availability mode j . The duration of an availability mode is just the difference between the end of the availability mode and its start. This calculation is explained in the following example.

Example

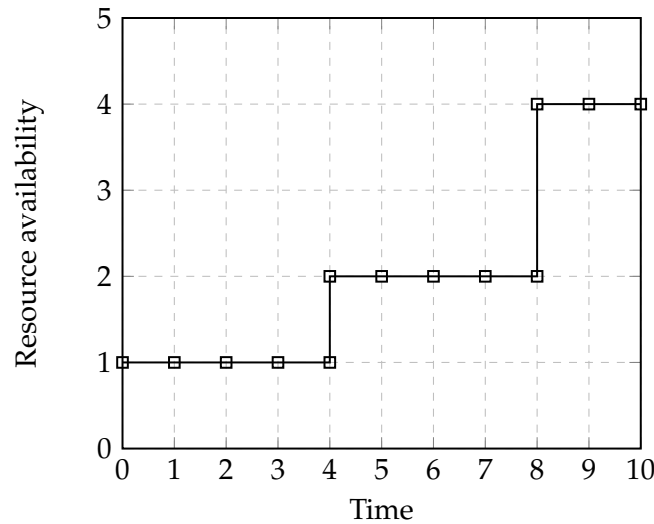


FIGURE 3.3: Resource availability trend

In the example resource availability trend shown in Figure 3.3, the resource availability changes two times during the project duration: at $t = 4$ the availability changes from 1 to 2 and at $t = 8$ the availability increases by 2.

The weighted sum of resource availabilities calculated based on equation 3.7 looks as follows:

$$\text{Resource Supply} = (1 \times (4 - 0)) + (2 \times (8 - 4)) + (4 \times (10 - 8)) = 20$$

Upon dividing the numerator by the denominator, we have found a good estimate for the resource's likelihood of impacting the project duration. This parameter is always non-negative and ideally less than one, with lower values indicating a lesser likelihood of the resource impacting the project duration. A value exceeding the threshold of one indicates that the project duration will depend upon the respective resource with a 100% probability unless there is a resource with an even higher value.

By dividing the total resource demand by the total resource supply, we can assess the resource's likelihood very well as shown in the next example.

Example

Suppose the resource supply (i.e. the denominator) is the one found in the previous example and is equal to 20. Consider now the following three resource WCAC examples: 10, 20 and 25. The values for the likelihood parameter are shown in Table 3.1. We can see that when the total demand is low compared to the total resource supply (scenario 1), the likelihood of the resource impacting the project's final duration is relatively low. This intuition is easy to follow as you will have more freedom to schedule your activities and you will be less constrained by this resource when constructing your baseline schedule. However, when your total demand exceeds your total supply (scenario 3), this resource will very likely have an impact on your project duration. Suppose that all your activities are non-precedence related and this resource is the only resource used in the project. In this case, the project's planned duration will be increased by the fact that not all activities can be scheduled simultaneously because of the resource constraint. So the likelihood that your project duration will be impacted is very high.

Scenario	Demand	Supply	Likelihood
1	10	20	0.5
2	20	20	1
3	25	20	1.25

TABLE 3.1: Resource likelihood example

The construct I created for determining the risk associated with a given resource consists of two parameters that were previously explained: the resource's potential impact and its likelihood of affecting the project duration. The equation for calculating the risk of a given resource i is presented in Equation 3.8

$$\text{Resource risk}_i = \text{Impact}_i \times \text{likelihood}_i \quad (3.8)$$

Factor	Formula
<i>Activity Variability</i>	σ_i
<i>Possible activity effect</i>	$\frac{E(TF_i)}{d_i}$
<i>Morphological structure</i>	<i>number of successors activity i / total number of activities</i>
$MOI2_i$	$\frac{\sigma_i}{\sigma_{max}} \times \frac{1}{E(TF_i)/d_i - POST_{DENSITY_i} + 1}$

TABLE 3.2: Classification factors activities

Next to these two factors constituting the riskiness of a resource, there are still some other elements that can affect a resource's risk. One class of factors that can be impactful are the factors that determine how easily a resource can be resupplied when the resource is out-of-stock when a certain resource is not appropriate anymore for use (perishable products),... If one of these events occurs, a project manager/firm has the choice between (re-)purchasing the resource and so making some of the activities wait, or it can just take the required number of resources needed for that activity from another activity. This second choice will be justified if this idle activity would be more critical than the other activity. Making this decision will depend on how easily and how quickly a resource can be replenished to a project and depends on several factors:

1. *Replenishment lead time*: the time lag between observing the resource shortage and receiving the additional required amount of resources.
2. *Influence resource providers*: as you can see in Table 2.2 this factor is made up of four components that will together model the influence a resource provider can exercise on a firm.
3. *Environmental buffering factor*: next to the influence resource providers can have on the supply of resources, firms can also counteract this influence by having a diversified number of suppliers. A more diversified set of suppliers will increase the probability a certain resource can be re-supplied within the required time frame.

In my research, I decided to not further elaborate upon these factors as this would lead us too far from the main purpose of this dissertation, but they certainly can be a useful input for future research.

All the factors and formulas used to classify activities and resources into risky and less risky ones are summarized in Tables 3.2 and 3.3.

Factor	Formula
$Impact_i$	$\frac{newPD_i - originalPD}{originalPD}$
$Likelihood_i$	$\frac{WCAC_i}{Resourcesupply_i}$
$Risk_i$	$Impact_i \times Likelihood_i$

TABLE 3.3: Classification factors resource level

3.2 Corrective actions

In this section, I will describe four corrective actions which I will make use of during the project control phase. Two of them will be appropriate for controlling a project on the activity level and two of them will be applied when operating a resource level control. For each corrective action, I will clarify its impact on the project's time and cost performance. As you will read in the remainder of this section, it is assumed that taking a corrective action will reduce the project's expected duration but this will come at the expense of an increased project cost. This sequence will particularly be appropriate for projects maintaining the minimal project duration objective. When a project's objective is to minimize costs, however, the impact of corrective actions will have a reversed effect on the project: increasing its duration and decreasing its cost. This is why (most of) those corrective actions will be appropriate for any project objective. To maintain simplicity, I will only describe one of these sequences. However, it should be noted that for each corrective action, the reversed sequence is also possible if it better suits the project objective better.

Activity Crashing

This first corrective action, activity crashing, entails investing additional effort in a particular activity with the aim of reducing the mean activity duration and eventually the total project duration. Song et al. (2021) present two types of activity crashing in a resource-feasible RCPSP schedule. The first type deploys the traditional view on activity crashing: reducing an activity's mean duration by investing additional resources. The second type is a revised version of this first type and implies reducing the activity's resource demand resulting in an increased activity duration. Those two types are closely connected as they are both subject to the same principle explained by Figure ???. Increasing effort/resources on a specific activity will decrease its mean duration while decreasing an activity's resource demand will increase its mean duration. This relationship will only hold when an activity's work content is held constant. This does not necessarily need to be the case as explained by Song et al. (2021). In this study three different ways of doing activity crashing are defined:

- *Homogeneous*: the activity work content is the same for all crash modes. So adjusting an activity's duration or resource demand will not affect the work content (will remain at 100% for all modes). Performing a homogeneous way of activity crashing assumes the resource's performance remains constant.
- *Efficient*: the activity work content will decrease as the activity duration or resource demand is changed. This situation might occur when better quality resources are added to crash the activity resulting in a lower work content (<100%).
- *Inefficient*: changing the activity duration or resource demand will increase its work content (>100%). These inefficiencies can be caused by multiple resources working together (Ballesteros-Pérez et al., 2019).

These different ways of doing activity crashing are briefly explained for the traditional type of activity crashing in the following example.

Example

Assume we have an activity as depicted in Figure 3.4 with a duration of 4 and a resource demand of 3 resulting in a work content of 12 ($= 3 \times 4$).

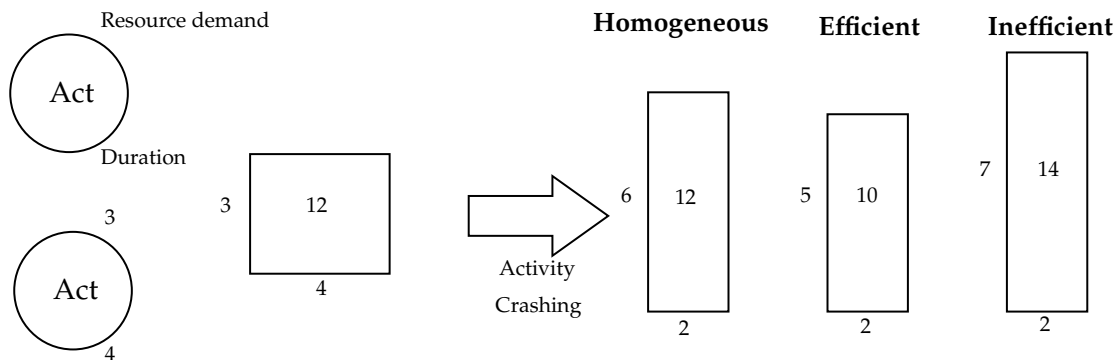


FIGURE 3.4: Activity crashing types

The calculations for the activity crashing types are as follows:

- *Homogeneous*: by reducing the activity duration from 4 to 2, the resource demand is increased from 3 to 6. This results in a new work content of 12 ($= 6 \times 2$).
- *Efficient*: by reducing the activity duration from 4 to 2, the resource demand is increased from 3 to 5. This results in a new work content of 10 ($= 5 \times 2$).
- *Inefficient*: by reducing the activity duration from 4 to 2, the resource demand is increased from 3 to 7. This results in a new work content of 14 ($= 7 \times 2$).

For the remainder of my research, I will opt for the inefficient activity crashing type when performing an activity crashing corrective action. A first reason for this is that Vanhoucke &

Debels (2007) found that most activity trade-offs are either linear or convex corresponding with a homogeneous and inefficient activity crashing mode respectively. Secondly, I will assume that when performing an activity crashing action, it is necessary for the project manager to allocate additional quantities of each required resource to the corresponding activity. However, this process is likely to require a brief setup period during which inefficiencies might occur and lead to the wastage of resources. For example, inefficiencies may arise when adjusting machinery's settings or when the project leader has to invest additional time in providing instructions regarding the assigned tasks to newly assigned workforce members.

A last reason for opting for an inefficient activity crashing mode is to avoid adverse effects on my results when the costs of performing an activity crashing action would be zero while the project would still end up being finished earlier. To ensure that the trade-off between time and cost is made clear in my results, I will use the inefficient mode of doing activity crashing.

More precisely, the new work content will be calculated based on Equation 3.9

$$New\ WC = Old\ WC \times (WC_{rate}^{Crash\ Quantity}) \quad (3.9)$$

with *Crash Quantity* being the number of time periods an activity is been crashed and old and new WC being the old and new work content related to the crashed activity. The parameter WC_{rate} will define how much the work content will increase and will always be higher than one (inefficient).

By taking the power of the WC_{rate} , we ensure a convex time/cost relationship as shown in Figure 3.5. The exact value of this parameter will be determined later.

To determine how much an activity should be crashed, I will rely on the difference between the planned project duration and the expected project duration (Equation 3.10). The planned duration can be generated from the baseline schedule and the expected duration is calculated according to Equation 3.11.

$$Needed\ crash\ quantity = Expected\ Duration - Planned\ Duration \quad (3.10)$$

$$Expected\ Duration = \frac{Actual\ Duration}{Percentage\ Completed} \quad (3.11)$$

The maximum quantity an activity can be crashed is its remaining duration-1 to make sure that at least one time period is left to perform the remaining work. When the *Needed crash quantity* would exceed the remaining duration of the selected activity, this activity will be crashed until its remaining duration is one, and the residual crash quantity will be executed on the subsequent activity. This procedure will be repeated till the total crash quantity is completely consumed. The costs associated with implementing an activity crashing corrective action are linked with its fixed set-up cost. More specifically, the cost incurred from crashing an activity *i* will be proportional to the increase in the resource demand for each resource *j* (Equation 3.12)

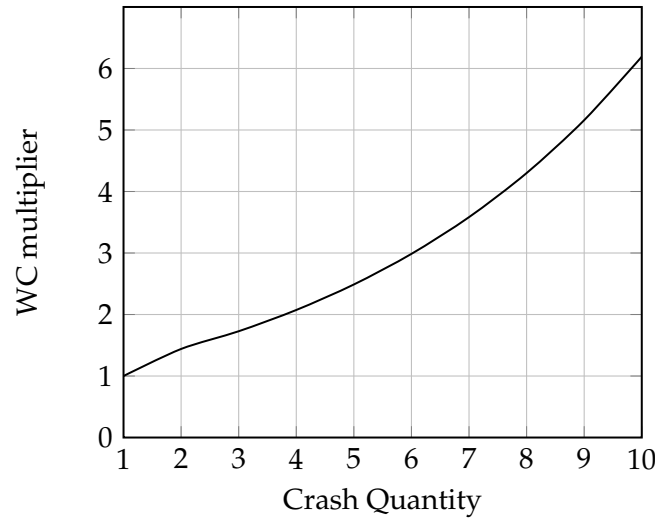


FIGURE 3.5: Inefficient activity crashing WC multiplier

$$New\ cost_{i,j} = \frac{FC_{i,j}}{d_{i,j}} \times (d'_{i,j} - d_{i,j}) \quad (3.12)$$

with $FC_{i,j}$ = fixed setup cost of activity i related to resource j
 $d_{i,j}$ = the old resource demand of activity i for resource j
 $d'_{i,j}$ = the new resource demand of activity i for resource j

The fixed cost related to a specific resource type will be calculated by dividing the total activity's fixed cost by the number of resources required for executing that activity.

Activity Variability Reduction

A second corrective action that can be taken when controlling a project on the activity level is the action of reducing an activity's variability.

As explained in section 3.1.1, the activity's variability is represented by the standard deviation of the corresponding activity duration probability distribution, i.e. the lognormal distribution. In this section, the unrobustness of the arithmetic mean m and standard deviation s of the lognormal distribution was also covered. However, despite their unrobustness, those distribution parameters are easy to interpret and widely used for defining activity duration distributions.

Therefore, the original activity duration distributions, without performing any activity variability reduction actions, will still be represented by m and s , as was done in a study performed by Martens & Vanhoucke (2019). They used these parameters for specifying the relative real activity durations $\frac{d_i}{\hat{d}_i}$ with d_i the real duration and $\hat{d}_i$ the estimated duration for activity i .

After setting the values for the arithmetic mean m and standard deviation s , the values for μ , σ , e^μ and e^σ can be calculated according to Equations 3.1 and 3.3. The values for the parameters of the original activity distributions will be set in a later section.

When performing the corrective action of reducing an activity's variability, the variance component of the duration distribution will decrease. But since m and s are not robust parameters for the lognormal distribution, we will modify the geometric standard deviation σ to define a new activity duration distribution with a standard deviation $\hat{\sigma}$.

In theory, each activity's standard deviation can be decreased continuously as long as the ratio $\frac{\hat{\sigma}}{\sigma}$ is higher than zero and lower than one. However, in my research, I will assume that each activity's variability can only be decreased a limited number of times. Therefore, I have established four levels of uncertainty that can be applicable to an activity's duration. More precisely, I will consider three reduced levels of uncertainty (RLU) next to the original level of uncertainty, namely an RLU of 75, 50 and 25 % of the original variability. Consequently, only three activity variability reduction actions can be performed on a specific activity, resulting in the lowest RLU level of 25%, or $\frac{\hat{\sigma}}{\sigma} = 0,25$.

It is evident that taking corrective measures to reduce an activity's variability comes with a certain additional cost. The cost function related to the corrective action of reducing the activity variability was built on the cost function for activity crashing to make these two corrective actions comparable in terms of their costs. I decided to set the costs of reducing an activity's variability somewhat lower than the cost of crashing an activity for the following reason. When inefficiently crashing an activity, its related work content will increase and so the resource demand for each resource will rise. However, when reducing an activity's variability, you will also (probably) decrease its total duration, and again I will assume this will occur inefficiently, but to a smaller degree than when you are crashing that activity. The underlying rationale behind this is that reducing an activity's variability is implemented over a relatively brief period of time resulting in a work content increase that will be limited in terms of magnitude and scope. For example, a project manager can assign more effort to generate more accurate estimates regarding the activity's sub-procedures durations, the resource demand, ... When crashing an activity, on the other hand, you have to provide sufficient resources to the activity during its entire duration. The additional required amount of resources can be very high for a short duration or can be lower for a relatively longer duration leading to a work content increase that will be more extended than the increase for a variability reduction action.

