"Uncertainty Robustness in Construction Scheduling"

"Unsicherheitsrobuste Zeitplanung im Baubetrieb"

Von der Fakultät für Bauingenieurwesen der Rheinisch-Westfälischen
Technischen Hochschule Aachen
zur Erlangung des akademischen Grades eines Doktors
der Ingenieurwissenschaften genehmigte Dissertation

vorgelegt von

Nuno Manuel Pereira Migueis **Cachadinha**

aus

Lissabon, Portugal

Berichter: Universitätsprofessor Dr.-Ing. R. Seeling
Universitätsprofessor Dr.-Ing. K. Meskouris
Universitätsprofessor Dr. rer. pol. Dr. h.C. mult. H.-J. Zimmermann

Tag der mündlichen Prüfung: 30. April 2002

Acknowledgements

This is the part of my work where I can make most of the mistakes. I would like to thank those people who contributed in making this work possible, be it through direct help, financially, by sharing their knowledge and enthusiasm or simply through their friendship, support, patience and love. They were so many that I am faced with a huge task and risk not mentioning someone that deserves at least as much recognition as those presented here. In thanking all these people, I am caught between two phases in my life: before Aachen and in Aachen. This work was carried out in a new city, a new country and a new reality. I will always remember those first warm days of the year in Aachen and all the life and joy that they brought with them, the beauty of this great small city and the woods and fields around it. Its flair, its cafés and terraces, its students. I want to thank everybody at the Studentendorf for the help they gave me everyday in over the years.

A special thanks goes to DAAD and Fr. Hillers for their financial support, in the form of my scholarship.

Prof. Petzschmann from TU Cottbus and Dr. Hangzen Han provided me with the simulator Simunet which played an important role in directing my work and was a vital tool in its execution.

I want to thank all the colleagues from BVT Lehrstuhl, particularly Bettina, Marco and Alex for their help when I was getting settled and for all the talks we had. In my institute, I want to thank the deceased Jörg Bierbaum for his programming work (I said I would mention you, Jörg), Gregor Hengefeld for always being there whenever a problem popped up, and very specially Christian Seeling. You always had a solution in your mind and a smile in your face.

Fr. Vorhagen was my guardian angel in the faculty. Whenever things got tough and I couldn’t find a way out, she always pointed it out to me. Sometimes she even made an extra one just for me. A great lady, I’ll always be grateful for her.

I had two right arms during the course of the research work I had two right arms: Jörg Schubert and Raghavendra Kulkarni. Jörg was efficient and always up for a laugh. Raghu was imaginative and a well of energy. It was great fun working with you both.

I thank my good friend and neighbor Udo Hitze for listening, for his advice, and for our long conversations in the kitchen and while working out. And above all, for solving graphical problems at the very end of this doctorate that seemed insurmountable.

And then there where those persons that guided and enriched my work with their suggestions and experience. My recognition goes to Prof. Meskouris for accepting to be my supervisor at a delicate time, for his good will and decisive intervention for the successful delivery of this work. I want to thank Prof. Zimmermann for having the patience to listen to and advise me over a long period of time, sometimes through situations which might have made him think that he was wasting his time. And he doesn’t have much to spare. My recognition also goes to Prof. Reinhard Seeling and his human feeling, which helped me solve several personal and some work problems during this long path.

And what about all those that I owe the joy in life, their listening, support, encouragement and advice that makes everything possible: I thank all the Latinos and the salsa dancers of Aachen. I thank Petra, Mahfuz, Christine, Martina, Christoph, Pia, Eduardo, Inan, Ingrid and Kaya. And especially all those that should be here and aren’t.

I thank my grandfather Joaquim. He always had other plans for me, this whole thing never really made much sense to him. But he always respects my choices and supports them wholeheartedly.

I thank my father for his technical support, his knowledge about life generally and for listening to me when I needed dedication, patience and love.

I thank Raluca for sharing her life with me, for her advice, her long waiting, for her tenderness and, above all, for her love.

Finally, I would like to mention my mother Efigénia. She is the real academic in the family. Twisted ways kept her from reaching where I am now, even if she deserved it twice as much as I do. But here I am now. As we say in Portugal, “Deus escreve direito por linhas tortas” (God writes straight on twisted lines). Mother, this work is dedicated to you.

Aachen, May 22th 2002

Nuno Cachadinha

TABLE OF CONTENTS

1. Introduction

Production in the construction industry is a complex and highly sensitive process. The projects are unique production objects which take several years to complete. Upon signing a contract, the contractor or project manager commits himself to a completion date. Furthermore, there has been a recent trend to further shorten the duration of construction projects. This trend carries with it the increased risk of deadline overruns. Moreover, increasing specialization in construction companies means that the completion of any given project may require a number of autonomous, specialized companies which are themselves committed to meet their deadlines and equally liable to fail.

Presently, any medium-sized construction company in the industrialized nations will be familiar with the ISO 9000 set of norms, and are likely to have developed their own quality manual, if not even be certified or on the way to become certified as complying to these set of norms. Many prominent spokespersons have voiced their support in favour of the gradual introduction of a policy which only allows accredited companies to bid for larger, more complex or more critical design, construction or construction management projects. This strong support behind this motion has led to the emergence of *Quality Management System* and, although sounding extremely uncompromising and difficult to achieve, many companies in the traditionally conservative construction sector have adopted quality management as one of their goals. In fact, Burbridge (1988) already mentioned that many companies were making it a condition for doing business that their contractors/suppliers had qualified Quality Management System programs in place.

Thus, a lot effort has been put into making the construction industry capable of delivering quality projects within the planned delivery date and cost. Yet, reports in the media about engineering failures, time and cost overruns are nonetheless still frequent.

However important the process of planning and scheduling may be for the outcome of any project, this area has surprisingly been left out of this trend towards quality management. Quality in scheduling has been mostly assessed through the CV of the schedulers involved and through the means and software utilized. No consensual criteria for assessing the quality of a schedule have been established. Its implementation on site mostly consists of updating the progress of existing schedules and producing “schedule updates” and “recovery plans”. In the manufacturing industry, this practice corresponds to quality control and defect patching of a product. Applied to the project management services, the product would be the schedule. Neither the quality of the schedule produced nor the reputation among clients is guaranteed through this approach. It has proven to be slow, prestige damaging and expensive instead.

External Project Management sells the achievement of objectives and expectations. The first concrete product that it gives to a client or investor is a schedule and its corresponding cost-estimate. Project management generally takes 1.5% of the total cost of a project. In large scale projects this value easily reaches figures on the dozens of million Euros.

The efforts to industrialize the construction sector to a degree which is comparable to that of the manufacturing industry are not new. The first major results of this effort are starting to show. Concepts, methods, norms and expectations have been taken over in a real technology transfer process. An example for this is the adoption of quality management systems, such as the ISO 9000 certification of the construction companies.

Project management done by external consultants is a relatively new business field which has steadily grown in importance over the last 15 years. Its biggest challenge is the reduction of uncertainty in the duration and cost of construction projects.

This brings the author to the fundamental questions of this work.

1. Can the project management business undergo a technology transfer from the manufacturing industry in order to adopt its procedures and methods to achieve quality assurance for its own products? If this is proven to be possible, time-planning would surely be one of the most important fields.

2. Is it possible to establish a standardized method of identifying, assessing and reducing duration uncertainty in time-planning?

Scheduling and time planning have been heavily researched since the beginning of the 50s. The literature on this subject is extensive and will be reviewed in the next section of this chapter. The field of duration uncertainty is approached according to two major methodologies, namely:

— Methods or techniques that consider stochastic duration activities and deterministic schedule structures, where duration uncertainty only applies to the preset critical path. These approaches derive from CPM.

— Stochastic scheduling techniques, where the schedule structure itself is stochastic. In these approaches the relationships between the activities are defined based on probability. Recent developments in the use of these techniques considers both the duration of activities and their relationships to each other as fuzzy numbers.

Thus, all previous approaches consider predefined, unchangeable schedule topologies. The aim of these methods is to quantify the activities' durations and the probability or possibility of occurrence of precedences as accurately as possible. However, the effect of the schedule topology on the duration uncertainty of projects has until now been neglected. In practical construction scheduling, the scheduler can choose from a wide range of possible, acceptable, time and cost optimized schedule topologies. The standard approach is to chose one credible topology, carry out a cost or time optimization, monitor the progress of the project and update the original schedule. When differences between predicted and actual schedules occur, the scheduler often ends up changing the original topology throughout the course of the construction phase.