The function to calculate the new work content (Equation 3.13) shows that your work content will only increase by $WC_{rate}^{NrReductions}$ with $NrReductions$ being the number of variability reductions performed on the activity. This parameter will have a maximal value of 3 when the activity's variability has been reduced three times to its RLU=0.25 level. Compared to the *Crash Quantity* parameter used in Equation 3.9, which maximal value is the activity duration-1, the work content increase related to reducing an activity's variability will be somewhat lower than the work content increase of crashing an activity.

$$New\ WC = Old\ WC \times (WC_{rate}^{NrReductions}) \quad (3.13)$$

The costs related to reducing an activity's variability will simply be calculated by adding 25% of the activity's fixed cost to its total cost. These costs come from investing additional time and effort (and money) in generating more accurate information regarding the activity's duration and reducing different duration variability sources.

Resource Availability Increase

When controlling a project on the resource level, one of the corrective actions a project manager can take to bring a project back on track is increasing a resource's availability. This can allow certain activities that are being executed in series, although they are not precedence related, to be performed in parallel. Consequently, this can in its turn cause some other activities to be shifted forward in time such they are completed sooner, and in the end enable the project to be completed earlier than expected.

For my research, it is assumed that the resource availability can be augmented an unlimited number of times, with each augmentation being a 25% increase of the initial availability. The resource availability trend of a resource with an initial availability of one that has received three availability increases at $t=3, 5$ and 8 is depicted in Figure 3.6.

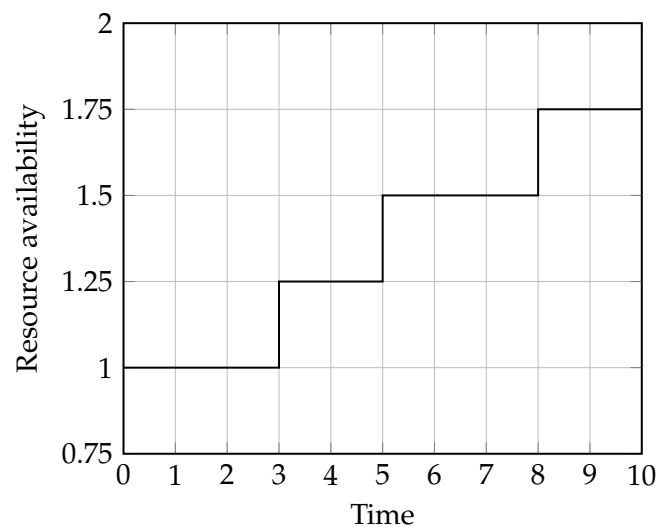


FIGURE 3.6: Resource availability trend with three availability increases

The costs that come along with increasing the availability can easily be calculated by using the equation that was used for calculating the resource's total supply (Equation 3.7). Multiplying a resource's total supply over the project duration by its resource unit cost will generate the total cost related to that resource type. So when the resource's availability would be increased at a specific point in time, this will increase the total resource's supply regardless of whether that additional amount is being used during the project execution or not. This will in its turn be reflected in the resource's total cost and in the end in the final project cost.

A concluding remark I want to make about the corrective action of increasing the resource availability is that this corrective action will have the same impact on a project then increasing the quality/efficiency of a resource. A quality or efficiency increase will cause the demand of your activities for a certain resource to be lower than initially planned. This can again allow multiple non-precedence-related activities to be executed in parallel by addressing the resource constraints. Increasing the quality or efficiency of a resource can in practice be done by hiring better-skilled employees, buying higher quality materials, . . . This leads us back to the second type of activity crashing covered earlier in this section under the activity crashing corrective action.

Resource Boosting

The last corrective action I will use is the resource boosting action. I developed this action completely by myself and already provided a short description of it in section 2.3.2. This corrective action is very similar to the one of increasing the resource's availability, yet differs in three aspects:

- *Duration*: while the 'resource availability increase' measure will increase a resource's availability for the entire project duration, the 'resource boosting' action will only increase the availability for a short amount of time. The exact duration of the availability increase depends upon the planned project duration and the expected project duration and will be calculated in the same way as in the activity crashing corrective action (Equations 3.10 and 3.11). After this time frame, the resource availability will be reset to its original value.
- *Availability increase*: the 'resource availability increase' action involves a gradual, incremental increase of the resource supply by 25% each step. For the 'resource boosting' corrective action, on the other hand, a "whatever it takes" policy will be applied. This will result in a new resource availability that can theoretically be set equal to infinity such that all resource constraints are made abundant during this time frame. In reality, this entails a company will assemble all possible resources it can make available during this resource boosting period. So in my research, I will make sure that each resource's availability is increased with an amount that will enable the project to be executed without any resource constraints during the action period.
- *Number of impacted resources*: the 'resource boosting' corrective action will impact all the resources included in the project, while only one resource will be impacted by the 'resource availability increase' action. This is again to ensure that no resource constraints are present during the boosting period.

The exact value for the availability increase will be determined by calculating the maximal possible demand for a resource according to a baseline schedule constructed without taking into

account the resource constraints. This maximal demand will then be rounded up to the closest multiple of 0.25 to include a certain safety margin. Note that each resource's availability will be increased up to this amount independently of the actual resource quantity that would be required to start every activity taking into account only the precedence relations.

The costs corresponding to this resource boosting action will be calculated in the same way as for the resource availability increase, except for the fact that the availability increase will be much higher but the duration will be shorter as explained in the next example.

Example

Assume the project's expected duration exceeds its planned duration by 4 time units and the project only makes use of 1 resource with an availability of 1, a maximal demand of 1.5 and a unit cost of 10. In this case, the cost related to the resource boosting action is calculated as follows:

$$\text{New Cost} = (1.5 - 1) \times 4 \times 10 = 20$$

The cost when the resource boosting action would not have been taken is:

$$\text{Cost} = 1 \times 4 \times 10 = 40$$

So the total cost for the resource boosting period, taking resource boosting action, would be 60 instead of 40.

4 Simulation model

This chapter presents a summary of the simulation model I will use to review whether an activity or resource level control approach will be more appropriate for controlling a diverse range of projects. In Section 4.1, the various project characteristics that could potentially impact the efficacy of one or both control approaches will be explored. The next section, Section 4.2, outlines the step-by-step procedure to run the simulation of controlling a specific project using the two distinct control approaches. In the third section, Section 4.3, I will present some preliminary hypotheses regarding the impact of each project characteristic on the relative efficacy of one control approach over the other one.

4.1 Project characteristics

The primary objective of this study is to evaluate the efficacy of a resource level control approach compared to the activity level control approach for controlling a wide variety of projects. In my research I will assume each of the following factors can have an impact on the effectiveness of each of the two control methods:

- **S/P-value:** the topological structure of a project is indicated with the serial/parallel indicator, which takes a value ranging from 0 to 1. More precisely, a higher (lower) S/P-value indicates a more serial (parallel) project. In the conducted experiments, the impact of increasing the S/P parameter on the efficacy of the two control methods will be examined by setting the S/P parameter at four different levels: 0.2, 0.4, 0.6 and 0.8.
- **Level of activity variability:** the influence of activity duration variability within a project on the effectiveness of both control methods will also be investigated. To achieve this, the variability related to the activity duration will be modified intentionally and its impact on the project objectives, using both control approaches, will be measured.

As explained in Section 3.1.1, the arithmetic mean m and standard deviation s are not robust parameters for the lognormal distribution. Therefore the parameter σ will be modified to generate activities with a lower or higher level of duration variability. More precisely, the σ parameter will be set at four levels: 0.2, 0.3, 0.4 and 0.5 while the parameter μ will be held constant at 0.0594. The related parameters m , s , e^μ and e^σ can be calculated using Equations 3.1 and 3.2. Note that for the corrective action of reducing an activity's

variability, the value of σ (and the other parameters) for the different RLU levels will also have to be recalculated based on the new activity duration variability.

- **Number of activities:** the total number of activities to be performed in a project will possibly have an impact on the effectiveness of the control approaches. Therefore projects of varying sizes (10, 15, 20, 25 and 30 activities) will be controlled using both control methods.
- **Number of resources:** the total number of resources that are required by all activities. As I will only make use of renewable resources in my experiments, this factor is equal to the number of renewable resources included in the project. Projects containing 1, 2, 3, 4 or 5 resources will be conducted in a simulation experiment and their corresponding performance, in terms of the different objectives, will be tracked and compared to each other.
- **Resource similarity:** to what extent are resources similar in terms of their resource scarceness? This parameter will enable me to differentiate between projects that make use of very similar resources and projects with significant differences among their resources and their scarceness values. Computing this parameter will be done by dividing the maximal resource scarceness over all resources by the minimal value for this parameter. This parameter will always have a value larger than or equal to 1 with higher values indicating a lower level of similarity.

A resource's scarceness represents the extent to which the resources are available to the project compared to their demand by the activities. This parameter is influenced by two parameters, based upon the "generate renewable resource demand" function included in the P2Generator class of the P2Engine software (Vanhoucke, 2014):

- Resource Usage (RU_i): this is the average number of activities that make use of a certain resource as a fraction of the total number of activities included in the project. The higher the value of this parameter, the higher the resource scarcity will be.
- Resource Constrainedness (RC_i): this is the average resource demand for each activity as a percentage of the total resource availability. Again higher values of this parameter will indicate a higher degree of resource scarceness.

The resource scarceness of a specific resource will be calculated by multiplying its resource use by its resource constrainedness:

$$RS_i = RU_i \times RC_i \quad (4.1)$$

In my experiments, the resource similarity parameter will be set at four levels: 1, 2, 3, and 4. This will be achieved by modifying the RU and RC values for the different resources.

- **Other parameters:**

- **Objective:** this will determine the main focus during the execution of the project. This research will exclusively be focused on the objective of minimizing the project duration, as it is widely recognized as the most common objective in real-life project scenarios. This focus reflects the common practice and prevailing emphasis placed on reducing the total project duration within various industries and sectors. Investigating the efficacy of the activity and resource level control approach for other project objectives can be prone to future research.
A short explanation regarding the different project objectives was given in Section 2.1.3 and will not be repeated here.
- **WC rate:** this parameter will determine the increase in an activity's work content when performing an activity crashing or activity variability reduction corrective action on it. This parameter will have a value of 1.2 and will be held constant for all simulation experiments
- **Project execution policy:** as will be explained further in Section 4.2.2, the roadrunner policy (RR) will be used in each simulation experiment to simulate a project's execution.

A summary of the maintained parameters and their corresponding values can be found in Table 4.1 below.

Parameter	Values
S/P	0.2, 0.4, 0.6, 0.8
Act variability	0.2, 0.3, 0.4, 0.5
#Activities	10, 15, 20, 25, 30
#Resource	1, 2, 3, 4, 5
Resource similarity	1, 2, 3, 4
Objective	Min duration
WC rate	1.2
Execution policy	RR

TABLE 4.1: Parameter values

4.2 Simulation procedure

The general procedure I will follow is been summarised in Figure 4.1 and was based on the research methodology applied in an article covering the usage of Schedule Risk Analysis with resource constraints for project control (Song et al., 2021). To perform my research and to simulate the desired experiments I will make use of the scripting-enabled project scheduling and

control tool P2Engine (Vanhoucke, 2014). In what follows I will briefly go over the three main steps included in my simulation experiments: the scheduling, execution and evaluation stages.

4.2.1 Scheduling stage

The scheduling stage consists of two steps: creating a precedence- and resource-feasible baseline schedule and generating the required activity and resource characteristics.

Constructing baseline schedule

The project's baseline schedule will be generated by scheduling the project according to five different priority rules. Vanhoucke (2013, pp. 125–126) classified priority rules into four different categories: activity-based rules, network-based rules, critical-path-based rules and resource-based rules. One priority rule was picked from each category as was done by Song et al. (2021) next to the Latest Start Time (LST) priority rule as this is one of the best performing classical priority rules (Kolisch, 1996). The set of priority rules that will be applied are:

- Shortest Processing Time (SPT)
- Most Immediate Successors (MIS)
- Earliest Starting Time (EST)
- Greatest Resource Work Content (GRWC)
- Latest Start Time (LST)

Eventually, the priority rule generating the baseline schedule with the shortest (planned) project duration will be used to set the baseline schedule.

Generating activity and resource characteristics

After having generated the baseline schedule, some activity and resource characteristics will have to be calculated based on this schedule.

Activity characteristics:

- *Fixed activity costs:* a random fixed cost will be generated for each activity as a measure of its setup costs. These costs can be related to setting up machines to perform a new activity, the waste that is generated while modifying the settings of a certain resource, transportation of required resources for an activity,...

These costs will be formed for each activity by generating a random number in the interval [100,1000] using a random number generator included in the P2Engine software.

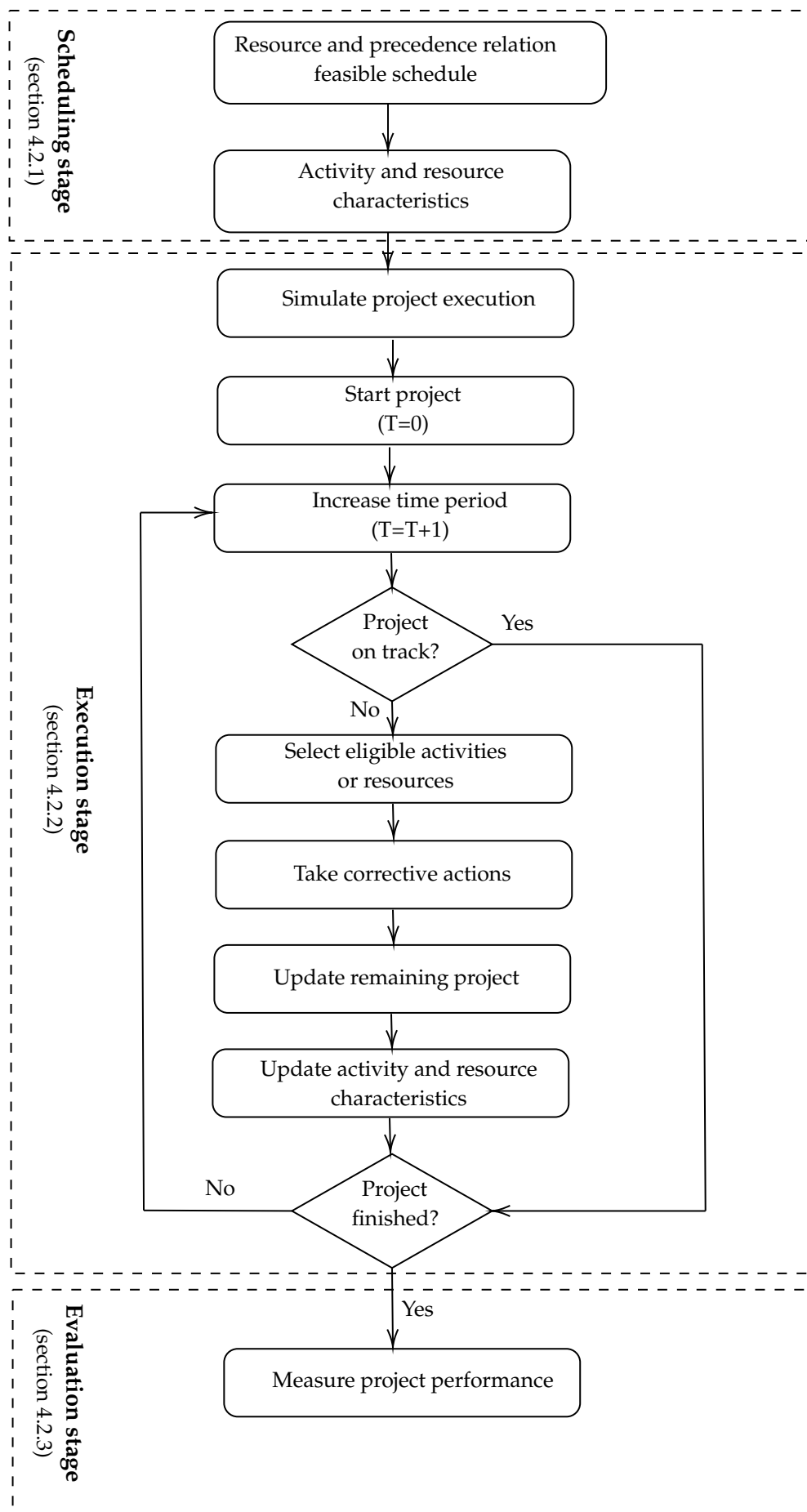


FIGURE 4.1: Simulation procedure

- *Activity duration*: the actual duration of all activities will have to be generated for each simulation run based upon the activity duration distribution. These real activity durations are likely to differ from the planned duration and will be drawn from the lognormal distribution with its corresponding values for the mean and standard deviation. Note that the values derived from the lognormal distribution, having a standard arithmetic mean m of 1.1 and standard deviation s of 0.3, represent the relative real activity duration, i.e. the real duration d_i over the estimated duration $\hat{d}_i$. Therefore the real activity duration d_i can be found by multiplying the number generated from the lognormal distribution with the estimated activity duration $\hat{d}_i$.