The main aim of this paper, therefore, is to identify a schedule topology that minimizes the influence of activity duration uncertainty on the total project duration. This would greatly increase the robustness and relevance of the original schedule. It would also provide a reliable, less duration uncertainty sensitive basis for work preparation and commitment negotiation by the stakeholders.

This work has an predominantly engineering and, therefore, practical nature. It deals with projects involving many persons, where uncertainty is due to the unpredictability of human interactions rather than due to physical or natural phenomena. The research instrument chosen, therefore, was simulation as it serves as a more empirically-valid substitute for strict mathematical analysis.

This chapter will review the literature and current thought with respect to the subject of quality. It will then propose a new form of Scheduling Quality, as well as the means to assess and achieve it.

1.1 STATE OF THE ART

King (1965) was one of the first authors to approach the topic of quality management, relating this concept to the Project Evaluation and Review Technique (PERT) which had just been developed in the USA for the Polaris Missiles Program.

The American Society of Civil Engineers (ASCE) conducted a workshop back in 1984 to discuss the quality of the constructed project and came up with 8 recommendations, ranging from planning to the further development of procedures and codes.

Chadwick (1986) discusses the impact of design and cost on construction quality, highlighting the numerous causes of poor quality, which permeate the entire engineering process.

During the 90s the number of publications on this subject boomed. In his paper, Mikkelsen (1990) concludes that the most vital means of creating quality lie in professional project management and professional project work. He argues that quality management needs to be integrated with project management.

The "Renaissance in Quality" first occurred in 1993, however, when Juran (1993) published his article of "Fitness for Use". He split the quality of the project into two categories:

1. Satisfactory cost and schedule performance or 'General Quality'
2. The more specific operational or functional compliance

He further argues that while cost and schedule aspects can be quantified and thus measured with some degree of accuracy, quantifying the 'quality' of the project is more difficult. In his view, quality is more than just mere performance and includes many factors which are subjective in nature. Juran (1993) goes on to argue that "Chronic quality problems are the ones which have been occurring for a long time and are accepted as inevitable." A 2% level of poor quality in the form of defective products translates into a habit of producing 2% more products than is actually required, buying 2% more materials, increasing the level of inventories by 2%, hiring 2% more labor – until such time when these levels are considered normal and begin to go unnoticed.

In the same year and arguing along similar lines, Graves (1993) focuses on core questions and discussions about whether or not Total Quality works in engineering management at all. The concept of Total Quality has already been addressed in this paper, as well as in Mallon (1993), which states that within the framework of construction industry, quality is often an abstract condition that is influenced by a great number of factors that have always been difficult to measure and/or quantify. It is usually a slippery concept, easy to visualize but extremely hard to define precisely. Hellard (1993) also addresses the topic of Total Quality when he stresses the need to apply the principles of quality management in building projects. He points out that "there are two ways to improve quality: people and processes. Faulty processes cause about 85% of quality problems and the rest are people problems, so it is best to focus on improving the work processes." This article had pioneer contribution to the trend of focusing on the production process in order to achieve product quality. It is a baseline for the research presented in this thesis.

Bubshait (1994) explains the relationship between owner involvement in public construction projects and the level of project quality. He concludes that, in many cases, the success or failure of projects is directly related to the level of owner involvement. In his view, it is up to the owners to set the desired level of quality by communicating the project objectives and requirements correctly.

More recently, Arditi and Gunaydin (1998) describe the factors that affect the process quality in building projects by ranking them according to their degree of importance.

Thus, many efforts have been made in the last four decades to define, assess and achieve the General Quality in projects by examining the relationship between construction planning and individual processes. The manufacturing industry has set the trend in the last decade. Its aim has been to guarantee quality *a priori*, replacing the traditional *a posteriori* Quality Control approach. Traditionally, over-quality was considered a source of unnecessary cost. Traditional systems can not compute the cost of *unquality*, and it was generally accepted as an inevitable part of the business itself. Nowadays, the leitmotif seems to be that, if over-quality causes unnecessary costs, so does *unquality*, and they are higher and deeper; they indicate that the whole structure is functioning in sub-optimal way.

The State of the Art trend shifts the focus of effort from the ready product to its entire process of creation, spanning from its inception to its delivery to the client.

In a recent survey conducted by ISO Technical Committee 176 to identify the market requirements for ISO 9000 (ISO 9000 News Sept/Oct 1998), the users' response included, among seven others, a process approach model.

Accordingly, the new version of ISO 9000:2000 incorporates this demand. It was prepared by international quality experts and is based on eight management principles. In the recommendations issued in May 97 by the Members of ISO/TC 176/SC 2 (1997) it is stated as "Principle 4" of their "Quality Management Principles and Guidelines on their Application" the Process Approach: "A desired result is achieved more efficiently when related resources and activities are managed as a process."

1.2 QUALITY ASSESSMENT IN CONSTRUCTION SCHEDULING

A schedule should be pragmatic and robust. It should predict the progress and sequence of work accurately, thus serving as a reliable tool for the coordination of work, equipment, manpower and efforts. The direct savings in time and costs obtained by a high level of schedule reliability are obvious. The indirect costs of frequent re-scheduling and re-organisation are difficult to quantify. Both re-scheduling and re-organisation impact on the motivation of stakeholders and their attitude towards the project. They also increase the potential for conflict between stakeholders. These indirect costs should, therefore, not to be underestimated.

Thus, the schedule presents itself as a vital tool, a product of thinking, to which the State of the Art quality principles, methods and tools can and should be applied.

Quality is hard to define, and even harder to assess and achieve. This uncertainty has led to at least some of the diversity in opinions that can be found in the literature on this subject, as reviewed in the previous section 1.1.

Thus, the proposal to incorporate Scheduling into the Quality framework made above presents the author with the responsibility of clearly defining the concept of Quality in Scheduling, as well as to guarantee its assessment and propose ways of achieving it.

The quality of a schedule is defined by the level of accuracy with which it correctly predicts the construction process. This includes accuracy in terms of the sequence of activities, individual activity duration time and, last but not least, the project delivery date.

The author proposes the assessment of this quality concept by considering the number of times the master schedule needs to be updated and changed during the construction phase within the same project scope of works. Thus:

- A low number of schedule changes and updates implies a high level of schedule quality

1.2.1 Limitations

Construction projects are often subject to a high number of change orders and other interventions by the owner or architect that alter the scope of works. The latest trend for fast track projects, where the construction phase starts while the design is still being finalized, and the increasingly large and complex types of projects have worsened this situation.

A schedule is a plan to achieve a certain objective, and its relevance merges with the realization of the objectives. If the objective, in this case, the constructed product as defined by the Scope of Works, is significantly changed, it becomes a new objective. Rescheduling is then inevitable, since the initial objective ceased to exist. A new project, or the remainder of one, then emerges, and with it a new schedule. The author considers the schedules resulting from these situations as new schedules for new objectives, not as schedule changes and updates. Thus, they do not fall within the scope of the assessment principle proposed in section 1.2.

Ways of Achieving Quality Assessment in Construction Scheduling The concept proposed would be of no practical interest if there were no clear means of achieving it. The author proposes the following:

1. Guaranteeing the relevance of the activity sequence and of the project delivery date by making the schedule robust to its intrinsic uncertainty, defined by the parameters proposed in section 4.3.3.

2. Changing the way in which a schedule is viewed, that is, from a merely auxilary part of work preparation or contractual obligation to an integral part of production, a product in itself. Its quality should be considered in the evaluation of performance, just as much as the quality of the final product.

The aim of this paradigm change is to the extension of quality concepts, trends and optimization methods common in the manufacturing industry to the scheduling industry. Specifically, the author proposes the application of manufacturing optimization methods to the topology of the schedule, in order to make it more robust to its intrinsic uncertainty.

2. Baseline Studies Defining the Major Factors Affecting Total Project Duration

2.1 PRINCIPLES AND OBJECTIVES

Variation in the durations of activities defined in the work preparation phase mostly consists of delays, recoveries or the unexpected early completion of works. Thus, variability basically causes the duration of the activities to either increase or decrease. However, experience tells us that not all delays can be absorbed by recoveries later in the construction phase. This raises the following questions:

- Does decreasing the duration of some activities make up for the increase of others (i.e. does the end date remain unchanged)?
- How does this affect the project total duration?
- What are the variables that characterize a schedule? Which of those can be controlled by the scheduler?
- What is the influence of those variables on the degree of impact of activity duration changes (increases and reductions) on the total duration of the project?