By generating a new number from the lognormal distribution for each new simulation, it is expected that the duration of a specific activity will vary across different simulation runs.

- *Activity MOI 2*: the activity's MOI 2 can only be calculated after the baseline schedule has been constructed. As shown in Equation 3.5, this parameter consists of three elements: the possible effect of an activity, the morphological structure and the activity variability. The first two parameters will be calculated using the equations displayed in Table 3.2. The third parameter, the activity's risk, is calculated by simply multiplying the activity's duration arithmetic standard deviation m by two.

Note that the values for this MOI 2 parameter will have to be updated each time a corrective action has been taken and the schedule has been adjusted.

- *Activity resource demand*: generating the resource demand for all activities will happen based on the values of the Resource Usage and Resource Constrainedness parameters for each resource. The procedure for setting the resource demand of an activity for a specific resource is illustrated in Figure 4.2. Note that each activity's resource demand will be a number in the range of 0 to 1 and will be expressed as a fraction of the total resource supply, which will in its turn be equal to one for each resource.

Resource characteristics:

- *Resource unit cost*: this cost represents the cost of using one unit of a specific resource for one unit of time and will be generated using the function 'generate resources for project' included in the P2Resource class. This function requires amongst others two input parameters determining the minimal and maximal value for each resource's unit cost. In my experiment, these parameters will have a value of 10 and 100 respectively and therefore the resource unit cost will have a random value in between this range.
- *Resource risk*: this parameter stands for the riskiness of a resource and is computed using Equation 3.8. The two factors constituting this parameter can be calculated according to the Equations shown in Table 3.3. As these parameters will be impacted by adaptations to the baseline schedule, they have to be recalculated each time a corrective action has been performed.

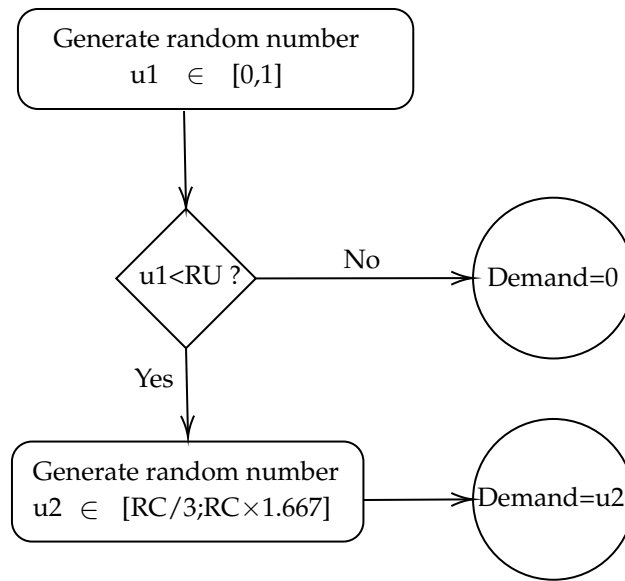


FIGURE 4.2: Resource demand calculation

- *Resource scarceness*: this parameter will be calculated for each resource based on its Resource Usage and Resource Constrainedness as illustrated in Equation 4.1.
- *Resource similarity*: the calculation of this parameter depends upon each resource's scarceness value as was explained in the previous section.
- *Resource maximal demand*: this parameter represents the maximal demand that a resource can face according to a schedule that only takes into account the precedence relations and will be needed for the 'resource boosting' corrective action.

Next to the computation of those activity and resource characteristics, there are also some project characteristics to be determined from the baseline schedule. More precisely a project's Planned Duration, Budget At Completion and Work Content At Completion will be set from the baseline schedule and will be key for assessing the project's performance by comparing the real duration, cost and work content to the scheduled ones.

4.2.2 The execution stage

This section presents the simulation process for project execution with and without the implementation of corrective actions. The project's progress will be performed using Monte Carlo simulations to imitate the project execution under uncertainty. Modelling the uncertainty related to the actual activity duration will be done using the lognormal distribution with an arithmetic mean m of 1.1 and a standard deviation s of 0.3. The resulting values for μ , σ , e^μ and e^σ are shown in Table 4.2. The outline of this section is described as follows. The first part will describe two alternative execution policies to generate the simulated project execution. Secondly,

the strategies to decide which activities or resources should be selected for corrective actions are detailed in the second part. Subsequently, the different types of corrective actions will be summarized together with some parameter settings regarding these actions. Finally the procedure for dynamically rescheduling the remainder of the ongoing project after corrective action interventions will be described in the fourth part of this subsection.

Simulated project execution

When constructing a simulated project execution, two policies can be deployed: the roadrunner (RR) and railway (RW) execution policies. The roadrunner policy will force activities to be executed as soon as possible to make the best use of the early finishes of predecessors. The main goal of this policy is to deliver the project on time. The railway execution policy on the other hand will aim to increase the stability of the project by not allowing activities to be executed earlier than their planned start times generated from the baseline schedule (Herroelen & Leus, 2004).

For my research, I will solely focus on the roadrunner policy, as the objective of generating a stable project execution will not be included in my study.

To determine the appropriate values for the $SPI(t)$ and $SPI_{ESWC}(t)$, a small simulation experiment was performed.

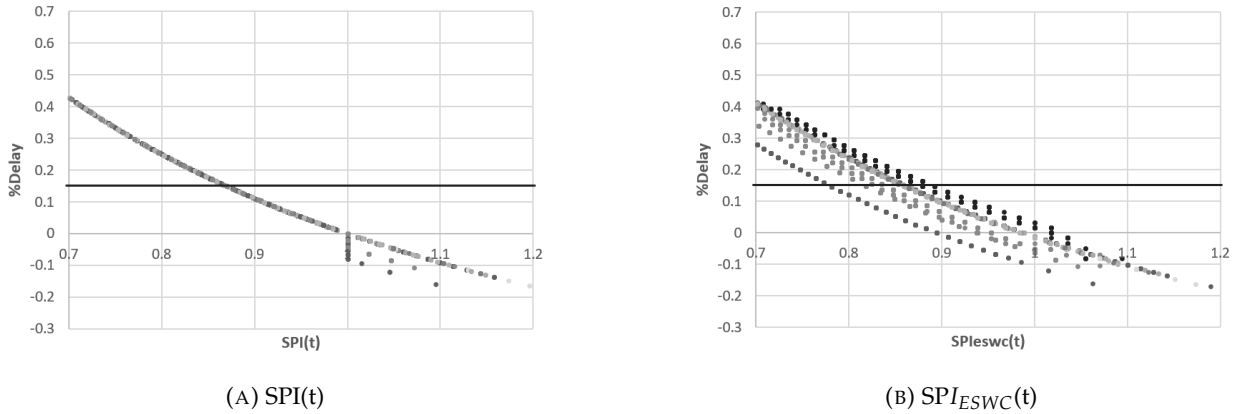
The $SPI(t)$ threshold was obtained by simulating a small number of project examples and comparing their final project duration with the planned project duration. More precisely, ten projects with the standard parameter values, which will be explained in Chapter 5, were simulated 1000 times each. For each run, the percentage of delay was calculated using Equation 4.2 and compared to the corresponding $SPI(t)$ value for the project.

$$\%delay = \frac{Real\ project\ duration - Planned\ project\ duration}{Planned\ project\ duration} \quad (4.2)$$

Afterwards, these $SPI(t)$ values were ranked in increasing order and plotted on a scatterplot together with their $\%delay$ values. Figure 4.3a contains the scatter plot for all projects.

The first thing we can notice in this figure is that the $SPI(t)$ value is indeed an appropriate parameter for assessing the project's time performance. We can see that projects having a huge delay return very low values for their $SPI(t)$ parameter while projects performing very well in terms of time, return $SPI(t)$ values that are higher than one. To determine the value for the $SPI(t)$ threshold, a $\%delay$ of 15% was assumed to be acceptable. As long as the delay does not exceed 15% of its planned duration, this can still be managed by a project manager by including some safety time in their proposed baseline schedule using a project buffer. However, when the delay would exceed 15% of its planned duration, this is not assumed to be acceptable anymore.

Therefore the $SPI(t)$ threshold was set at a value that corresponds with a 15% delay. By following

FIGURE 4.3: SPI(t) and SPI_{ESWC}(t) scatter plots

the horizontal line on the figure, which indicates a 15% delay, we see that an SPI(t) threshold value of about 0.875 corresponds with this delay. For the sake of simplicity and to include a safety margin, the threshold value for the SPI(t) parameter will be set at 0.85.

Generating the SPI_{ESWC}(t) parameter was done in a similar way as the SPI(t) threshold value. The same projects were each subject to a simulation of 1000 runs but now the final SPI_{ESWC}(t) values were calculated at the end of the project. By ranking these values and comparing them with the %delay, a new scatter plot was created (Figure 4.3b). On this scatter plot, we can see that the accuracy of the SPI_{ESWC}(t) is somewhat lower than the SPI(t)'s accuracy. Further on, the SPI_{ESWC}(t) is overall a more stringent parameter and penalizes smaller delays somewhat higher than the SPI(t) parameter. For example, projects with a delay of around 30%, have a SPI_{ESWC}(t) value of 0.7, while their corresponding SPI(t) value is only around 0.75. Again a 15% delay was assumed to be acceptable and therefore the threshold value for the SPI_{ESWC}(t) was set at 0.875, somewhat higher than the SPI(t) value to obtain more or less the same level of parameter severity.

Activity/resource selection policies

During project execution, the project manager should identify the most appropriate activities/resources for corrective action taking. Which activities/resources should be selected depends on the type of corrective action that will be performed.

Martens & Vanhoucke (2019) describe three different strategies that can be deployed for determining the eligible activities.

- *Interventive strategy*: only activities that are being executed can be selected. This strategy deploys a more traditional view on taking corrective actions for project control as only the remaining duration of the activity will be affected.

- *Preventive strategy*: the project manager will only perform corrective actions on activities that have not been started yet. Consequently, the entire activity duration will be affected instead of only the remaining part.
- *Hybrid strategy*: this is a combination of both strategies and enables a project manager to perform corrective actions on both active and future activities.

Now I will determine which selection policy will be used for each of the four corrective action types.

Activity crashing: interventive strategy.

For the 'activity crashing' corrective action, I decided to only focus on the active activities. The rationale behind this decision lies in the large complexity associated with scheduling activities for future crashing. As the expected activity duration is subject to relatively high uncertainty, the real activity duration may be much higher (or lower) than its expected duration. However, the duration variability remains uncertain until the activity is active. So crashing an activity before it is being executed could result in wasting resources, as it is difficult to predict the impact of an activity on the project duration before any information is collected regarding its actual execution. It could be that the riskiness is much lower than initially expected and that crashing this activity will only result in a cost increase without impacting the project duration. Once the activity is executed, a project manager can more easily track its actual progress, forecast its expected duration and compare this to the planned duration. Based on this comparison, this activity can be selected to be crashed if it is expected to impact the project duration.

Activity variability reduction: hybrid strategy.

Reducing the variability of an activity can be applied to both active and future activities. This corrective action will require the project manager to collect more accurate information regarding an activity's duration and resource use. This can be done effectively while the activity is being executed and or when it is still waiting to start.

After the eligible activities have been selected, they will be ranked according to decreasing *MOI 2* values. In this way, the activity with the highest *MOI 2* value will be selected first and will be subject to a corrective action measure. If performing the corrective action is not possible, i.e. its remaining duration is one (activity crashing) or its variability is already set at the lowest level (activity variability reduction), the subsequent activity will be selected from the ranked list. Note that after taking corrective action, the values for the *MOI 2* index will be recalculated for each activity. In this way, the set of most critical activities will be updated and different activities will be selected for taking the next corrective measure.

Selecting the eligible resource will be easier as compared to selecting an eligible activity because the number of resources is usually lower than the number of activities. Additionally, each resource is likely to be used during the entire project duration and no distinction between future, active and finished resources can be made.

Resource availability increase: the resources will just be ranked according to decreasing resource risk values. Again the first activity from the list will be selected and its availability will be increased. Afterwards, the project will be rescheduled and the resource risks will be recalculated.

Resource boosting: for this corrective action, all resources will be selected and therefore no selection has to be made.

Corrective actions

The corrective actions were already extensively explained in Section 3.2 and will not be repeated here. In this part, the parameters used as input for the different corrective actions will be determined.

Both the activity level control corrective actions will make use of a WC_{rate} to calculate the work content increase related to taking the corrective measure (Equation 3.9 and 3.13). The value for the WC_{rate} will be set at 1.2.

For the activity variability reduction corrective action, the values for the parameters modelling the reduced activity duration variability function have to be determined.

The original activity duration probability function, before any corrective actions are taken, will be represented by an arithmetic mean m of 1.1 and a standard deviation s of 0.3. The resulting values for μ , σ , e^μ and e^σ , calculated according to Equations 3.1 and 3.3, are represented in the first row of Table 4.2 (No action). But as these parameters are not robust parameters for skewed distributions, adapting the variation of the original distribution by modifying s for a fixed m would not be appropriate. The arithmetic mean would decrease as the probability of generating high values from the right tail would decrease by reducing the activity variability. Hence both the arithmetic mean and standard deviation would decrease upon reducing an activity's variability without any linear relation being present between the mean reduction and standard deviation reduction. Accordingly, I will reduce the standard deviation σ for a fixed mean μ , resulting in a constant geometric mean e^μ for each RLU and a geometric standard deviation e^σ that will be decreased with a factor $e^{-1(1-RLU)\sigma}$. This approach will result in lower arithmetic means for lower RLU's, while the geometric mean and arithmetic median (which is equal to the geometric mean by definition) remain constant. A summary of the parameters can be found in Table 4.2.

	Arithmetic moments				Geometric moments	
	Activity durations		ln(activity durations)		Activity durations	
	m	s	μ	σ	μ	e^σ
No actions	1.1000	0.3000	0.0594	0.2679	1.0612	1.3072
RLU 0.75	1.0829	0.2197	0.0594	0.2009	1.0612	1.2225
RLU 0.50	1.0708	0.1441	0.0594	0.1340	1.0612	1.1433
RLU 0.25	1.0636	0.0713	0.0594	0.0670	1.0612	1.0693

TABLE 4.2: Activity distribution parameters

For the resource level corrective actions, no specific parameters are required as input. It is important to bear in mind that increasing a resource's availability will deploy gradually and incrementally by increasing the selected resource's availability by steps of 25%. For the resource boosting action, the availability increase will depend upon the difference between the maximal expected demand and the current resource availability.

Update remaining project execution

After taking corrective actions on the selected activities or resources, new precedence relation or resource conflicts might occur as a result of impacting the activity durations or resource availabilities. Further on it is also likely some activities can be shifted forward in time as a result of the corrective action, resulting in a shorter project duration. Therefore, it is necessary to reschedule the remaining part of the ongoing project to update its information. Note that only activities that have not been started yet will be rescheduled as the start times of active or finished activities cannot be impacted anymore.

Rescheduling the remaining part of the project will be done using the same five priority rules applied to construct a baseline schedule: SPT, MIS, EST, GRWC, and LST. The priority rule resulting in the shortest project duration will be selected to eventually reschedule the remaining part of the project, independently of the priority rule used to create the baseline schedule. After the project has been rescheduled, the parameter values for the activity *MOI2* and resource risk will be recalculated. This step will be necessary for controlling the remaining part of the project as the riskiness of each activity and resource will be impacted by adaptations to the schedule. So if the project manager wants to make sure to select the most critical activity or resource for performing the next corrective action, these parameters will have to be updated first.