The objective of this chapter is to set up a body of qualitative, theoretical knowledge to backup schedule optimization efforts, defining the way in which the structure propagates or mitigates the single activity uncertainty to the project total duration.

To answer these questions, the software application *ProSim* was created for the purposes of this thesis. It is a simple network planning tool that carries out the classic network planning forward calculation based on the equations (Seeling (1996)):

$$ES_j = \max_{i \in V_j} EE_j \qquad (2.2.1)$$

$$EE_j = ES_J + D_j \qquad (2.2.2)$$

$$PD = \max EE_i, \qquad i=1,\dots,n \qquad (2.2.3)$$

where

i, j – activities from a network plan

V_j – set of predecessors of activity j

ES – Early start

EE – Early End

D – Duration

PD – Project duration

The user enters the duration of activities and their precedences, followed by a percent deviation and the number of times the project will be calculated. On each of the calculation runs, the program randomly increases or decreases the duration of each activity by the percent value entered at the beginning. The project duration is then calculated using equations (2.1) to (2.3) and stored together with the sequence number of its calculation run. *ProSim*'s output consists of a table with the sequence number of each run and the project duration obtained.

2.2 DEFINITION OF TERMS

Applying previously defined scientific terms to the specific and very particular research carried out with *ProSim* is likely to lead to misleading associations. A specific set of terms was, therefore, created to convey the exact meaning of concepts as intended. These are:

Row - set of activities connected by simple sequential predecessor - successor precedences, corresponding to a constructive process (e.g.: form - cast – strip)

Deterministic project duration (DPD) - total project duration obtained through the classical Critical Path Method (CPM), hence considering defined and constant activity durations for the structure entered.

Expected value of the project duration (EW) – (from the German "Erwartungswert" – expected value) this value is obtained from the set of results of the various runs of each simulation, using the classical concept "Expected Value" from Statistics. It is frequently utilized in this work in association with the DPD, through the variation percentage of the EW from the DPD.

Maximum/minimum values - lowest/highest project duration obtained in all the runs of a simulation. It is generally given in form of a percent deviation from the DPD.

Horizontal development - Increase of the number of activities on the various rows of a project, without changing the number of rows.

Vertical development – Increase of the number of rows, without changing the number of activities in each row.

Ties – Simple sequential predecessor-successor precedence relationships between activities, as defined in the Network Scheduling Theory

2.3 PROSIM

This software program applies Monte Carlo Simulation to Network Scheduling. The user enters a schedule structure and percent variation value for the single activity durations, and a random generator reduces or increases the duration of the activities by the percent value entered. This procedure is repeated over the number of runs defined by the user. The schedule is then calculated according to the traditional Network Scheduling Theory. The average total project duration is calculated and a table with the durations obtained for each of the runs is created, enabling the user to create cumulative curves and manipulate the simulation data obtained statistically.

This program was developed at the Institut für Planungsverfahren im Baubetrieb (RWTH Aachen) within the framework of the research that gave rise to this doctorate.

2.3.1 Method Statement

For each simulation, the project to be simulated is defined by entering its activities with ID number, duration and precedences. The user then defines the percent value for the variation of the single activities' durations to be used in that particular simulation and the number of runs to be carried out. The program calculates the project and defines the deterministic schedule, just like any current scheduling application. Next, it increases or decreases the duration of the activities randomly by the percent value of variation defined by the user for this simulation. This routine is repeated for each run until the number of runs previously defined by the user is reached. For each run, the following data is stored:

- start and end date of each activity

- total project duration obtained

These values are associated with the number of the run for which they occurred and stored in a table.

Finally, the total project durations obtained for each run are stored in a table and its average calculated.

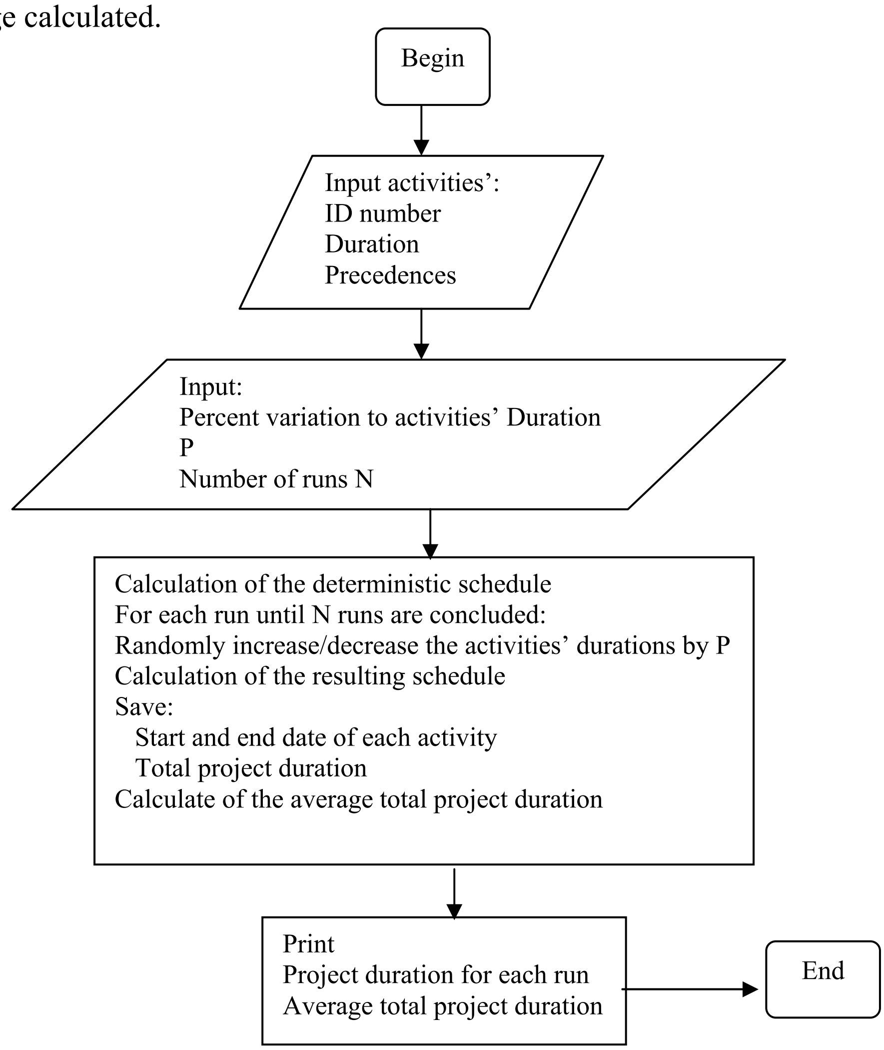


Fig. 2.1: ProSim – Flowchart

2.3.2 Statistical Validation of the Random Generator

It is of paramount importance to the significance of the study that the Random Generator creates approximately as many increased durations as it does decreased durations.

This was ensured by comparing the number of decreases in activity durations with the number of increases in several test projects, described later. All of these projects had a total of 12 activities, structured differently. Each project was simulated twice, for 101 and for 501 runs.

The schedules simulated were:

1. N16 12 rows of 1 activity each
2. N17 6 rows of 2 activities each
3. N18 4 rows of 3 activities each
4. N14 3 rows of 4 activities each
5. N19 2 rows of 6 activities each

All activities had the same duration. For a visual example, please refer to schedule N14 in Fig. 2.6.

2.3.2.1 Results

For each simulation, the number of activities which had their duration increased/decreased was stored in Tab. 2.1. The respective percent value from the sum of all the simulated activities was then calculated.

Project	# of runs	# of activities simulated	# of increased activities' durations	# of decreased activities' durations	Increase %	Decrease %
N16	101	1212	587	625	48,43	51,57
N17	101	1212	585	627	48,27	51,73
N18	101	1212	615	597	50,74	49,26
N14	101	1212	603	609	49,75	50,25
N16	501	6012	3004	3008	49,97	50,03
N17	501	6012	2964	3048	49,30	50,70
N18	501	6012	3004	3008	49,97	50,03
N19	501	6012	2964	3048	49,30	50,70

Tab. 2.1: Random generator test - Simulation results

Comparison of the 8 increase/decrease percentage value pairs shows a maximal deviation of the ideal 50/50 percentage of 1,83% at 101 runs and 0,7% at 501 runs.