4.2.3 The evaluation stage

When the project has been finished after being controlled using one of the two control approaches and a corresponding corrective action, the effectiveness of that control approach and the corrective action will have to be measured. Martens & Vanhoucke (2019) used the *time effectiveness* and *cost effectiveness* measures to determine the time and cost performance of a

control method. I will make use of the same performance parameters while making a few adaptations to the *cost effectiveness* parameter.

In terms of time performance, a project manager will apply effort to a project and intervene if necessary to decrease the project duration and minimise delays. Accordingly, the delay reduction after corrective actions will be used to evaluate the time performance of the different policies. More precisely the *time effectiveness* parameter will be calculated to assess a policy's time performance. This performance measure indicates the relative average delay reduction that can be achieved by controlling a project using a specific type of corrective action and is calculated using Equation 4.3

$$time\ effectiveness = \frac{\overline{Delay_{No}} - \overline{Delay_{Yes}}}{\overline{Delay_{No}}} \quad (4.3)$$

with $\overline{Delay_{No}}$ the average delay when a policy without corrective actions has been applied and $\overline{Delay_{Yes}}$ the average delay when a policy with one of the corrective actions has been imposed.

Certainly, decreasing a project's duration will come at a certain cost. One way the costs will be impacted is by the fact that real activity durations will differ from their planned durations and therefore the activity-related work content will change. As the activity cost related to one specific resource is calculated by multiplying the activity's resource-related work content by the corresponding resource's unit cost, the total activity cost will be affected by the real activity duration. Secondly, taking corrective action will also entail additional costs and have to be included in the total project cost. So in the end it is likely the total project cost will vary from the project's planned total cost, i.e. its BAC. This impact will be represented by the *cost effectiveness* parameter, which is calculated similarly to the *time effectiveness* parameter (Equation 4.4).

$$cost\ effectiveness = \frac{\overline{Cost_{Yes}} - \overline{Cost_{No}}}{\overline{Cost_{No}}} \quad (4.4)$$

with $\overline{Cost_{No}}$ the average difference between the project cost without applying any corrective actions and the project BAC. The parameter $\overline{Cost_{Yes}}$ represents the average difference between the project cost related to a policy including one of the corrective actions and the project BAC.

4.3 Initial Hypotheses

In this subsection, I will outline my initial hypotheses regarding the performance of the activity level vs resource level control for controlling projects with low and high values for the previously mentioned factors. All these hypotheses will be validated during the simulation stage of the project and will be reviewed later on.

- **S/P-value:** the higher the S/P value, the more serial a project and the higher the efficacy of an activity level control approach compared to the resource level approach.

When a project is a 100% serial, all its activities will be executed one after another. This entails that no matter the resource availability, each activity will nevertheless have to wait for its predecessor(s) to be finished before it can be started. So increasing the availability of one or more resources will not have any impact on the project duration. However, when you achieve to reduce the duration of one or more activities, this will allow all these activities to be shifted forward in time and reduce the final project duration. Therefore the activity level control approach will be more effective in controlling projects with a high S/P-value.

When the S/P-value of a project decreases and more activities can be executed in parallel, the level of resource utilization will increase and as a result, the effectiveness of the resource level control is likely to increase. Increasing a resource's availability will probably allow more activities, that are not precedence related, to be executed simultaneously and therefore reducing the final project duration.

H₁: the higher the S/P-value of a project, the higher the efficacy of an activity level control approach compared to the resource level approach

- **Level of activity variability:** a higher level of activity variability will result in a higher (possible) deviation between the actual and mean duration of the activity. Imposing a lognormal distribution on the activity duration will especially result in higher values in the right tail of the distribution and therefore in a higher activity duration. However, values that are lower than the mean duration are still possible, but in general, increasing an activity's variability will result in higher activity duration.

This will in its turn cause the final project duration and its total work content to increase. Nevertheless, a resource level control approach will not provide a viable solution for this event as increasing the availability of one or more resources will not impact an activity's duration and will not lower the project duration significantly. The activity level control approach on the contrary will be able to reduce an activity's duration, by either crashing the activity or reducing its variability, and will therefore be more effective in controlling this kind of project.

Further on I also believe the efficacy of reducing an activity's variability will increase with increasing activity variability. This is because the variability will always be decreased gradually in steps of 25%, but the higher the initial value of the variability, the higher the variability decrease in absolute terms and so the higher the probability of generating lower activity durations.

H₂: the higher the activity variability level, the more effective an activity level control approach compared to the resource level control approach

H₃: the higher the activity variability level, the more effective the 'activity variability reduction' action will be compared to the 'activity crashing' measure

- **Number of activities:** the more activities involved in a project, the higher the probability of having some very critical activities, with high values for the MOI 2 parameter, but also the more activities that are non-precedence related.

The first consequence, i.e. having more critical activities, gives an advantage of the activity level control approach over the resource level approach. These activities with a high MOI 2 value will impose a high risk on the project and its final duration. Therefore taking corrective actions on these activities can have a significant impact on the project. When applying a resource level control approach on the other hand, this will not allow a project manager to distinguish between risky and less risky activities and each corrective action will impact both types of activities and therefore losing some of its efficacy.

The second consequence, i.e. the more non-precedence-related activities, will in its turn give the advantage of a resource level control approach. Increasing the availability of one or more resources will allow these non-precedence-related activities to be executed in parallel instead of in series. This will in its turn decrease the final project duration.

However, I believe that the impact of reducing the riskiness of very critical activities will have a more significant impact on the project duration than executing more activities in parallel. Therefore I suppose the effectiveness of an activity level control approach compared to the resource level approach will increase when the number of activities increases.

H₄: the more activities involved in a project, the more effective an activity level control will be compared to the resource level approach

- **Number of resources:** the more resources are involved in a project, the more resource constraints are imposed on the execution of the activities. Therefore I believe the resource level control method will be more effective as the number of resources increases. Also, the efficacy of resource boosting action compared to increasing the availability of only one resource will increase with an increasing number of resources. This is because when a large number of resources is used, only increasing the availability of one of them will not be sufficient to shift many activities in time as they will still be constrained by other resources. On the other hand, when increasing the availability of all resources, while only a few of them is a big constraint for the project, will unnecessarily increase the costs significantly. So whether or not resource boosting will be more effective than increasing the availability of one resource, will depend upon the objective of the project.

H₅: the more resources involved in a project, the higher the efficacy of the resource level control,

- **Resource similarity:** the higher the resource similarity parameter, the higher the disparities between the scarceness values of the resources, and the more effective a resource level control approach will be compared to the activity level approach.

More precisely, when the resource similarity parameter increases, there will be at least one resource that has higher values for its resource scarceness. This entails that the total demand for that specific resource will be relatively high compared to its total availability causing the resource constraints for the project to be more constraining than the precedence relation constraints. Therefore I believe the resource level control approach will be more effective for controlling projects with a low degree of resource similarity. Especially increasing the resource availability will be an effective tool to bring a failing project back on track as this action will increase the resource supply and therefore somewhat lower the resource scarceness values. Resource boosting will be less appropriate in this case as increasing the availability of all resources, including the ones with a low resource scarceness, will unnecessarily increase the project costs more than needed.

On the other hand, when the resources are very similar to each other, increasing the availability of one of them will not influence the project's final duration that much as the other resources will still impose a huge constraint on the possible parallel execution of non-related activities. In this case, it would be more advantageous to increase each resource's availability simultaneously to speed up the project execution.

H₆: the higher the resource similarity parameter, the higher the efficacy of the resource level control compared to the activity level control

H₇: the higher the resource similarity parameter, the higher the efficacy of the 'resource availability increase' action compared to the 'resource boosting' action

It is crucial to bear in mind that in the special case of all resources having a high resource scarceness value, the resource similarity parameter will correspondingly have a low value. However, I believe that in this case, the resource level control approach will still outperform the activity level approach in terms of efficacy.

5 Computational experiments

In the first section, Section 5.1, the various computational experiments to be conducted will be presented. This entails a comprehensive examination of the experiment's design, including the specific parameter values related to each experiment. Subsequently, the results of these computational experiments will be discussed in Section 5.2. More precisely, I will analyse the impact of modifying the S/P-value (5.2.2), the level of activity variability (5.2.3), the number of activities (5.2.4), the number of resources (5.2.5) and the resource similarity (5.2.6) on the effectiveness of both the activity and resource level control approaches.

5.1 Experiment design

Table 5.1 represents the set of experiments that will be conducted in my research. Each entity of these experiments will be subject to a simulation including 100 projects with the associated parameter values. As a consequence, 1800 ($=18 \times 100$) projects are generated and will be tested in the experiment. This large set of fictitious projects with a predefined number of activities and a topological network structure was generated by a project network generator RanGen2 (Vanhoucke et al., 2008). The other project characteristics, i.e. the level of activity variability, the number of resources and the resource similarity were added to these generated projects using the P2Engine software and its included packages and functions.

Each of these projects will be simulated 1000 times to obtain a reliable estimate of its performance. However, some of these projects, denoted by an asterisk, were only simulated 500 times due to computational limitations and time constraints. More specifically, these experiments could take up to seven days and were therefore only simulated 500 times. Nevertheless, the results after simulating the projects 500 times are still expected to be a reliable estimation of the average project performance. Below, I provide a more detailed explanation of the six sets of experiments to be conducted complemented by a description of their intended goals.

- **Standard:** this set of experiments will serve as a point of reference for all subsequent sets of experiments. The parameters associated with this standard design can be found in Table 4.1, with their corresponding values indicated by underlining.

In each of the following sets of experiments, one of the project characteristics of this standard project design will be modified while keeping the other parameters constant. This will allow me to identify the impact of altering that specific parameter on the effectiveness

Topic	Nr	No action	Activity level control			Resource level control		Obj	WC rate	S/P	Act var	#Act	#Res	RS
			Act crashing	Act var reduc	Res avail incr	Res boosting								
Standard	1	x	x	x	x	x*	x*	Min dur	1.2	0.6	0.3	20	3	3
S/P	2	x	x	x	x	x*	x*	Min dur	1.2	0.2	0.3	20	3	3
	3	x	x	x	x	x*	x*	Min dur	1.2	0.4	0.3	20	3	3
	4	x	x	x	x	x*	x*	Min dur	1.2	0.8	0.3	20	3	3
	5	x	x	x	x	x*	x*	Min dur	1.2	0.6	0.2	20	3	3
Act var	6	x	x	x	x	x*	x*	Min dur	1.2	0.6	0.4	20	3	3
	7	x	x	x	x	x*	x*	Min dur	1.2	0.6	0.5	20	3	3
#Act	8	x	x	x	x	x*	x*	Min dur	1.2	0.6	0.3	10	3	3
	9	x	x	x	x	x*	x*	Min dur	1.2	0.6	0.3	15	3	3
	10	x	x	x	x	x*	x*	Min dur	1.2	0.6	0.3	25	3	3
	11	x	x	x	x	x*	x*	Min dur	1.2	0.6	0.3	30	3	3
	12	x	x	x	x	x*	x*	Min dur	1.2	0.6	0.3	20	1	3
#Res	13	x	x	x	x	x*	x*	Min dur	1.2	0.6	0.3	20	2	3
	14	x	x	x	x	x*	x*	Min dur	1.2	0.6	0.3	20	4	3
	15	x	x	x	x	x*	x*	Min dur	1.2	0.6	0.3	20	5	3
	16	x	x	x	x	x*	x*	Min dur	1.2	0.6	0.3	20	3	1
RS	17	x	x	x	x	x*	x*	Min dur	1.2	0.6	0.3	20	3	2
	18	x	x	x	x	x*	x*	Min dur	1.2	0.6	0.3	20	3	4

TABLE 5.1: Design of experiments

of the four corrective action types. Note that in my design of experiments only the main effects of each project parameter will be investigated and no cross-effects will be identified. To examine the cross effects, one has to modify two or more parameters at once to verify whether the effect of adapting the two individual parameters is strengthened or compensated when modifying multiple parameters at once. The results I will obtain for the main effects could be a good starting point to investigate the cross effects in future research.

- **Serial/parallel value (S/P):** in this second set of experiments, containing experiments number 2 to 4, the impact of an increasing S/P value on the efficacy of both control methods will be investigated. The S/P-value will be increased incrementally in increments of 0.2 while keeping the remaining project parameters constant.
- **Level of activity variability (Act var):** experiments 5 till 7 investigate the effect of an increased activity duration variability on the effectiveness of both control methods. The activity duration variability, parameterised by s will be altered by increasing the arithmetic standard deviation σ in increments of 0.1 and keeping the arithmetic mean μ constant. Observe that again the parameter σ will be altered and not the s parameter because of its unrobustness. In Table 5.1, the values for the standard deviation σ are given. The corresponding values for the arithmetic mean m and standard deviation s can be calculated using Equation 3.2. For the activity variability reduction corrective action, also the arithmetic mean and standard deviation were recalculated based on the initial activity variability value. This was done by first recalculating the arithmetic standard deviation σ for the different RLU levels and keeping the mean μ constant. Thereafter the values for the mean m and standard deviation s were recalculated using Equations 3.2.
- **Number of activities (#Act):** in the fourth set of experiments, the effect of altering the number of activities included in the project was investigated. Projects with 10, 15, 20, 25 and 30 activities were subject to a simulation experiment using one of the four corrective action types or using no project control approach at all.
- **Number of resources (#Res):** the impact of modifying the number of resources used in a project was investigated in experiments 12 to 15. The values for the resource usage (RU) and resource constrainedness (RC), and eventually the resource scarceness (RS), that were used in each of the experiments can be found in Table C.1 in Appendix C. Note that when only using one resource for the project, the value for the resource similarity inherently equals 1.
- **Resource similarity (RS):** a last factor that was investigated was the effect of adapting the resource similarity parameter on the effectiveness of both control approaches. The resource similarity value was increased gradually in increments of one resulting in values within the

range of 1 (experiment 16) to 4 (experiment 18). The exact values of the resource usage constrainedness and scarceness are displayed in Table C.2 in Appendix C.

5.2 Results analysis

5.2.1 Global results

Table 5.2 and Figure 5.1 display the average performance of both control methods over all sets of experiments. The results of the activity level control approach are a result of averaging the performance of the activity crashing and activity variability reduction actions. Taking the average performance of the resource availability increase and resource boosting action resulted in the resource level control approach performance.

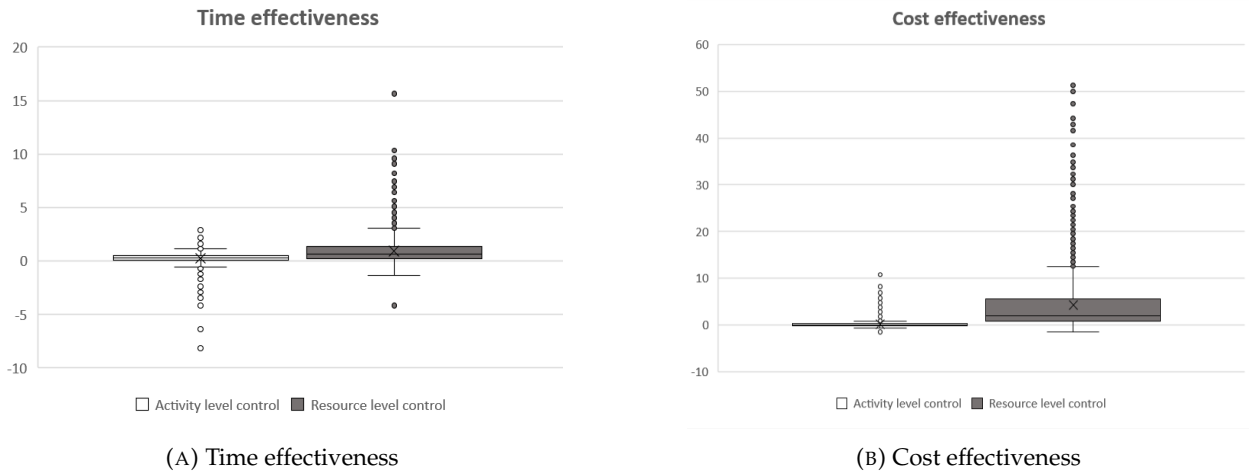


FIGURE 5.1: Activity and resource level control performance plots

The layout of each boxplot represents the following key measures:

- The **minimal and maximal values** are represented by the boxplot's whiskers
- The **quartiles** are represented by the lower boundary of the box (Q1), the line indicated inside the box (Q2 or median) and the upper boundary of the box (Q3)
- The **inter quartile range (IQR)**, which is the range between the first and third quartile, is represented by the box height
- The **average value** is represented by a cross inside the boxplot's box
- The **outliers**, which are points that differ from the lower or upper quartile by more than 1.5 times the IQR, are represented by individual points beyond the whiskers

The formulas for calculating the time and cost effectiveness values are shown by Equations 4.3 and 4.4. For the time effectiveness values, a higher value indicates a smaller delay as compared

	Activity level control		Resource level control	
	Mean	Sd	Mean	Sd
Time effectiveness	0.236	0.460	0.937	1.106
Time effectiveness/action	0.105	0.134	0.154	0.390
Cost effectiveness	0.136	0.639	4.250	5.801
Cost effectiveness/action	0.048	0.238	0.290	0.432

TABLE 5.2: Activity and resource level control performance results

to the delay when executing a project without any control policy, and therefore a better time performance. For the cost effectiveness value, on the other hand, higher values result from an increased project cost as compared to the project costs incurred when running the project without taking any corrective actions, and therefore a worse performance in times of costs.