This indicates a tendency to convergence toward the ideal 50/50 percentage as the number of runs increases. The deviation is already less than 1% for 500 runs.

A number of 1000 runs was adopted for all the simulations done. This guarantees the relevance of the results obtained.

2.4 SCHEDULE STRUCTURE AND ITS CHARACTERIZING PARAMETERS

2.4.1 Introduction

There are several variables that characterize a schedule. Keeping in mind the objective of schedule optimization, this section identifies and separates these variables according to the ability of the scheduler to control them. It then further examines the schedule characterization by analyzing variables that are related, not only to the structure, but also to the activities of the schedule. This provides a comprehensive framework for the analysis of the factors that impact the schedule's total duration.

2.4.2 Definition of Terms

2.4.2.1 Controlled Parameters

When preparing a schedule, the scheduler often has to choose between creating longer or shorter rows, interconnecting them more or less frequently, or adopting a strategy of parallelism or sequencing. He may decide to shift the resources from one sector to the next in order to cut costs or rotate a new piece of equipment or a system through several teams. This would interconnect the project progress on the various sectors, thus increasing the number of ties between rows. On the other hand, he may prefer to keep the various sectors or processes independent from each other, giving them separate resources and, thus, decreasing the interconnections between rows. Another choice that the scheduler may have to make is between planning several simultaneous processes or sequencing these processes. This might have several reasons, the most obvious being to reduce the volume of resources allocated by sequencing or reduce the duration by making processes run simultaneously. The choices made by an experienced scheduler on these issues point towards his scheduling strategy, his "feeling" about the project and most of his past experience. Thus, the controlled parameters can be divided in two types:

Structural

- *Level of horizontal development* - Number of activities in one row
- *Level of vertical development* - Number of parallel rows

Interconnection between rows (Density of precedence ties between different rows)

- *In one direction* – two or more rows have one or more ties between them, where the predecessors are all in one of the rows and the successors are all in the other
- *In crossed directions* - the schedule rows alternate predecessors and successors of activities in other rows, creating a crossed mesh of ties between rows
- *Maximum density of ties* – all possible finish-to-start ties applied between activities at the same horizontal location in all the rows

This is illustrated in Fig. 2.6, Fig. 2.7 and Fig. 2.9 in later sections.

2.4.2.2 Partially Controlled or Uncontrolled Parameters

These parameters are determined by the effects of uncertainty or imposed by different types of constraints, ranging from good practice in construction to the laws of physics. Furthermore, the characteristics of those parameters which are strongly affected by uncertainty is not yet clear at the inception phase, and thus they can only be estimated. They are:

Relationship between the durations of the activities – existence of uniformity in the activities' durations, activities which are significantly longer or shorter than the average, as well as their relative weight in the total number of activities.

Percent value of the change in the activities' durations – corresponds to the delays that occur during various activities and resulting reductions in activities' duration later in the schedule in a bid to recover the delay in the project. This parameter is obviously unknown to the scheduler at the work preparation phase. Thus, it can't be considered in the schedule.

2.4.3 Research Procedure

The study was conducted in a sequential manner. The different main groups mentioned in section 2.4 were isolated and studied separately. Within each group, the effect of each variable was studied first, and then a sequential combination of the first and second, first, second and third, and so on until the combination of all factors were studied. The main observations obtained in each group were taken into consideration when studying the next group, and a sequential combination was also carried out for the different groups. This is a basic but safe way of obtaining observations about the isolated effects of the variables and the correlation between those effects.

2.4.3.1 Variation to the DPD

Except for the study of the deviation from the deterministic value (described in section 2.4.7), all schedules were simulated with a preset percent deviation value of 20. This assumption can be considered to fall within the upper quarter of the activities' delays in construction projects. Its impact is large enough to be clearly observable without being high enough to be unrealistic.

2.4.3.2 Duration of the Activities

After generating the durations of the activities, the schedule is calculated according to the traditional CPM. Thus, certain activities will be found to build a critical path which will have paramount influence in the output data of the schedule simulated. This critical path is defined by the set of precedences applied and by the single durations of the activities.

Therefore, if some activities have durations that, even when reduced by the defined percent value during simulation, are still most likely to be bigger than the rest of the activities, they will necessarily “draw” themselves into the critical path in almost all the simulation runs, thus having more influence on the results than the others. This would be contrary to the objective of this study. The focus here is the structure and the uncertainty of the durations, considering the total set of durations as a whole. A preset, clearly identifiable critical path would bias the results. The research would have to be focused on this critical path, and the effect of the rest of the activities would not be clear.

A second point is that one of the results studied is the average total project duration obtained. If activities with different durations exist in the schedule, the comparison between the average total project durations of different simulations would be irrelevant, since it would be conditioned, not by the changes made to the variables, but by the activities’ durations which were increased/decreased in each run. It would even be impossible to obtain consistent, stable simulation results within the same schedule.

To address these points, all activities were assigned the same duration, which was set at the value 2. This solves both problems mentioned above:

Point 1: Prior to simulation, all rows, regardless of the ties between them, are potential critical paths. The critical path in each simulation run will be defined by the random duration increase of some activities and by the structure of the schedule. Thus, simulation results depend exclusively on duration uncertainty and schedule structure.

Point 2: Given that all rows are potential critical paths and that the expected number of duration decreases/increases is the same, the absolute value of duration decrease/increase in the whole schedule is the same. Thus, the changes in the expected value of the project total duration are guaranteed to be exclusively conditioned by duration uncertainty and the schedule structure.

Hence, the relevance of the results and of the conclusions drawn from them is guaranteed.

2.4.3.3 Presentation of Results

The data to be analyzed in this study is obtained through simulation. It represents the attempt to generate virtual historical data out of projects that could not be repeated the amount of times necessary to obtain real data. Thus, models and Monte-Carlo Simulation are used.

The results are sets of discrete data. Due to their nature and the predominantly statistical data processing carried out, the clearest means of display and compare the results is by using cumulative curves. They have several advantages to other representations:

1. The expected value is clearly identifiable (cumulative frequency = 0,5)
2. The range of results is directly visible in the graph
3. The slope of the curve can be followed along its whole range and allowing local particularities to be observed
4. These type of curves can be easily superimposed onto each other for comparison and the derivation of evolution tendencies

Given that the main objective of this study is to obtain qualitative tendencies and the correlation of effects, the results for the most significant cases studied for each section will be presented in form of cumulative curves in an orthogonal table. The rows will show the main variable studied in the respective section, and the columns the secondary variables, generally, vertical development and density of ties. For comparison purposes, the last column will have a diagram with all curves of the respective row superimposed onto each other, and the last row will receive the diagrams with all the curves in the respective column superimposed onto each other.

Whenever the DPD varies within the row (e.g.: due to horizontal development and consequent increase of the DPD), the curves of the different cases become spaced from each other. This makes their comparison difficult. To solve this problem, every time this occurred, a modified superimposed diagram was created, where all duration values of the curves to be modified were reduced by the difference between the DPD of the respective schedule and the lowest DPD of all the cases superimposed. This is the case in Fig 2.4 (Vertical and Horizontal Development), Fig. 2.10 (Ties) and Fig. 2.15 (Balance of Durations). This problem does not arise in the vertical superimposed diagrams, since the DPD is the same for all cases.

2.4.4 Structure

2.4.4.1 Horizontal Development

The research will start with the analysis of the horizontal development, the most basic structure change. This consists of increasing or decreasing the number of activities in one row, without changing any of the other characterizing parameters.

Single Row

Three cases were studied: a row with 4, 8 and 12 activities. The results obtained are given in Tab. 2.2.

	Schedule designation	DPD	EW	Increase [%]	# of runs	Minimum [%]	Maximum [%]
a)	N1	8	8,0392	0,49	500	-20	+20
b)	N2	16	16,036	0,23	600	-20	+20
c)	N3	24	24,105	0,49	1000	-16,67	+16,67

Tab. 2.2: Horizontal development – Results for single row cases

Observations:

With the increase in the size of the row, the expected total project duration hardly deviated from the deterministic project duration. The variation is almost negligible at less than 0.5%. Nevertheless, the deviation always took place to the right side of the DPD (increase of the total duration).

When increasing the number of activities, the range of dispersion of the simulation results, given by the sum of the absolute minimum and maximum values, diminishes. This indicates that, assuming the same degree of uncertainty in single activities' duration, the uncertainty of the total duration diminishes with increasing row size. Thus, longer rows enable a more reliable prediction of the total duration.

Multiple Rows

The study was then expanded to include schedules with multiple rows, in order to assess the influence of the number of rows on the results already obtained for a single row. As mentioned before, all rows always have the same number of activities. The results of the schedules simulated are given in Tab. 2.3.

Schedule designation	# of rows	# activities per row	DPD	EW	Increase [%]	Minimum [%]	Maximum [%]
N13	2	4	8	8,41	5,13	-20	+20
N20	2	8	16	16,6	3,75	-10	+20
N45	2	12	24	24,74	3,08	-13,3	+16,7
N14	3	4	8	8,66	8,25	-10	+20
N55	3	8	16	16,968	6,05	-10	+20
N57	3	12	24	25,106	4,61	-10	+20
N10	4	4	8	8,78	9,75	-10	+20
N11a	4	8	16	17,15	7,19	-10	+20
N12	4	12	24	25,41	5,88	-5,7	+20

Tab. 2.3: Horizontal development – Results for multiple row cases

Observations:

As visible in

Fig. 2.2 below, an increase in the expected value of the total project durations always follows the same trend line, irrespective of the number of rows in the schedule.

The absolute values of the increase rise with the rising number of rows. This rise is particularly sharp when the number of rows is small, fading out when the number of rows increases.

Just as in the single row case, the range of dispersion diminishes with increasing row size. This can be observed as a trend and occurs irrespective of the number of rows.

The points mentioned above, together with Fig. 2.4, show that of the number of rows changed the values of the parameters measured without changing their trend. This seems to indicate that an increase in the number of rows (vertical development) merely added its effect to the already known effect of horizontal development, as seen in the study carried out with a single row.

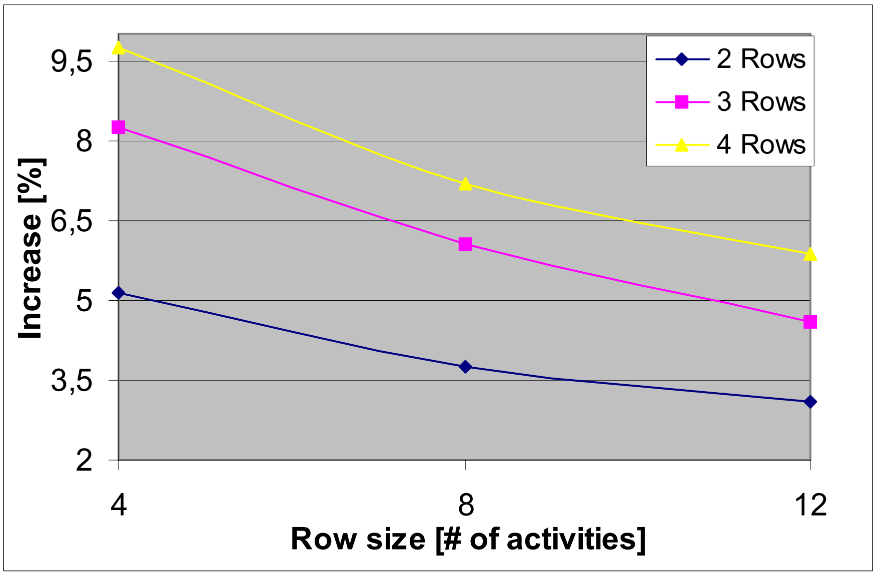


Fig. 2.2: Horizontal development - Comparison of the EW increase for multiple row cases

2.4.4.2 Vertical Development

The effect of increasing/decreasing the number of parallel rows in a schedule will now be studied. As mentioned before, the number of activities per row will be held constant. The results obtained are given in Tab. 2.4.

Schedule designation	# of rows	# activities per row	DPD	EW	Increase [%]	Minimum [%]	Maximum [%]
N13	2	4	8	8,41	5,13	-20	+20
N14	3	4	8	8,66	8,25	-10	+20
N10	4	4	8	8,78	9,75	-10	+20
N20	2	8	16	16,6	3,75	-10	+20
N55	3	8	16	16,968	6,05	-10	+20
N11a	4	8	16	17,15	7,19	-10	+20
N45	2	12	24	24,74	3,08	-13,3	+16,7
N57	3	12	24	25,106	4,61	-10	+20
N12	4	12	24	25,41	5,88	-5,7	+20

Tab. 2.4: Vertical development – Results

Observations:

As can be seen in Tab. 2.4 and Fig. 2.2

1. Fig. 2.2, the variation of the EW increase is marked. Its effect becomes less striking with increasing row size.
2. The range of project durations obtained shifts to the right, into the delay area. This is particularly obvious when looking at schedules with larger rows.

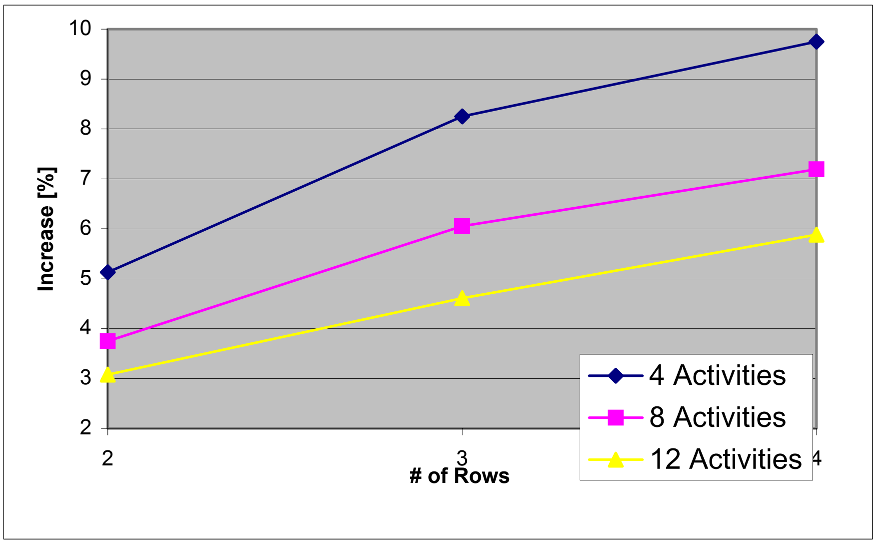
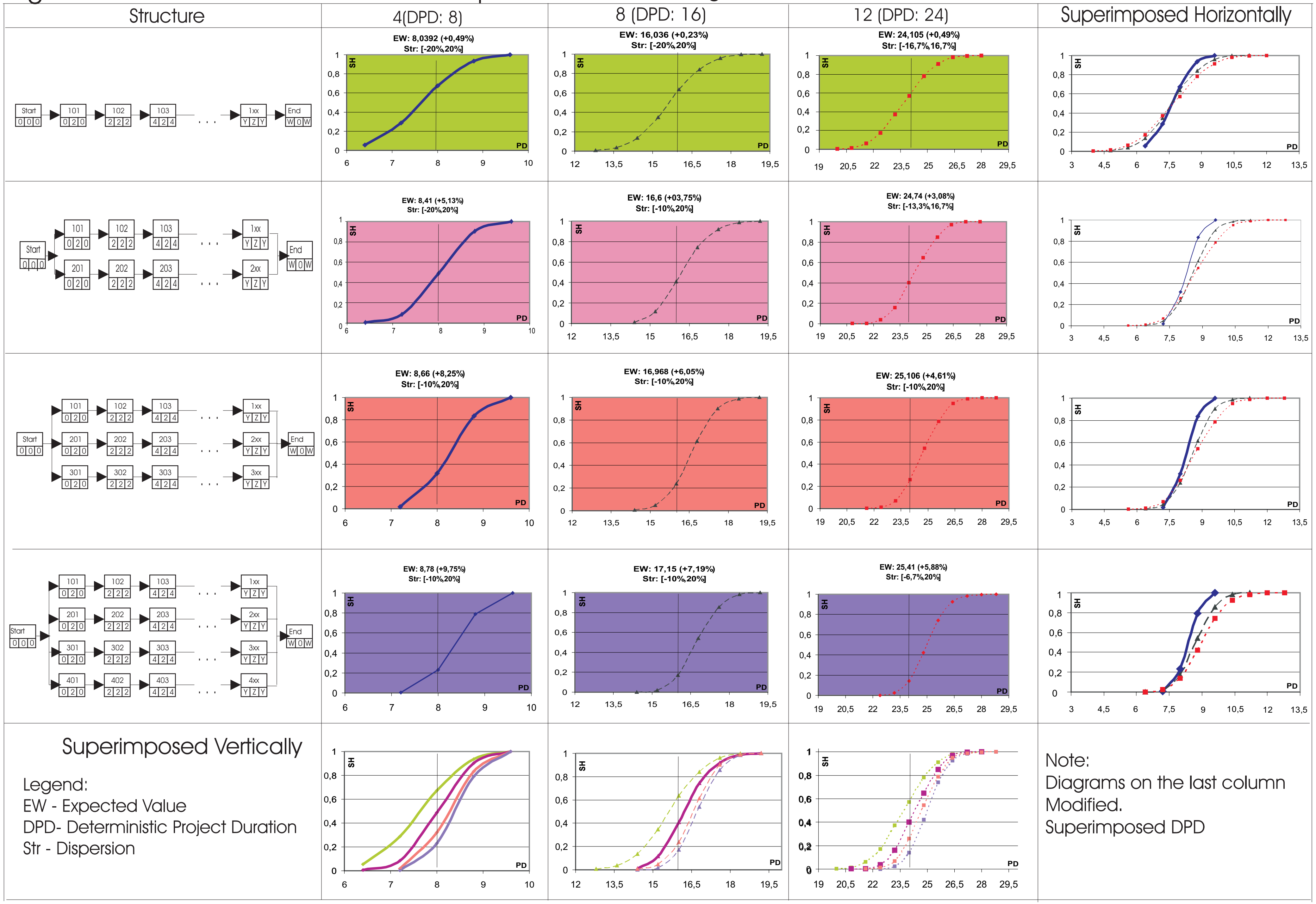