Based on Figure 5.1 and Table 5.2, we can conclude that in general, the resource level control approach outperforms the activity level approach in terms of time performance. However, the average cost performance of the resource level control is much worse than the cost performance of the activity level control approach. It could have been expected, according to the traditional time/cost trade-off, that the costs related to the resource level approach would be higher than the cost for the activity level approach as also its time performance is better. But that the cost increase is so significant was not expected and deserves some special attention in the subsequent parts. Further on, the standard deviation of both the time and cost effectiveness parameters is very high for the resource level control approach.

The time and cost effectiveness values for the four corrective actions separately can be observed in Table 5.3 and Figure 5.2. These results are again an average over all the simulations performed in this research.

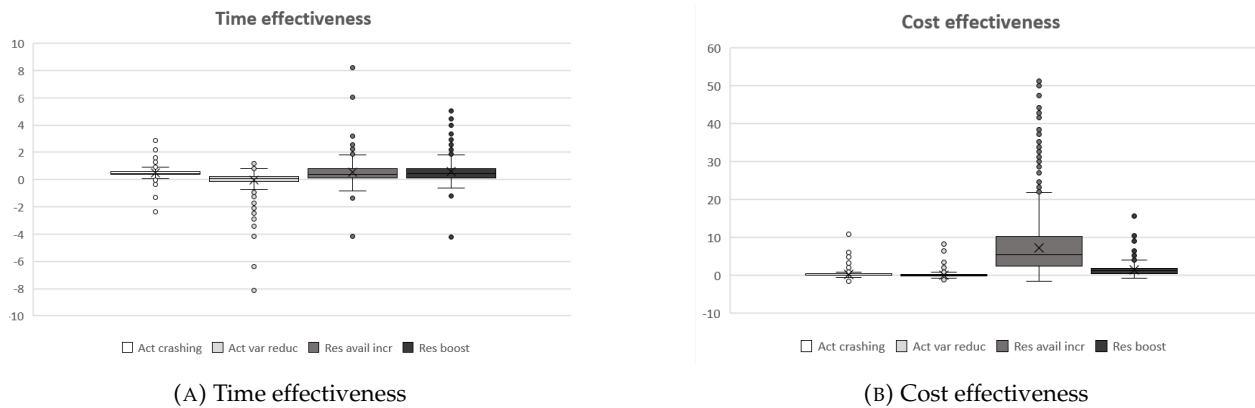


FIGURE 5.2: Corrective actions performance plots

The first conclusion we can draw is that again both resource level corrective actions outperform

	Activity crashing		Act var rteduc		Res avail incr		Res boosting	
	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Time effectiveness	0.492	0.230	-0.020	0.388	0.527	0.598	0.577	0.639
Time effectiveness/action	0.207	0.115	0.002	0.045	0.104	0.212	0.163	0.468
Cost effectiveness	0.250	0.743	0.022	0.489	7.161	6.978	1.347	1.324
Cost effectiveness/action	0.099	0.326	-0.002	0.045	0.375	0.324	0.204	0.504
Avg actions/project	2.593	1.091	14.257	5.226	17.524	12.407	15.550	11.687

TABLE 5.3: Corrective actions performance results

the activity level actions in terms of their average time performance. The activity crashing action's time performance is still comparable to the resource level actions, but the activity variability reduction action is performing very badly and does not impact a project's delay on average. Further on, Table 5.3 also shows that the variability in times of time performance for the resource level actions is again very high as compared to the activity level actions resulting in high standard deviation values.

Also, the cost performance of the resource level actions, and especially the resource availability increase action, is very high compared to the resource level actions.

When observing the average time performance per corrective action, the activity crashing is the most effective in impacting a project's delay, followed by the resource boosting and resource availability increase actions. The activity variability reduction action shows again having no significant impact on the project's delay.

The cost effectiveness per corrective action on its turn, is again very high for the resource level actions and is the lowest for the activity variability reduction action.

Without going into too much detail, some irregularities immediately show up in these results:

- **Perfect negative correlation between time and cost effectiveness for the activity variability reduction action:** this is caused by the fact that on average, the resource variability reduction action failed to impact and reduce the project delay. As shown in Table 5.3, this corrective action even increased the project delay by 2% on average. In some cases, however, the activity variability reduction action has indeed achieved to reduce the project delay significantly, as will be shown in the remainder of this section. But in some other cases, as shown by the positive outlier points in Figure 5.2, reducing the activity variability even increased the project duration. This resulted in an elevated standard deviation of the time effectiveness parameter. The cost effectiveness shows some similar behaviour as the time effectiveness parameter. On average the project costs were increased, which can be expected from taking corrective actions. However, this increase is very moderate when compared to the cost effectiveness values for the other corrective actions

and also shows a very high standard deviation.

Further on, Table 5.3, also shows that on average, the time effectiveness per activity variability reduction action was almost zero. This is caused by the fact that reducing an activity's variability could increase or decrease the activity's duration. However, the possible activity duration decrease is rather limited as it is constrained by the activity's (remaining) duration. The possible duration increase on the other hand is more significant as a lognormal distribution was used to model the activity's duration. Evidently, the possibility that an activity's duration would be decreased is higher than the possibility of increasing that activity's duration. But as the potential increase is much higher than the potential decrease, the average time effectiveness per corrective action approached zero. The average cost effectiveness per corrective action is somewhat higher than zero. Based on these findings, we can conclude that reducing an activity's variability usually did not decrease the project delay and only incurred additional costs. Therefore projects being controlled using the activity variability reduction action often returned low time effectiveness and high cost effectiveness values when the number of actions performed increased.

- **High costs related to the corrective action of increasing a resource's availability:** as can be seen in Figure 5.2, increasing the availability of a resource performs very badly in terms of its cost performance when compared to the other corrective actions. Two main reasons are responsible for these elevated costs:
 1. **High cost per corrective action:** the cost for performing one corrective action is very high as compared to the other corrective actions as can be seen in Table 5.3. For the activity crashing and variability reduction actions, the cost per action is calculated as a fraction of the activity's fixed cost, which lies in the range of 100 to 1000, and possibly some additional costs related to a temporary increase of one of the resource's availabilities as a result of the increased work content and resource demand of the impacted activity. For the resource boosting action, the additional cost is expressed as a multiple of the resource unit costs for all resources. However, as the resource boosting duration is usually relatively short compared to the project's total duration, these costs are still relatively low. For the resource availability increase action, the costs are also a multiple of the impacted resource's unit cost, but this time this cost will be incurred during each period of the remaining project's duration. This results in a high cost per action compared to the other corrective actions.
 2. **High number of corrective actions per project:** Table 5.3 also shows that on average, the number of corrective actions taken during each project run is very high for both resource level correction actions.

- **High variability in the performance of the resource level actions:** the standard deviation of the time and cost effectiveness parameters for the resource level actions are relatively high compared to the activity level actions. This results from the fact that the resource level actions are less robust than the activity level actions. As will be explained in the remainder of this section, modifying one of the project characteristics will impact the resource level actions more than the activity level actions. This results in the resource level control approach clearly outperforming the activity level approach for some project instances, while being underperforming for some other project instances. Therefore both the resource availability increase and resource boosting actions return high standard deviations for their time and cost performance.
- **Lot of outlier points for the activity variability reduction action:** this can be explained by the fact that reducing the activity's variability can have a very diverse impact on the corresponding activity's duration. In the simulation experiments, the new activity duration was just generated from drawing a random duration from the lognormal distribution with the reduced standard deviation. This will usually cause your activity duration to decrease, but the extent to which this decrease will happen is uncontrollable. Further on, reducing an activity's variability also exceptionally results in an increased activity duration. So in many of those outlier points, the activity variability reduction action was very ineffective and even somewhat increased the activity's duration resulting in a very late finish of the project. However this was a rather unusual event and in most of the cases, the activity duration was indeed decreased resulting in a shorter project duration.
- **Lot of outlier points for resource level corrective actions:** these outliers are caused by projects whose time or cost performance is already very good, even when being executed without applying any control policy. This caused the average delay and/or average cost deviation without taking any corrective action to be close to or even below zero. As the average delay and project cost are used in the denominator in the formulas for calculating the time effectiveness parameter (Equation 4.3) and cost effectiveness (Equation 4.4), these values were largely impacted by relatively small changes in the project delay and total cost after corrective action taking. This caused many of the simulations of those projects to return very high (low) values for the time and/or cost effectiveness parameters and therefore was responsible for the positive (negative) outlier points shown in Figure 5.2. The occurrence of the outlier points will be repeated in many of the following boxplots but they will always be caused by projects performing very well in terms of their time and/or cost performance when they are being executed without any control policy unless stated otherwise. These outliers rarely occur for the activity crashing actions. This is because the impact of those actions is less extreme, in both the negative and positive way, compared to the resource level actions. This is confirmed by the low average standard deviation of the time and cost effectiveness values for the activity crashing action (Table 5.3).

5.2.2 S/P results

The effect of increasing the S/P-value on a project's time and cost performance using an activity and resource level control approach can be observed in Figure 5.3. For the mean and standard deviation values of the performance measures, I refer to Table D.1 and Appendix D.

Time effectiveness

When observing the time effectiveness of the four corrective action types for increasing levels of the S/P-value, we can see that the time effectiveness of the resource level control approach, containing the resource availability increase and resource boosting actions, decreases significantly as the S/P-value increases. Furthermore, we can see that also the effectiveness of the activity crashing action slightly decreases upon increasing the S/P-value, while the efficacy of the activity variability reduction action seems to increase slightly.

Moreover, the resource level corrective action types clearly outperform the activity level corrective action types for low S/P-value ($SP=0.2$ and $SP=0.4$), while the activity level actions seem to be slightly more effective for controlling highly serial projects ($SP=0.8$). This finding is perfectly in line with the initial hypothesis H_1 we made in Section 4.3 regarding the impact of an increasing S/P-value on the effectiveness of both control approaches.

The reason behind this finding can be understood from the fact that when controlling highly parallel projects, it is more effective to increase the resource availability rather than decrease an activity's duration. This is because by increasing the availability of one or more resources, you will probably allow more activities, that are not precedence related, to be executed in parallel instead of in series resulting in a reduced project duration. On the contrary, decreasing the duration of an individual activity will probably not have a significant impact on your project duration as there are many activities already being executed in parallel. Consequently, reducing the duration of one of those activities would not necessarily allow an earlier start of its successors as they would still be contingent on the completion of its other predecessor activities.

In Figure 5.3a and in Table D.1 in Appendix D, we can also observe that the variability in the time effectiveness also decreases as the S/P-value increases. This is because projects with low S/P-values usually have a shorter project duration than more serial projects. This is evident as both project types have the same number of activities, but for projects with a low S/P-value, more activities can be executed in parallel resulting in shorter project duration. This was also confirmed in the simulation data as projects with an S/P-value of 0.2 had an average planned duration of 52.68, while projects with an S/P-value of 0.4, 0.6 and 0.8 had an average duration of 60.95, 73.06 and 90.47. Consequently, reducing the project duration by one time unit will have a larger impact on projects with a shorter duration than on projects with a long project duration, resulting in a higher variability in the time effectiveness parameter.

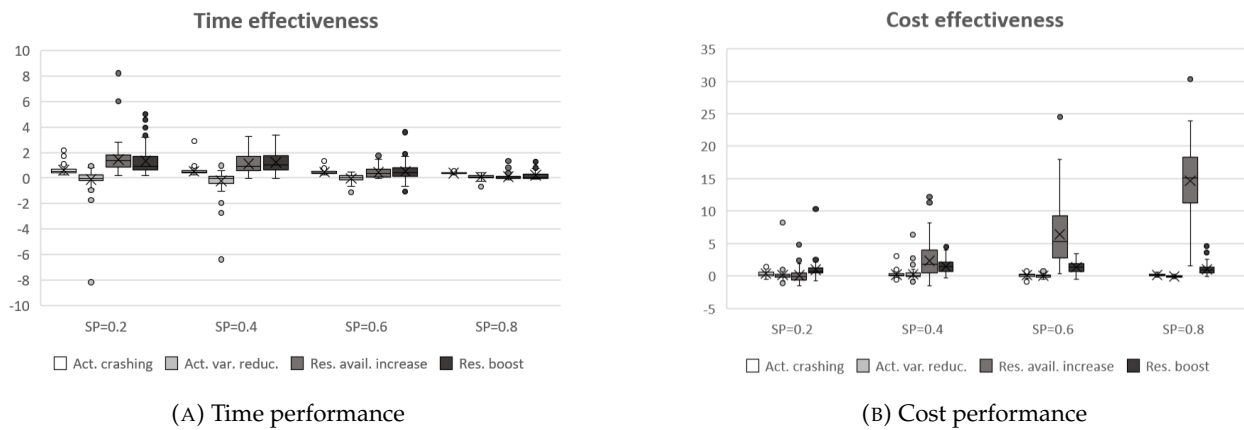


FIGURE 5.3: Impact of S/P on the time and cost performance

Figure 5.3a also indicates that for the activity variability reduction, resource availability increase and resource boosting corrective actions, there are some significant outliers. The causes underlying these outliers were explained in the previous part.

Cost effectiveness

When looking at the cost effectiveness of both control approaches, Table D.1 indicates that the costs related to the activity and resource level actions do not seem to behave according to the time/cost trade-off shown in Figure 3.5.

For the activity crashing action, this time/cost trade-off was respected as decreasing values for the time effectiveness parameter, i.e. a worse time performance, correspond with decreasing values for the cost effectiveness parameter, i.e. a better performance in terms of cost.

For the resource boosting action, this trade-off can also be observed in the results, except for the S/P=0.2 level. However, for the resource availability increase action, projects with a decreasing time performance also seem to perform worse in terms of their cost performance. This behaviour is very surprising and deserves some further clarification.

Table 5.5 shows the cost effectiveness, average number of corrective actions and average time effectiveness per action for each set of experiments. These data were arranged in descending order based on the cost effectiveness values. The average time effectiveness per action was calculated by dividing the time effectiveness by the number of corrective actions performed in each simulation run. Thereafter the average over all simulation runs and all project instances was taken to generate the time effectiveness per action for all experiments.

First of all this table explains why for the S/P=0.2 level, the cost effectiveness related to the resource boosting action is lower than the cost effectiveness for the other S/P levels, while also the time effectiveness of the S/P=0.2 level is the best out of all S/P levels. The lower right panel of Table 5.5 shows that for the S/P=0.2 level, time effectiveness per action was very high as compared to the other S/P levels. This caused the number of corrective actions required to

Act crashing				Act var reduc			
	Cost effect.	#Actions	Time effect./ action		Cost effect.	#Actions	Time effect./ action
SP=0.2	0.351	3.73	0.176	SP=0.4	0.220	14.02	-0.013
SP=0.4	0.189	2.85	0.204	SP=0.2	0.133	13.32	-0.004
SP=0.6	0.110	2.44	0.200	SP=0.6	0.029	13.49	0.000
SP=0.8	0.110	2.04	0.201	SP=0.8	-0.076	14	0.008
Res avail incr				Res boosting			
	Cost effect.	#Actions	Time effect./ action		Cost effect.	#Actions	Time effect./ action
SP=0.8	14.665	34.05	0.007	SP=0.4	1.427	5.71	0.500
SP=0.6	6.418	16.79	0.055	SP=0.6	1.330	15.78	0.129
SP=0.4	2.341	7.39	0.267	SP=0.8	1.014	30.72	0.013
SP=0.2	0.079	3.14	0.575	SP=0.2	0.939	2.91	0.865

TABLE 5.4: Average cost effectiveness, number of actions and time effectiveness per action for S/P set of experiments

control the project and their related costs to be very low. Taking into account the high effectiveness of each action, the project's duration could be decreased significantly without incorporating a lot of project control costs. The combination of the low corrective action costs and the cost savings from a reduced project duration caused the execution of highly parallel projects to outperform more serial projects in terms of cost (and time) effectiveness

The cost effectiveness trend for the resource availability increase action can be explained in a very similar way. For projects with low S/P-values, the effectiveness per corrective action was relatively high. Therefore taking a few corrective actions was sufficient to decrease the project duration significantly, leading to low corrective action costs and high cost savings from having a reduced project duration and resource supply. However as the S/P-value increases, the time effectiveness per action reduces significantly to almost having no impact for projects with an S/P-value of 0.8. This causes the final project delay reduction to approach zero for highly serial projects. More precisely, when taking corrective actions to bring a project back on track additional costs will be incurred independently of the effectiveness of that specific action. So when the corrective actions fail to reduce the project's final duration, the project will require new corrective actions during each subsequent time period incurring a high amount of corrective action costs. But as these actions are very ineffective in reducing your project duration, there will be no cost savings from a reduced project duration to compensate for these high corrective action costs, resulting in a very high total project cost at the end.

The ineffectiveness of each resource level corrective action for more serial projects is caused by the fact that in serial projects, the resource utilisation is generally very low. Many activities are required to be executed in series because of their precedence relations and not because their

parallel execution is constrained by the resource availabilities. So increasing the availability of one of your resources will generally not result in a reduced project duration, leading to a very low time effectiveness per action.

This causes the resource availability increase action to have the best cost performance for projects with an S/P-value of 0.2 to having by far the worst cost performance for projects with higher S/P-values. This trend is probably the major shortcoming of this corrective action type.

5.2.3 Activity variability

The effect of increasing the level of activity variability on a project's time and cost performance after being controlled using any of the corrective action types is displayed in Figure 5.4. The mean and standard deviation values of the time and cost effectiveness values are summarised in Table D.2 in Appendix D.

Time effectiveness

Figure 5.4a and Table D.2 illustrate that there is a relationship between the level of activity variability and the time performance of both control methods. For the activity level corrective actions, the time effectiveness increases as the level of activity variability increases while for the resource level actions, the opposite relation can be observed.

Further on we see that the activity crashing corrective action outperforms the resource level corrective actions for high levels of activity variability (Var=0.4 and Var=0.5), while for lower levels of activity variability (Var=0.2), the resource level actions are more effective in reducing a project's average delay. This finding is in line with the initial hypothesis H_2 regarding the impact of the level of activity variability on the performance of an activity versus resource level control approach.

The activity variability reduction action is the least effective corrective action in terms of time performance for all activity variability actions. Even more, for the activity variability levels Var=0.2, Var=0.3 and Var=0.4, it fails to reduce, or even increases, the project delay as compared to executing the project without taking any corrective actions. This is strongly inconsistent with hypothesis H_3 regarding the performance of the activity variability reduction action. H_3 assumed that the effectiveness of the activity variability reduction action compared to the activity crashing action would increase upon increasing the level of activity variability. This assumption was not confirmed in the time effectiveness results.

However Table D.2 indicates that the effectiveness of the activity variability reduction action increases with increasing levels of activity variability. This increase even exceeds the rise in the time effectiveness of the activity crashing action upon increasing the activity variability. If this trend is continued for even higher levels of activity variability, the activity variability reduction action would outperform the activity crashing action in terms of time performance. This

hypothetical finding could potentially provide supporting evidence for hypothesis H_3 but requires an additional set of experiments to be validated and confirmed.

The last aspect that will be discussed here, is the positive and negative outlier points for the activity level and resource level corrective actions for both the time and cost effectiveness value. As was explained previously, these outlier points are usually caused by projects performing very well even when being executed without any control policy. This reasoning will be proved here using an example.

Example

The projects responsible for the outlier points shown in Figure 5.4a consistently involve the same projects (i.e. projects with ID 72 and 76). When going a little deeper into the simulation data, these projects seem to have a very low delay as compared to the average project delay even when no corrective actions have been performed on them. The average project delay for projects 72 and 76, expressed as a fraction of the average project delay across all projects, varies as follows for the different activity variability levels: for project 72 the values are 0.35, 0.42, 0.55 and 0.65, for project 76 the values are 0.29, 0.47, 0.62 and 0.74. As the average delay without taking any corrective action was used in the denominator in the formula for calculating the time effectiveness parameter (Equation 4.3), these time effectiveness values were largely impacted by relatively small changes in the project delay after corrective action taking. This caused many of the simulations of those projects to return very high (low) values for the delay reduction and therefore was responsible for the positive (negative) outlier points shown in Figure 5.4a.

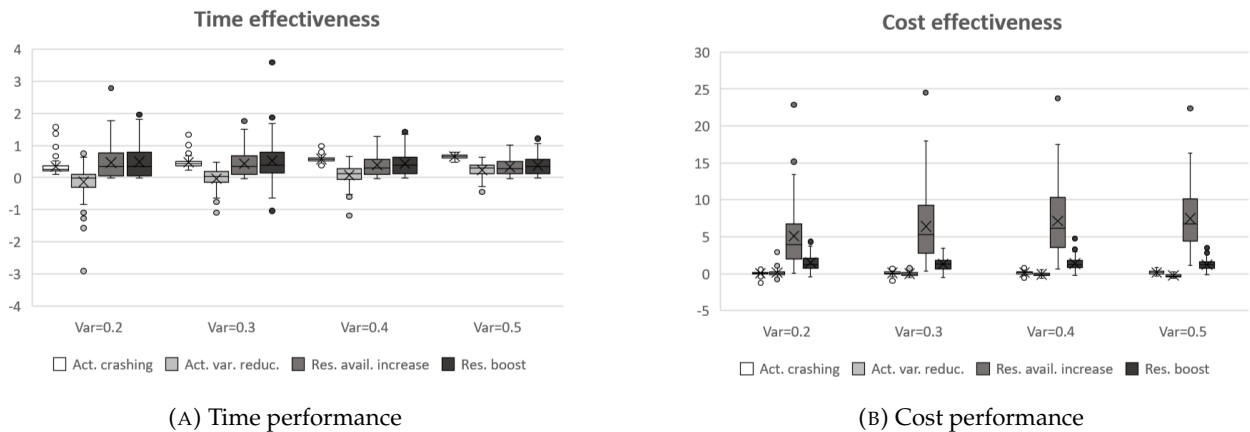


FIGURE 5.4: Impact of activity variability on the time and cost performance

Cost effectiveness

Regarding the impact of increasing the level of activity variability on the cost effectiveness of the different corrective action types, we can draw more or less the same conclusions as the impact of

an increasing S/P-value. For the activity crashing action, the trade-off between a project's duration and costs has been adhered to. The higher the activity variability level, the better the time performance (i.e. an increasing time effectiveness value) but the worse the cost performance (i.e. increasing cost effectiveness values). Further on, the cost differences over the different activity variability levels are more significant than the cost differences related to increasing the S/P-value.

This same relation can more or less be observed for the resource boosting action but, where an increasing project delay corresponds to a decreasing project cost, except for the Var=0.3 experiments.

However, for the corrective action of increasing the resource availability, the opposite relation can again be observed: an increasing project duration comes along with an increasing total project cost. To clarify this behaviour, Table 5.5 shows the average cost effectiveness, number of actions and time effectiveness per action for all corrective action types.

Act crashing				Act var reduc			
	Cost effect.	#Actions	Time effect./ action		Cost effect.	#Actions	Time effect./ action
Var=0.5	0.185	4.44	0.151	Var=0.2	0.139	9.69	-0.014
Var=0.4	0.154	3.42	0.173	Var=0.4	0.029	17.36	0.006
Var=0.3	0.110	2.44	0.200	Var=0.3	-0.078	13.49	0.000
Var=0.2	0.057	1.54	0.229	Var=0.5	0.226	19.72	0.013
Res avail incr				Res boosting			
	Cost effect.	#Actions	Time effect./ action		Cost effect.	#Actions	Time effect./ action
Var=0.5	7.485	32.54	0.016	Var=0.2	1.489	9.10	0.114
Var=0.4	7.122	24.44	0.028	Var=0.4	1.384	22.33	0.036
Var=0.3	6.418	16.80	0.129	Var=0.3	1.330	15.78	0.055
Var=0.2	5.103	10.13	0.117	Var=0.5	1.242	30.03	0.021

TABLE 5.5: Average cost effectiveness, number of actions and time effectiveness per action for Act var set of experiments

In the lower-left panel, we see that the effectiveness per resource availability increase action decreases significantly as the level of variability increases. This explains the unexpected behaviour of the time/cost relationship by the two following effects:

- **Increased corrective action costs:** because the effectiveness of each corrective action decreases when increasing the level of activity variability, more actions will be required to bring the project back on track, resulting in higher corrective action costs. The increase in the corrective action costs was more elevated than the corrective action costs for the other action types because of the high cost of the resource availability increase action.

- **Reduced project duration reduction:** even when implementing a large number of corrective actions, the impact on the final project duration is minimal resulting in very few cost savings from having a reduced project duration.

These two reasons cause the project costs to increase significantly when increasing the level of activity variability and disrupting the traditional time/cost relation.

The reason why the effectiveness of increasing the availability of a resource decreases as the level of activity variability increases, was not discovered in this research and will probably require a new set of simulation experiments.

5.2.4 Number of activities

The effect of increasing the number of activities involved in a project on the project's time and cost performance when being controlled using any of the four corrective action types can be observed in Figure 5.5. Table D.3 in Appendix D summarises the mean and standard deviation values for all performance measures.

Time effectiveness

The initial hypotheses H_4 indicating that the relative effectiveness of controlling a project using the activity level control approach as compared to controlling this project with a resource level control approach would increase with an increasing number of activities has not been confirmed by the simulation results. Even more, the opposite seems to be true: for projects containing a large number of activities (#Act=25 and #Act=30), both resource level corrective actions outperform the activity level actions in terms of their time performance. For projects including fewer activities (#Act=10 and #Act=15) on the other hand, the activity level control approach using the activity crashing action outperforms the resource level actions.

The reasoning behind this trend can be explained using the project's S/P-value, as was already partly assumed in Section 4.3, and was broadly confirmed in my simulation experiments. The S/P-value of a project is calculated by using Equation 5.1 (Batselier & Vanhoucke, 2017).

$$S/P = \frac{n_s - 1}{n_t - 1} \quad (5.1)$$

with n_s being the maximum number of subsequent activities in the network and n_t the total number of activities. In the simulation experiments performed to analyse the impact of an increasing number of activities, the S/P-value was set at 0.6. This means that on average, a maximal 60% of the activities would constitute the longest serial chain in the project network, leaving the other 40% of the activities to be executed in parallel with this chain. When interpreting this in absolute terms for projects with 10 and 30 activities, respectively 4 and 12 activities can on average be executed in parallel with this longest chain, if not constrained by any

resource constraints. This causes the efficacy of the activity level corrective action types, and especially the activity crashing action, to become less effective in controlling a project's time performance when the number of activities increases. More precisely, by reducing the duration of one of the activities, it is more likely the start of its successor(s) will be constrained by its other predecessors, resulting in a lesser impact on the final project duration. When increasing the availability of one or more resources, certain non-precedence-related activities will likely be allowed to be executed in parallel instead of in series. This will directly impact your final project duration, irrespective of the number of activities involved in the project.

Further on there is no clear relation visible between the number of activities involved in a project and the time effectiveness of the resource level corrective actions. The positive and negative time effectiveness outliers in Figure 5.5a again result from projects having relatively small delays when being executed without taking any corrective actions. This will cause your time effectiveness parameter to fluctuate heavily as explained earlier.

A last thing worth mentioning is that the standard deviation of the time effectiveness parameter decreases as the number of activities increases for all corrective action types. The reasoning behind this lies in the fact that projects with 10 activities will usually have a shorter duration than projects containing 30 activities. More precisely, the projects with 10 and 30 activities had an average planned duration of 56.51 and 115.09 time units respectively. Consequently, the impact of reducing an activity's duration by one unit of time or shifting an activity forward in time for one time unit will have a larger impact on the final project duration for projects with a smaller number of activities. This will cause the standard deviation of the time effectiveness parameter to be larger for projects with fewer activities.

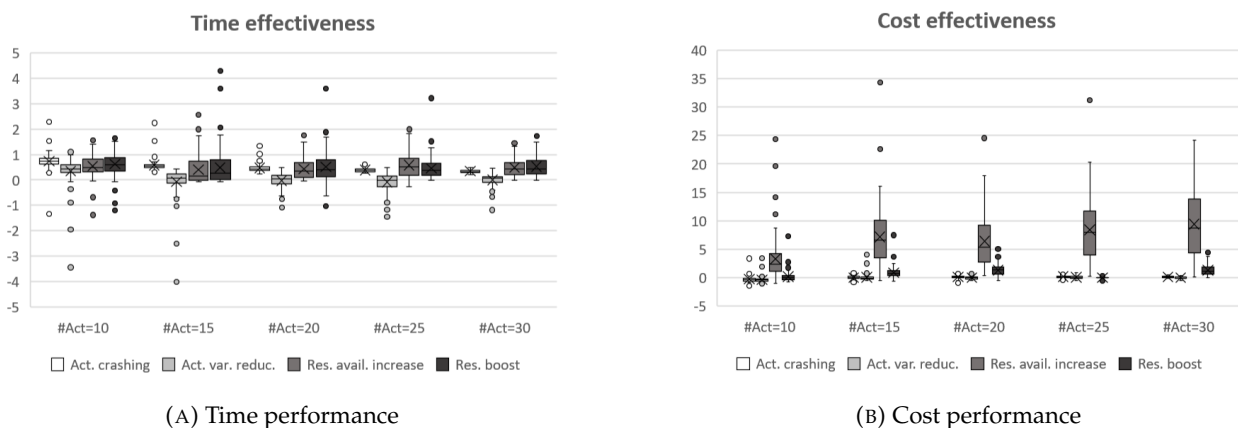


FIGURE 5.5: Impact of number of activities on the time and cost performance

Cost effectiveness

The cost effectiveness of the corrective action types shows some remarkable behaviour, especially for the activity level actions as can be seen in Figure 5.5b and in Table D.3.

The project time and cost effectiveness parameters related to the activity crashing action show a negative correlation trend: projects performing better in terms of time performance also seem to perform better in terms of their cost performance. This relationship is not what we expected from a traditional project management point of view which assumes reducing a project's duration can only be achieved upon investing additional effort and costs. However, in this set of experiments, the cost savings resulting from a decreased project duration completely compensated for the corrective action investments. This is confirmed by the limited number of corrective actions that were taken for projects with a low number of activities as displayed in Table D.3. The time

Act crashing				Act var reduc			
	Cost effect.	#Actions	Time effect./ action		Cost effect.	#Actions	Time effect./ action
#Act=25	0.179	2.81	0.147	#Act=25	0.084	19.04	-0.003
#Act=30	0.151	2.50	0.141	#Act=15	0.065	10.71	-0.002
#Act=20	0.110	2.44	0.200	#Act=20	0.029	13.49	0.000
#Act=15	0.037	2.22	0.288	#Act=30	0.000	22.05	0.001
#Act=10	-0.272	1.99	0.413	#Act=10	-0.353	6.64	0.073
Res avail incr				Res boosting			
	Cost effect.	#Actions	Time effect./ action		Cost effect.	#Actions	Time effect./ action
#Act=30	9.421	23.31	0.048	#Act=25	1.494	18.83	0.079
#Act=25	8.397	21.69	0.056	#Act=30	1.339	20.54	0.064
#Act=15	7.178	16.50	0.062	#Act=20	1.330	15.78	0.129
#Act=20	6.418	16.79	0.055	#Act=15	0.903	14.08	0.101
#Act=10	3.320	11.35	0.118	#Act=10	0.213	10.00	0.178

TABLE 5.6: Average cost effectiveness, number of actions and time effectiveness per action for #Act set of experiments

effectiveness per corrective action was very high for projects with a low number of activities and decreases as the number of activities increases. Therefore, projects with more activities require more corrective actions, which is evident, but the time effectiveness of each corrective action decreases significantly. So the additional costs incurred for performing more corrective actions were less compensated by a reduced project duration. This explains why projects with better time performance also perform better in terms of their costs.