Fig. 2.3: Vertical development - Comparison of the EW increase

2.4.4.3 Combined Development

The results obtained until now make it possible to analyze the combined effects of vertical and horizontal development. They are summarized in Fig. 2.4.

Fig. 2.4: Vertical and Horizontal Development



Observations:

1. In the last row of Fig. 2.4, it can be seen that there is almost no change in the positioning of the curves in all three vertically superimposed diagrams. Thus, the tendencies observed from the vertical development are not affected by superimposing it onto the horizontal development.

2. The last column in Fig. 2.4 shows that the curves become less steep with increasing horizontal development. Their point of intersection lies from a cumulative frequency of approximately 0,5 at one row to approx. 0,1 at 4 rows. Thus, the higher the number of rows, the more the curves shift to the right, into the delay area. As in the first point given above, the effects of the horizontal development at a constant number of rows did not change, irrespective of the number of rows. This confirms the observation made from the first point given above, namely, that the effects of these two variables are not correlated and can therefore be isolated to complex cases where superimposition occurs.

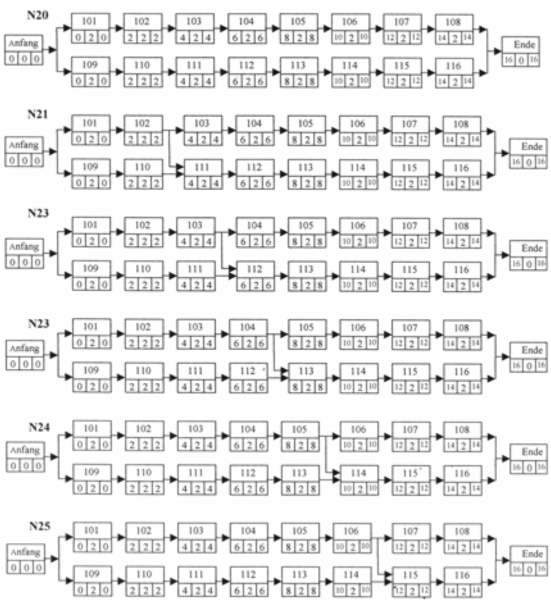
2.4.5 Ties

2.4.5.1 Ties Changes with Constant Structure

Apart from the horizontal/vertical development, the structure of the schedule is conditioned by the ties between different rows. This section will focus on the way in which the different rows are interconnected, both in terms of the direction (flow) of the ties and their density.

Constant Number of Ties

Taking a base structure of 2 parallel rows of 8 activities, one tie was shifted along the two rows as indicated in Fig. 2.5.



Note: Anfang – Start
Ende – End

Fig. 2.5: Constant Number of Ties – Tie Location Shift

The percent increase rose from 3,75% to 4,44%. The minimum and maximum values remained constant at respectively –15% and +20%. Thus, the impact of these changes is not significant. The study of the structures given in Fig. 2.6 below confirmed this conclusion.

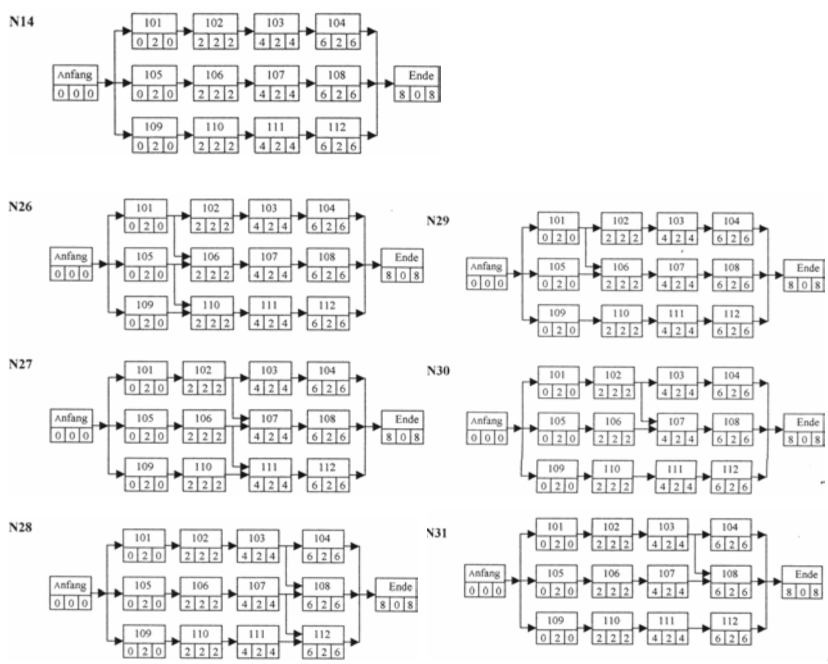


Fig. 2.6: Tie Location Shift – Confirmation Experiments

2.4.5.2 Variation of the Ties' Direction

In this section, the direction of the ties was changed, keeping their number and location constant, as shown in Fig. 2.7. The results obtained are given in Tab. 2.5 below.

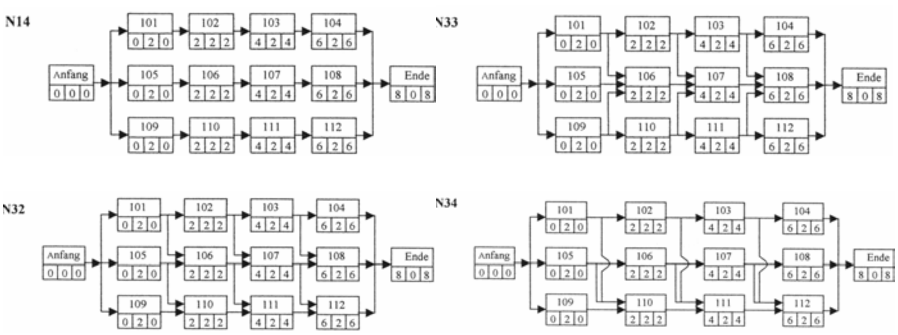


Fig. 2.7: Constant Number of Ties - Variation of the Ties' Direction

Schedule designation	DPD	EW	Increase [%]	Minimum [%]	Maximum [%]
N14	8	8,66	8,25	-10	+20
N32	8	8,89	11,13	-10	+20
N33	8	8,83	10,38	-10	+20
N34	8	8,83	10,38	-10	+20

Tab. 2.5: Variation of the ties' direction

Observations:

The schedule with the strongest increase is N32. This indicates that schedules where the direction of the ties flows throughout the whole schedule have higher EW increases than schedules where most of the ties between rows converge to a single row. Concentration decreases the impact, dispersion increases it.

These results were confirmed by a framework of 4 parallel rows at 4 activities each, as shown in Fig. 2.8 and Tab. 2.6.