For the activity variability reduction action, we again clearly see the almost perfect negative correlation between the time effectiveness and cost effectiveness parameters. This confirms once

again the conclusions drawn previously regarding the bad performance of the activity variability reduction action.

In this instance, the cost effectiveness of the resource level corrective actions seems not to be impacted by the number of activities involved in the project. Also, the relation between time and cost effectiveness is unclear. Once again the cost effectiveness is related to the average number of actions performed as shown in Table 5.6. When a project's execution requires a higher amount of corrective actions, because the effectiveness of each action decreases, the costs incurred for taking the additional corrective actions will be elevated. But as this does not result in a reduced project delay, the additional costs are not compensated by cost savings resulting from a decreased project duration and the total project cost will only increase.

5.2.5 Number of resources

Figure 5.6 and Table D.4 in Appendix D show the effect of increasing the number of resources used in a project on the project's time and cost performance for the different corrective action types.

It is worth mentioning that the results of simulating project number 55 were removed from the #Res=1 boxplots on Figures 5.6a and 5.6b to facilitate the interpretation of these plots. The simulation of this project resulted in very extreme values for the time and cost effectiveness parameters for all corrective action types. The time effectiveness values for the four corrective types were -2.15, 21.64, -8.90 and -8.42. The cost effectiveness values on the other hand were -7.63, -21.90, -86.95 and -116.03. These extreme values are caused by the exceptional event where the project's average delay (-0.33) and total cost deviation (-24.12) were negative and relatively close to zero after being simulated without any corrective action taken. As these values are used in the denominator for calculating the time and cost effectiveness parameters, these performance measures increased significantly, even when the project delay and total cost were only moderately impacted by the corrective actions. Therefore the time and cost effectiveness values for project 55 were removed from the boxplots of the #Res=1 set of experiments.

Nevertheless, these time and cost effectiveness values were still included in the calculation for the mean and standard deviation.

Time effectiveness

In Figure 5.6a it is observed that the number of resources involved in a project does not impact the time performance of the activity crashing and resource availability increase actions. For the corrective action of reducing an activity's variability, however, the average time effectiveness values decrease slightly upon increasing the number of resources. The time performance of the resource boosting action on the other hand increases when the number of resources increases. In

what follows the main causes of the time effectiveness behaviour for the different corrective actions will be explained.

For the activity crashing action, the time effectiveness is not impacted by the number of resources involved in the project. This is because the impact of crashing an activity on the project's duration will usually not depend on the number of resources involved in the project. More specifically, crashing an activity entails that the activity's duration will decrease, while its total work content will increase (inefficient activity crashing). When the increased work content would cause the resource availability to be exceeded, it is assumed that the project manager can make the additionally required amount of resources available to that activity for its entire duration. So the impact of crashing an activity on the project's duration will not be impacted by the number of resources involved in the project. The average cost for taking an activity crashing action however is expected to increase as the possibility of exceeding one or more resource availability increases. The activity variability reduction action is also not impacted by the number of project resources. Nevertheless, Figure 5.6a shows that this corrective action type performed exceptionally well on projects using only one resource. However, the standard deviation of this time effectiveness is very high (2.181) and therefore the reliability of this finding is very limited.

For the resource availability increase action, the number of resources again does not impact the time performance. The only remarkable finding is that the time performance for a project with only one resource is very low, as is the case for the resource boosting action.

Finally, the time effectiveness of the resource boosting action is largely impacted by the number of resources involved in a project. The average relative delay reduction is more than doubled upon increasing the number of resources from zero to five. This finding partly confirms the initial hypothesis H_5 . More precisely, for projects involving only one or two resources, the activity crashing action is preferred over the resource level actions for reducing the project delay. For projects involving four and five resources, however, the resource level actions, and especially the resource boosting action, outperform the activity crashing action.

Another remarkable aspect is that the average time effectiveness of the resource availability increase actions is in general very low compared to projects with low S/P-values for example. For projects with a low number of resources, this behaviour is rather surprising as increasing the availability of only one resource would be expected to directly impact the total project duration. However, the reason behind this limited effectiveness was already explained in the 'time effectiveness' part. The low effectiveness for projects with a large number of resources could have been expected. More precisely, when increasing the availability of one resource, it is likely that a parallel execution of non-precedence-related activities will still be constrained by other resources. Therefore the average number of actions taken while executing projects with more resources is relatively high. This also explains the high costs related to controlling the projects with four and five resources using the resource availability increase action.

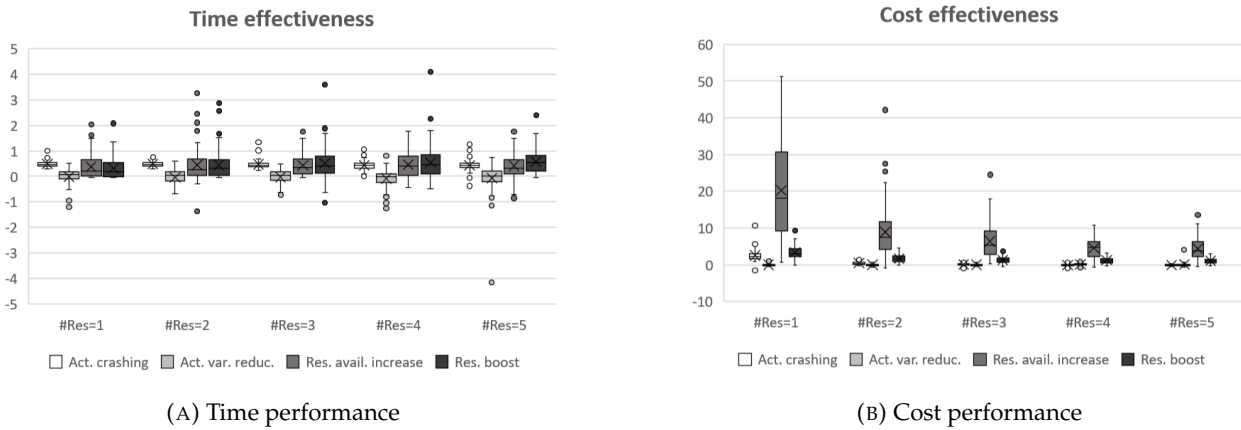


FIGURE 5.6: Impact of the number of resources on the time and cost performance

When comparing the standard deviation of the time effectiveness parameter for the different resource levels, we see that the standard deviation generally decreases as the number of resources increases for the resource level actions while the standard deviation remains more or less constant for the activity level actions. This is caused by the fact that the effectiveness of the resource level actions will largely depend on the number of resources involved, while this is not the case for the activity level actions.

Before proceeding to the cost effectiveness performance analysis, the remarkable behaviour of the time effectiveness parameter for the resource level actions will be explained in more detail. When controlling a project with only one resource, the effectiveness of the resource level control actions largely depends on the specific project's execution. More precisely, when a project is being executed and its $SPI_{ESWC}(t)$ exceeds its threshold, there are two different scenario's possible:

- At the specific moment where a corrective action is been required, the resource utilisation rate is relatively high. This entails that possibly, more activities could have been executed in parallel, but due to the resource constraint, this is infeasible. Therefore, increasing the availability of that resource at this point will be highly effective as it will decrease the resource utilization rate and probably also the project's remaining duration.
- At the specific moment where the $SPI_{ESWC}(t)$ exceeds its threshold, the resource utilisation rate is relatively low. This entails the parallel execution of multiple activities is probably constrained by the precedence relations and not by the resource constraints. Therefore increasing the resource's availability will not cause your project to reduce its duration. Consequently, the $SPI_{ESWC}(t)$ value will again exceed its threshold in the subsequent period(s) and require new corrective actions resulting in a high number of corrective actions taken without really impacting the final project duration.

This reasoning was confirmed for the majority of the projects being simulated. Let us for example compare the execution of projects 5 and 15, with only one resource, when controlling

them with a resource level control approach. Project 5 has an average delay of 11.86 when being executed without any control policy and project 15 has a delay of 10.39. So both projects are comparable in terms of their average delay but differ completely in their performance for both corrective action types.

The resource availability increase action was performed 2.98 times on average for project 5 and 25.11 times for project 15, while the resource boosting action was performed 2.15 and 30.99 times on average for projects 5 and 15. When comparing the average resource utilisation rate at the moment of the first corrective action, this rate had a value of 0.82 for project 5 and a value of 0.47 for project 15. This behaviour explains the relatively low mean value and elevated standard deviation related to the time effectiveness of the resource level actions for controlling a project with only one resource. When the number of resources increases, the time effectiveness of the resource level control actions will depend less on the utilisation of one single resource but on the utilisation of multiple resources. Therefore the standard deviation will decrease as the number of resources increases.

Act crashing				Act var reduc			
	Cost effect.	#Actions	Time effect./ action		Cost effect.	#Actions	Time effect./ action
#Res=1	2.433	2.43	0.162	#Res=4	0.083	14.16	-0.004
#Res=2	0.462	2.42	0.209	#Res=5	0.068	13.97	-0.003
#Res=3	0.110	2.44	0.200	#Res=2	0.043	13.70	-0.001
#Res=4	-0.049	2.25	0.196	#Res=3	0.029	13.49	0.000
#Res=5	-0.063	2.30	0.199	#Res=1	-0.195	13.02	0.018
Res avail incr				Res boosting			
	Cost effect.	#Actions	Time effect./ action		Cost effect.	#Actions	Time effect./ action
#Res=1	19.519	17.06	0.049	#Res=1	2.247	18.32	0.022
#Res=2	8.901	15.73	0.076	#Res=2	1.718	17.20	0.073
#Res=3	6.418	16.79	0.055	#Res=3	1.330	15.78	0.129
#Res=4	4.588	16.68	0.064	#Res=4	1.223	14.63	0.136
#Res=5	4.341	17.03	0.050	#Res=5	1.083	12.52	0.087

TABLE 5.7: Average cost effectiveness, number of actions and time effectiveness per action for #Res set of experiments

Cost effectiveness

Figure 5.6b shows the cost effectiveness values of the different corrective action types for projects with an increasing number of resources.

The costs related to the activity crashing action behave according to the traditional time/cost trade-off: incurring additional costs results in an improved time performance. However, the high

value for the mean and standard deviation of the cost effectiveness for projects with only one resource deserves some special attention.

Upon analysing the average cost deviation (from the BAC) across various project instances, big differences in these cost deviations occur for projects including an increasing number of resources. More precisely, the average cost deviation for projects containing only one resource is 621.80. For projects with 2, 3, 4 and 5 resources, this cost average cost deviation is 1295.25, 1964.28, 2730.91 and 2948.71. This is evident as also the total costs for projects with an increasing number of resources will increase.

Nevertheless, the cost of taking an activity crashing corrective action is a fraction of the activity's fixed cost and stays constant when the number of resources changes. Therefore, the impact on the total costs will be more significant for projects with fewer resources. This explains the high values for the mean and standard deviation of the cost effectiveness parameters related to both activity level actions.

For the activity reduction action, the cost effectiveness values again show a perfect negative correlation with the time effectiveness values. Further on, the standard deviation of the cost effectiveness parameter related to projects with one resource is again very high. This is also partly due to the high standard deviation in the time effectiveness value.

When observing the lower panels of Table 5.7, we again observe the typical behaviour of the cost effectiveness parameter values for the resource boosting action: the more corrective actions taken during project execution, the higher the cost effectiveness parameter. The cost effectiveness behaviour for the resource availability increase action, however, is not related to the number of corrective actions taken. In this case, the elevated cost effectiveness values for projects using fewer resources can be explained by the lower project cost for these projects. As was the case for the activity level actions, the costs for taking corrective actions remain constant and will impact the total project costs more significantly for projects with fewer resources. This reasoning cannot be applied to the resource boosting action, as these corrective action costs depend on the number of project resources and will decrease upon decreasing the number of project resources.

5.2.6 Resource similarity

The impact of increasing the resource similarity parameter on the project's time and cost performance for the different corrective actions is shown in Figure 5.7. The exact values for the mean and standard deviation of the time and cost effectiveness parameters are summarized in Table D.5 in Appendix D.

Time effectiveness

There seems to be no clear relationship between a project's resource similarity and the time performance of the corrective action types.

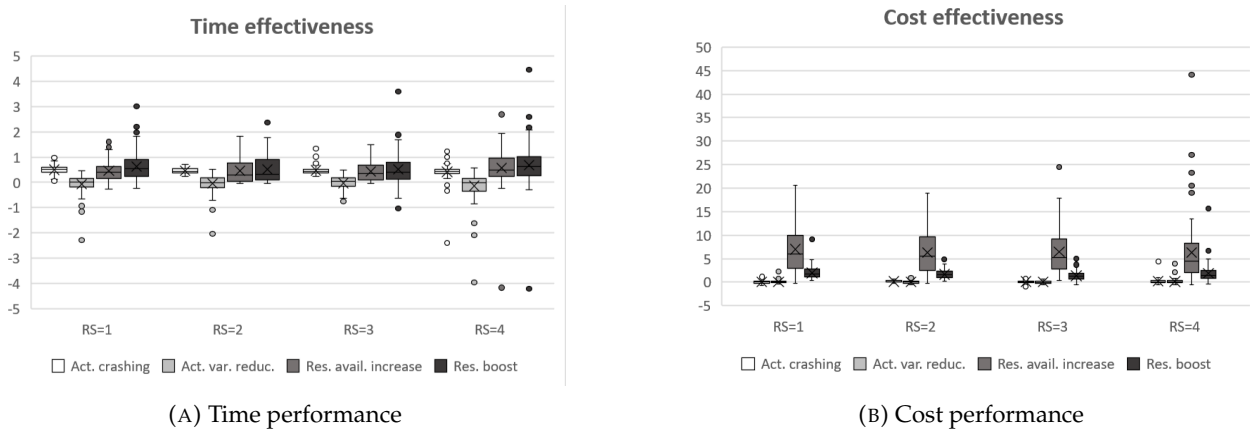


FIGURE 5.7: Impact of the resource similarity on the time and cost performance

For the activity crashing action, the performance decreases slightly upon increasing the resource similarity. The activity variability reduction action on the other hand is not impacted by the resource similarity parameter. Furthermore, this corrective action performs very badly on average for all resource similarity values and fails to reduce the project delay in all cases. However, the standard deviation related to the time effectiveness parameter is relatively high indicating that in some instances, this corrective action type will cause the project delay to be reduced.

The impact of the resource similarity parameter on the resource level corrective actions is also very limited. However, for the highest resource similarity value, the time effectiveness parameter for both corrective actions shows a noticeable leap. Verifying whether this is a random event or not should be tested by simulating projects with even higher resource similarity values to test if this trend is continued.

Both the initial hypotheses regarding the impact of the resource similarity parameter on the performance of the activity and resource level control approaches were not completely confirmed in this simulation study. H_6 assumed that the efficacy of the resource level control approach compared to the activity level control approach would increase. This hypothesis is only confirmed when the time performance of the resource level actions would continue to increase upon further increasing the resource similarity value. H_7 on its turn assumed the resource availability increase action to outperform the resource boosting action for high levels of the resource similarity parameter. However, the simulation results show that the resource boosting action outperforms the resource availability increase action for all similarity levels.

Cost effectiveness

Table D.5 shows that the cost effectiveness values related to the activity crashing action show some remarkable behaviour: projects performing better in terms of their duration, also perform better in terms of their cost performance. The rationale behind this is shown in Table 5.8. In the upper left panel, we see that the average number of actions taken during the project execution remains more or less constant when increasing the resource similarity parameter. Therefore the costs incurred for taking corrective actions will stay more or less constant. However, we also see that the time effectiveness per corrective action decrease as the resource availability increases. Therefore, the cost reduction related to a reduced project duration will decrease and the total costs will increase.