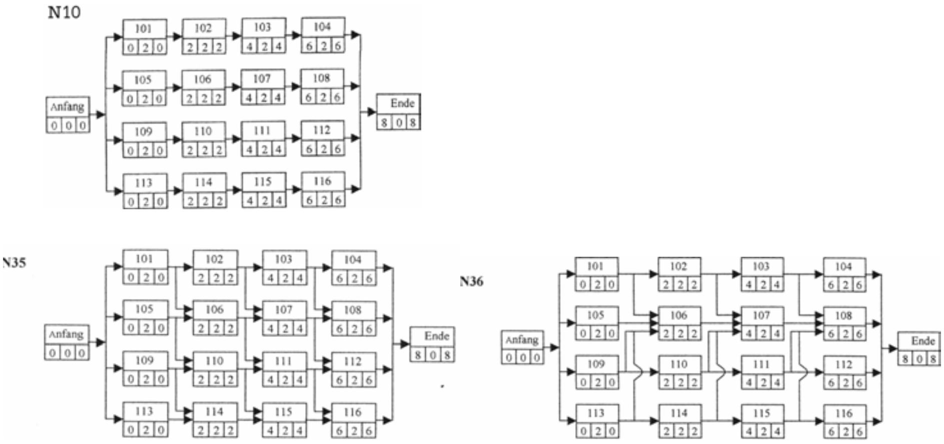


Fig. 2.8: Variation of the ties' direction – Confirmation experiments

Schedule designation	DPD	EW	Increase [%]	Minimum [%]	Maximum [%]
N10	8	8,66	8,25	-10	+20
N35	8	8,89	11,13	-10	+20
N36	8	8,83	10,38	-10	+20

Tab. 2.6: Variation of the ties' direction – Confirmation experiments

Variation of the Number of Ties

Using a base structure of 2 rows at 8 activities, the number of ties were sequentially increased, with an increment of one tie, ranging from 0 to 7, i.e.: from zero to the maximum density of ties. The results are given in Tab. 2.7 below.

Schedule designation	DPD	EW	Increase [%]	Minimum [%]	Maximum [%]
N20	16	16,66	4,11	-15	+20
N37	16	16,72	4,49	-15	+20
N38	16	16,73	4,52	-15	+20
N39	16	16,77	4,83	-15	+20
N40	16	16,83	5,19	-15	+20
N41	16	16,87	5,42	-15	+20
N42	16	16,93	5,81	-15	+20
N43	16	16,94	5,86	-15	+20

Tab. 2.7: Variation of the number of ties

Observations:

1. Although the difference caused by each single increment of one tie is small and almost unobservable, one clear trend can be identified.
2. A uniform rise in the EW increase when increasing the density of ties is visible. Their relationship was found to be proportional.

These two points were confirmed by the simulation of four extra schedules of 3 rows at 4 activities, whose topology is shown in Fig. 2.9 below. The results obtained from their simulation are given in Tab. 2.8.

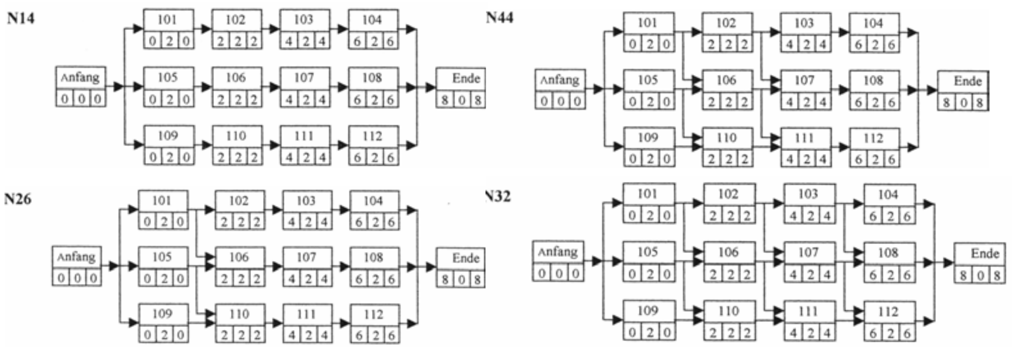


Fig. 2.9: Variation of the number of ties – Confirmation experiments

Schedule designation	DPD	EW	Increase [%]	Minimum [%]	Maximum [%]
N14	8	8,66	8,25	-10	+20
N26	8	8,76	9,50	-10	+20
N44	8	8,84	10,50	-10	+20
N32	8	8,89	11,13	-10	+20

Tab. 2.8: Variation of the number of ties – Confirmation experiments

2.4.5.3 Ties' Changes and Structure Changes Combined

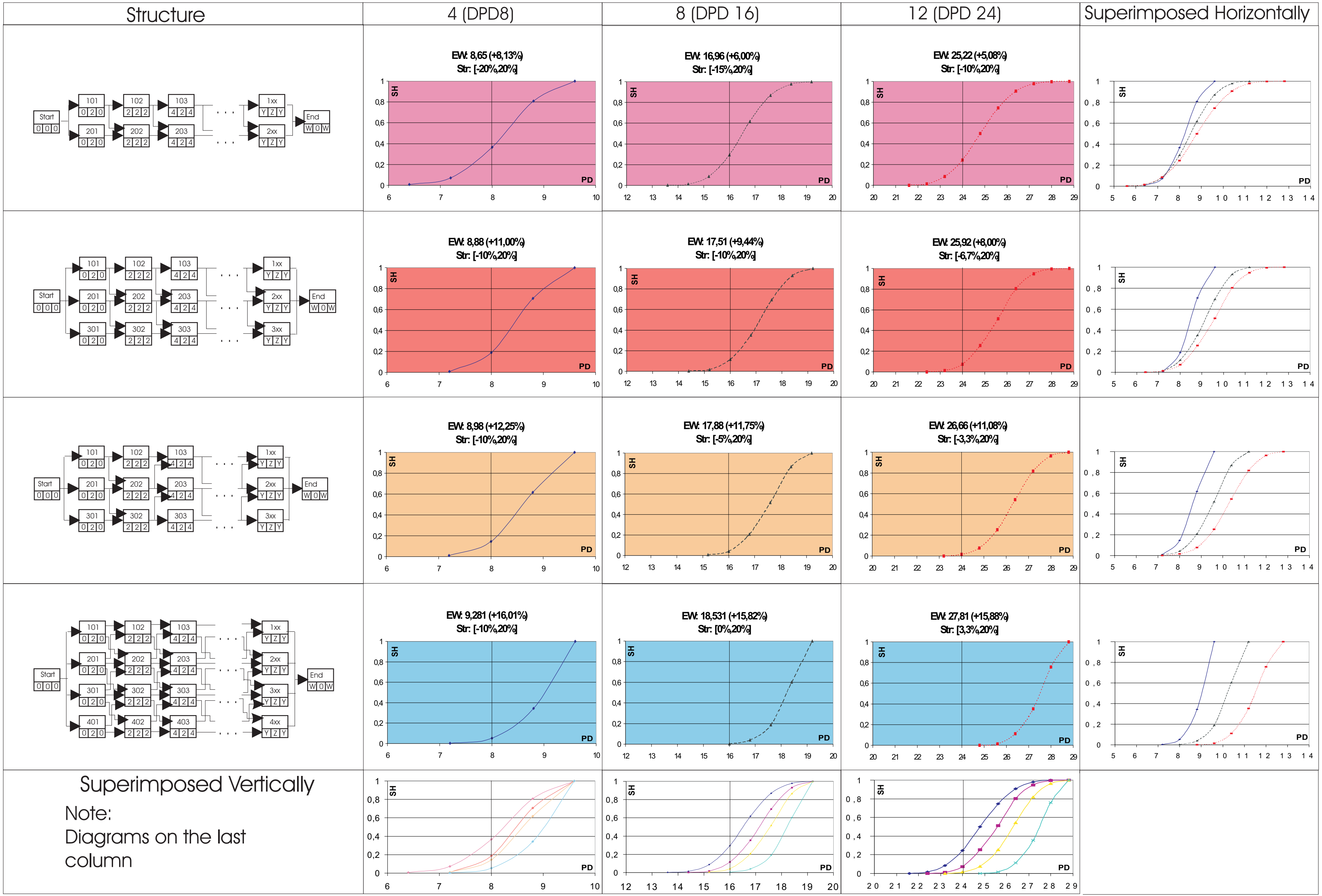
For this analysis, an orthogonal table was again used, as shown in Fig. 2.10 below. Its functioning principles were explained in section 2.4.3.3. The table contains a summary of the most significant cases already presented in section 2.4.5.3 and its subsections. It further includes two new cases, the first displayed in the third row and the second displayed in the second last row.