For the activity variability reduction action, the almost perfect negative correlation between the time and cost effectiveness values can be observed in Table D.5.

Act crashing				Act var reduc			
	Cost effect.	#Actions	Time effect./ action		Cost effect.	#Actions	Time effect./ action
RS=4	0.180	2.52	0.175	RS=4	0.145	13.62	-0.011
RS=3	0.110	2.44	0.200	RS=1	0.067	14.22	-0.002
RS=2	0.165	2.33	0.204	RS=2	0.049	13.88	-0.003
RS=1	0.048	2.46	0.218	RS=3	0.029	13.49	0.000
Res avail incr				Res boosting			
	Cost effect.	#Actions	Time effect./ action		Cost effect.	#Actions	Time effect./ action
RS=1	6.959	17.14	0.058	RS=1	1.974	12.65	0.167
RS=3	6.418	16.7931	0.055	RS=4	1.913	11.44	0.152
RS=4	6.296	14.6337	0.098	RS=2	1.670	13.12	0.147
RS=2	6.262	15.8497	0.085	RS=3	1.330	15.78	0.129

TABLE 5.8: Average cost effectiveness, number of actions and time effectiveness per action for RS set of experiments

For the resource level actions, the cost effectiveness values do not show a clear relationship with the time effectiveness values, nor with the number of corrective actions performed. Therefore additional simulation experiments would be required to generate more detailed data to explain the behaviour of the cost effectiveness parameter.

6 Conclusions

Drawing conclusions regarding whether or not the resource level control approach performs better than the activity level control approach based on this study would be erroneous. Nevertheless, this research clearly showed that the constructed resource level control method could be an innovative way of controlling projects. Especially highly parallel projects and projects with a lot of activities, both targeting a cost-minimisation objective, seem to benefit from being controlled using a resource level control approach instead of an activity level approach. However, for the resource level control approach to become competitive with the activity level approach, its high variability in terms of time and cost performance should be managed. Section 5.2 showed that the variability in the time and cost performance for the resource level corrective actions is very high compared to the activity level actions. Further on, the activity level actions also outperform the resource level actions for almost every project instance being investigated in terms of the project's total costs. This is another major drawback of the constructed resource level control approach and should be managed in order to improve the performance of the resource level control approach.

Nevertheless, this research showed the high potential of the resource level control approach and could surely be a good starting point for constructing an improved project control policy that focuses on a project's resources instead of its activities. I would invite future research to focus on the following aspects:

- **Decrease the performance variability of the resource level control approach:** as has been repeated multiple times, the variability in the time and cost performance of the resource level control approach was very high. This caused the efficacy of the resource availability increase and resource boosting actions to be less accurate and unrobust. Reducing this performance variability should be done by refining the resource level control approach and improving the corresponding corrective actions. More precisely, the resource availability increase and resource boosting actions should be adjusted such that the time effectiveness per corrective action is highly increased. This will decrease the total number of corrective actions taken during the project's execution and therefore decrease the related costs significantly.
- **Expand the scope of project characteristics:** in this research, only a limited number of project characteristics were expected to impact the performance of the activity and resource

level control approach. These project characteristics were assumed to be the most apparent in determining a control policy's performance. However, many more project characteristics could potentially impact a project control policy:

- Project objective: in this study, only projects following a cost minimisation objective were investigated. However, many more project objectives can be targeted when executing a project. Probably the resource level control approach performance will be impacted by the type of objective that has been used.
- Project planned duration: in my study, increasing many of the project characteristics, like the S/P-value and the number of activities, resulted in projects with an increased (planned) duration. As the results drawn for increasing the S/P-value and number of activities are somewhat similar, especially the time performance, it could be that these results are being affected by a third variable, i.e. the project's duration.
- Aggressive or conservative control policy: in this study, the threshold values for the $SPI(t)$ and $SPI_{ESWC}(t)$ were kept constant for each conducted experiment. Therefore it could be interesting to investigate the impact of applying a more aggressive policy, i.e. increasing the threshold value, or a more conservative, i.e. lowering the threshold value, on the activity and resource level control approaches.

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A Literature review: tables

A.1 Resource variability factors

Factor	Explanation	How to measure?
Industry profitability	Indication of the degree to which resources (revenues) are available to the firm	Firm's ROE
Industry growth rate	Indication of the degree to which resources (revenues) are available to the firm	Weighted average sales growth rate for each of the industries in which the firm does business
Industry instability	Indication of the degree to which the firm may encounter problems in acquiring resources for the firm	Standard deviation of the industry value of shipments for the last 3 industry censuses
Environmental control	Firms pursue within industry mergers → higher relative market share → increased market concentration and market power → impact on firm profitability (revenues=resources)	Market share (weighted average of relative market share for each of the industries in which the firm does business)
Number of director interlocks	Linkages in which the director of one company sits on the board of another	Count
Percentage of outside directors	Reflects the degree to which outsiders are represented on the board	Number of outside directors divided by the total number of directors
Joint ventures	When 2 or more organizations create a new entity	Number of joint ventures in which the organization reported it was currently involved

Continued on next page

Table A.1 – continued from previous page

Factor	Explanation	How to measure?
Firm size	The firm's ability to use its size to manipulate its exchange relationships with other firms	(log of) inflation-adjusted sales
Diversification	The extent of environmental buffering employed by the firm to reduce dependence on a single market	Complex formula
Current level of resources	The amount of resources a firm currently possesses	Net worth / total assets with net worth = working capital + cash-on-hand + potential cash flows

TABLE A.1: Factors contributing to resource variability

B Initial hypotheses

B.1 Hypothesised impact on different project objectives

Variability source	Variability class	Project mean cost	Project cost variability
The use of estimations for the activity durations	Activity duration (natural) variability	0	-
Positive bias towards the mean activity duration			
Unexpected and unplanned activities showing up	Project network variability	-	-
Rework			
Machine failures/ operator absenteeism			
Learning effects	Activity duration improvements	-	0
Multiple operators working parallel on the same activity			
Machine performance degradation	Activity duration increases	-	-
Fatigue among operators			

TABLE B.1: Hypothesized impact of activity variability factors on minimize cost objective

Variability source	Variability class	Project mean cost	Project cost variability
Late delivery of a resource	Resource scarcity / unavailability	-	0
Stock-out of a resource			
Industry profitability			
Industry growth rate			
Industry instability			
Number of director interlocks	Influence by resource providers	-	0
Percentage of outside directors			

Table B.2 – continued from previous page

Variability source	Variability class	Project mean cost	Project cost variability
Joint ventures			
Firm size			
Diversification		+	+

TABLE B.2: Hypothesized impact of resource variability factors on minimize cost objective

Variability source	Variability class	Project mean NPV	Project NPV variability
The use of estimations for the activity durations	Activity duration (natural) variability	0	-
Positive bias towards the mean activity duration			
Unexpected and unplanned activities showing up	Project network variability	-	-
Rework			
Machine failures/ operator absenteeism			
Learning effects	Activity duration improvements	+	+
Multiple operators working parallel on the same activity			
Machine performance degradation	Activity duration increases	-	-
Fatigue among operators			

TABLE B.3: Hypothesized impact of activity variability factors on maximise NPV objective

Variability source	Variability class	Project mean NPV	Project NPV variability
Late delivery of a resource	Resource scarcity/ unavailability	-	0
Stock-out of a resource			
Industry profitability			
Industry growth rate			
Industry instability			
Number of director interlocks	Influence by resource providers	-	0
Percentage of outside directors			
Joint ventures			
Firm size			
Diversification	Environmental buffering	+	+

TABLE B.4: Hypothesized impact of resource variability factors on maximise NPV objective

Variability source	Variability class	Project Resource Leveling performance	Project Resource Leveling variability
The use of estimations for the activity durations	Activity duration (natural) variability	0	0
Positive bias towards the mean activity duration			
Unexpected and unplanned activities showing up	Project network variability	-	-
Rework			
Machine failures/ operator absenteeism			
Learning effects	Activity duration improvements	0	0
Multiple operators working parallel on the same activity			
Machine performance degradation	Activity duration increases	0	0
Fatigue among operators			

TABLE B.5: Hypothesized impact of activity variability factors on resource leveling objective

Variability source	Variability class	Project Resource Leveling performance	Project Resource Leveling variability
Late delivery of a resource	Resource scarcity / unavailability	-	-
Stock-out of a resource			
Industry profitability			
Industry growth rate			
Industry instability			
Number of director interlocks	Influence by resource providers	-	-
Percentage of outside directors			
Joint ventures			
Firm size			
Diversification	Environmental buffering	+	+

TABLE B.6: Hypothesized impact of resource variability factors on resource leveling objective

Variability source	Variability class	Project mean total resource idle time	Project resource idle time variability
The use of estimations for the activity durations	Activity duration (natural) variability	0	0
Positive bias towards the mean activity duration			
Unexpected and unplanned activities showing up	Project network variability	-	-
Rework			
Machine failures/ operator absenteeism			
Learning effects	Activity duration improvements	0	0
Multiple operators working parallel on the same activity			
Machine performance degradation	Activity duration increases	0	0
Fatigue among operators			

TABLE B.7: Hypothesized impact of activity variability factors on optimising WC objective

Variability source	Variability class	Project mean total resource idle time	Project resource idle time variability
Late delivery of a resource	Resource scarcity / unavailability	-	-
Stock-out of a resource			
Industry profitability			
Industry growth rate			
Industry instability			
Number of director interlocks	Influence by resource providers	-	-
Percentage of outside directors			
Joint ventures			
Firm size			
Diversification	Environmental buffering	0	0

TABLE B.8: Hypothesized impact of resource variability factors on optimising WC objective

C Experimental design

C.1 Design of experiments parameters

		RU	RC	RS
#Res=1				
	Res 1	0.70	0.50	0.35
			Resource similarity	1.00
#Res=2				
	Res 1	0.70	0.50	0.35
	Res 2	0.30	0.38888	0.117
			Resource similarity	3.00
#Res=3				
	Res 1	0.70	0.50	0.35
	Res 2	0.50	0.45	0.225
	Res 3	0.30	0.38888	0.117
			Resource similarity	3.00
#Res=4				
	Res 1	0.70	0.50	0.35
	Res 2	0.50	0.45	0.225
	Res 3	0.50	0.40	0.2
	Res 4	0.30	0.38888	0.117
			Resource similarity	3.00
#Res=5				
	Res 1	0.70	0.50	0.35
	Res 2	0.50	0.45	0.225
	Res 3	0.50	0.40	0.2
	Res 4	0.40	0.40	0.16
	Res 5	0.30	0.38888	0.117
			Resource similarity	3.00

TABLE C.1: #Res set of experiments parameters

		RU	RC	RS
Resource similarity=1				
	Res 1	0.60	0.50	0.30
	Res 2	0.60	0.50	0.30
	Res 3	0.60	0.50	0.30
		Resource similarity		1.00
Resource similarity=2				
	Res 1	0.70	0.50	0.35
	Res 2	0.50	0.45	0.225
	Res 3	0.40	0.4375	0.175
		Resource similarity		2.00
Resource similarity=3				
	Res 1	0.70	0.50	0.35
	Res 2	0.50	0.45	0.225
	Res 3	0.30	0.3888	0.117
		Resource similarity		3.00
Resource similarity=4				
	Res 1	0.70	0.60	0.42
	Res 2	0.50	0.45	0.225
	Res 3	0.30	0.35	0.105
		Resource similarity		4.00

TABLE C.2: Resource similarity set of experiments parameters

D Results

	Act crashing		Act var reduc		Res avail incr		Res boosting	
	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Time effectiveness								
SP=0.2	0.601	0.295	-0.120	0.942	1.444	1.013	1.340	1.067
SP=0.4	0.537	0.280	-0.214	0.792	1.106	0.724	1.227	0.804
SP=0.6	0.472	0.168	-0.028	0.317	0.438	0.402	0.521	0.599
SP=0.8	0.397	0.078	0.076	0.181	0.120	0.267	0.210	0.350
Cost effectiveness								
SP=0.2	0.351	0.413	0.133	0.944	0.079	0.950	0.939	1.164
SP=0.4	0.189	0.401	0.220	0.792	2.341	2.630	1.427	0.997
SP=0.6	0.110	0.287	0.029	0.318	6.418	4.566	1.330	0.902
SP=0.8	0.110	0.172	-0.076	0.181	14.665	5.476	1.014	0.853

TABLE D.1: SP performance results

	Act crashing		Act var reduc		Res avail incr		Res boosting	
	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Time effectiveness								
Var=0.2	0.344	0.276	-0.138	0.459	0.463	0.490	0.485	0.497
Var=0.3	0.472	0.168	-0.028	0.317	0.438	0.402	0.521	0.599
Var=0.4	0.578	0.105	0.080	0.283	0.384	0.326	0.427	0.356
Var=0.5	0.655	0.075	0.237	0.226	0.335	0.263	0.376	0.292
Cost effectiveness								
Var=0.2	0.057	0.279	0.139	0.459	5.103	4.087	1.489	1.062
Var=0.3	0.110	0.287	0.029	0.318	6.418	4.566	1.330	0.902
Var=0.4	0.154	0.288	-0.078	0.284	7.122	4.368	1.384	0.860
Var=0.5	0.185	0.286	-0.235	0.226	7.485	3.949	1.242	0.736

TABLE D.2: Activity variability performance results

	Act crashing		Act var reduc		Res avail incr		Res boosting	
	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Time effectiveness								
#Act=10	0.743	0.314	0.354	0.526	0.549	0.434	0.630	0.477
#Act=15	0.588	0.288	-0.064	0.574	0.400	0.560	0.479	0.683
#Act=20	0.472	0.168	-0.028	0.317	0.438	0.402	0.521	0.599
#Act=25	0.390	0.092	-0.082	0.338	0.582	0.492	0.466	0.444
#Act=30	0.341	0.062	0.002	0.262	0.489	0.348	0.530	0.376
Cost effectiveness								
#Act=10	-0.272	0.520	-0.353	0.525	3.320	3.735	0.213	0.991
#Act=15	0.037	0.284	0.065	0.575	7.178	5.123	0.903	1.014
#Act=20	0.110	0.287	0.029	0.318	6.418	4.566	1.330	0.902
#Act=25	0.179	0.191	0.084	0.338	8.397	5.277	1.494	0.759
#Act=30	0.151	0.178	0.000	0.262	9.421	5.956	1.339	0.883

TABLE D.3: #Act performance results

	Act crashing		Act var reduc		Res avail incr		Res boosting	
	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Time effectiveness								
#Res=1	0.462	0.299	0.196	2.181	0.290	1.035	0.239	0.958
#Res=2	0.479	0.119	-0.042	0.297	0.439	0.621	0.440	0.515
#Res=3	0.472	0.168	-0.028	0.317	0.438	0.402	0.521	0.599
#Res=4	0.429	0.168	-0.082	0.326	0.452	0.461	0.548	0.640
#Res=5	0.433	0.211	-0.068	0.525	0.420	0.450	0.566	0.447
Cost effectiveness								
#Res=1	2.433	1.780	-0.195	2.208	19.519	17.100	2.247	12.068
#Res=2	0.462	0.396	0.043	0.296	8.901	7.074	1.718	1.162
#Res=3	0.110	0.287	0.029	0.318	6.418	4.566	1.330	0.902
#Res=4	-0.049	0.241	0.083	0.326	4.588	2.785	1.223	0.828
#Res=5	-0.063	0.294	0.068	0.525	4.341	2.829	1.083	0.850

TABLE D.4: #Res performance results

	Act crashing		Act var reduc		Res avail incr		Res boosting	
	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Time effectiveness								
RS=1	0.505	0.154	-0.066	0.384	0.462	0.412	0.629	0.538
RS=2	0.453	0.116	-0.047	0.367	0.450	0.453	0.511	0.495
RS=3	0.472	0.168	-0.028	0.317	0.438	0.402	0.521	0.599
RS=4	0.421	0.354	-0.143	0.573	0.576	0.701	0.674	0.818
Cost effectiveness								
RS=1	0.048	0.363	0.067	0.384	6.959	4.561	1.974	1.243
RS=2	0.165	0.253	0.049	0.367	6.262	4.378	1.670	1.005
RS=3	0.110	0.287	0.029	0.318	6.418	4.566	1.330	0.902
RS=4	0.180	0.544	0.145	0.574	6.296	6.577	1.913	1.930

TABLE D.5: RS performance results