The first case consists of a modification of the second row (all ties flowing in one direction throughout the schedule), where the flow of ties alternates between down and upwards, respectively.

The second portrays a model of maximum density of ties. It takes into account the observations of section 2.4.5.1, regarding the effect of dispersing the direction of the ties. It also expands the topology of schedules N26 (Fig. 2.6) and N35 (Fig. 2.5) – which are characterized by a ties' flow in one direction – into a dense mesh of ties were each activity is connected to the next two activities of both adjoining upper and lower rows. Please refer to Fig. 2.10, first column, third and the second last row for a clearer visual description of the two new cases mentioned.

Fig. 2.10: Ties

Row Length



Observations:

1. Just as in the first point given in the observations in section 2.4.4.3, the last row of Fig. 2.10 shows that there is almost no change in the positioning of the curves in all three vertically superimposed diagrams. Thus, the tendencies perceived from the vertical/horizontal development and increase in the density of ties are not affected when superimposed.

2. Observing the last row of Fig. 2.10 (diagrams superimposed vertically) on the right hand side of the diagrams, it is visible that the curves corresponding to greater row lengths tend to become less steep. This trend, although much less marked, is also visible in Fig. 2.4. It corresponds to the effect of horizontal development, in this case magnified by the other variables.

3. Through the analysis and comparison of the superimposed schedules, both vertically and horizontally, and particularly through the comparison of the relative location of each one of the curves in the superimposed diagrams, it can be argued that the impact due to the density of ties and their direction is not correlated with the effects studied in section 2.4.4 and its subsections. It furthermore it does not make those effects become correlated.

4. When comparing the dispersion range of the schedules with constant row length of 12 activities (second last column in Fig. 2.10), the reduction in the minimum value is particularly striking. It should be noted that, in this figure, the columns correspond not only to vertical development, but also to the increasing density of ties. This last factor proves to shift the EW into the delay area, but also to make its value more certain, since the dispersion range diminishes.

5. Although the schedules given in the 2nd and 3rd rows of Fig. 2.10 have the same number of rows and activities, as well as the same density of ties, the orientation of the ties proved to play a significant role in the results obtained: the case with uniform, one direction flow showed a smaller EW increase (8,00% against 11,08%) and a wider range of minimum values (-6,7% against -3,3%). This indicate that this factor carries a high degree of impact on the expected total duration of the schedules and their certainty.

6. In the row corresponding to the schedules with maximum density of ties, the range of dispersion decreases significantly with rising horizontal

development. The minimum value becomes zero at the intermediate case and is positive in the case with 12 activities. This means that in 1000 simulation runs, all total project durations were higher than the DPD, although the number of random increases and decreases in the activities' durations is approximately the same. Thus, for schedules with these characteristics, an increase in the project total duration is certain.

2.4.5.4 Fan-shaped Structures: A Specific Case

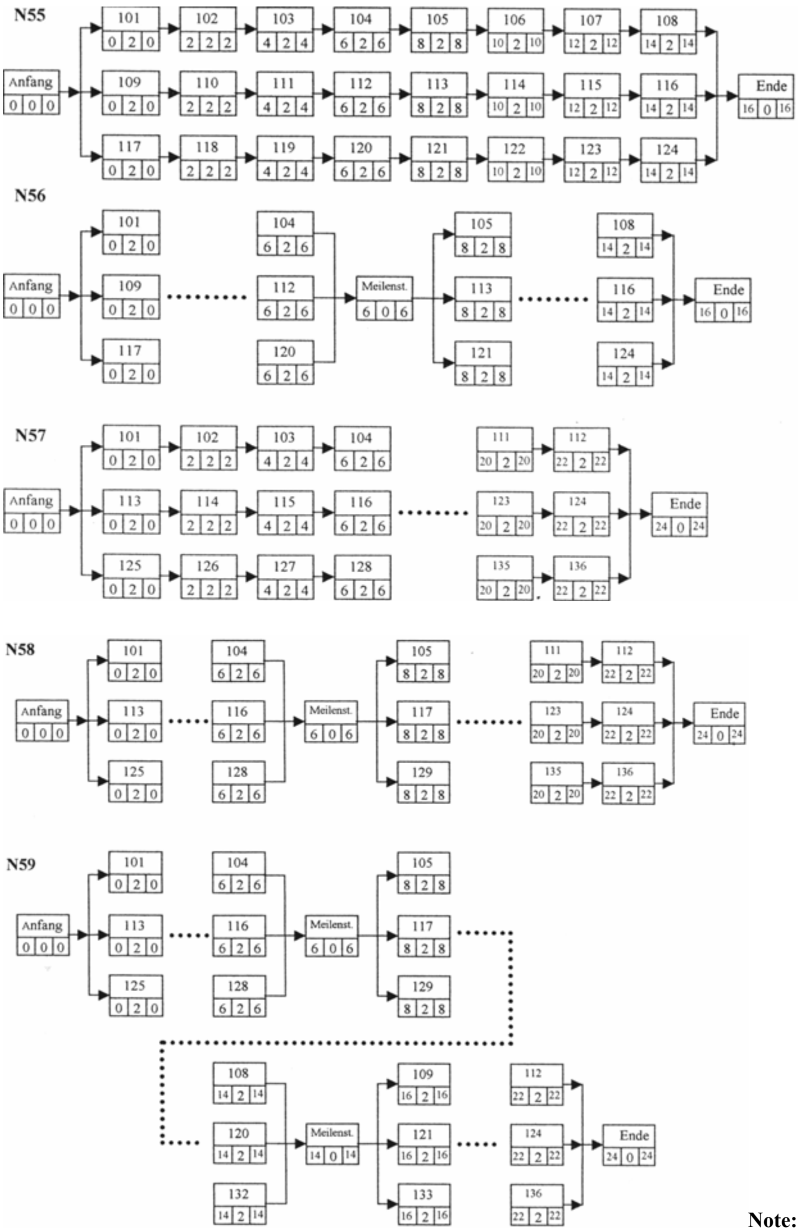
Within the framework of the ties analysis carried out in this section, the specific case of the convergence of several rows into one activity will now be carried out .

This represents, for example, special cases in which buildings must be made water tight before interior work can be begun or in which clearance must be obtained for certain actions (e.g.: construction permits) before construction work can be carried out.

In terms of schedule topology, this translates into linking all activities at a certain point in time to one milestone activity which is in turn linked to all the following rows. In this section, this was modelled on 2 base structures of three rows with 8 and 12 activities. The milestone activities were introduced at a four activity pace.

The effect of introducing milestone activities is presumably similar to the combined effect of increasing the density of ties and decreasing horizontal development. The importance of this last factor is due to the fact that by adding a milestone, the number of sequential activities with finish-to-start precedences are reduced (i.e., the rows are interrupted). Thus, according to the results obtained previously, 2 contrary effects will act upon the results of the simulation in these cases, making the milestone analysis an ideal case study for the validation of the non-correlation of effects and the possibility to overlap them.

The topologies of the 5 schedules studied are displayed in Fig. 2.11 below, followed by the results obtained from simulation in Tab. 2.9.



Note: Meilenstein - Milestone

Fig. 2.11: Milestones – Topologies of the Schedules Simulated

Schedule designation	# of activities per row	# of milestones	DPD	EW	Increase [%]	Minimum [%]	Maximum [%]
N55	8	0	16	16,92	5,75	-15	+20
N56	8	1	16	17,3	8,13	-10	+20
N57	12	0	24	25,11	4,61	-10	+20
N58	12	1	24	25,29	5,38	-10	+20
N59	12	2	24	25,74	7,25	-6,67	+20

Tab. 2.9: Milestones – Results

Observations:

1. The minimum values decrease significantly with increasing number of milestones. Both increasing the density of ties and decreasing the row size have this effect. Thus, the results obtained are consistent with the expectations mentioned previously in this section.
2. The percent increase in the EW increases exponentially with the increase in the number of milestones. This again corresponds to an overlapping of effects, as visible when comparing Fig. 2.12 with the trend curves in
3. Fig. 2.2 and with the results of Tab. 2.7.

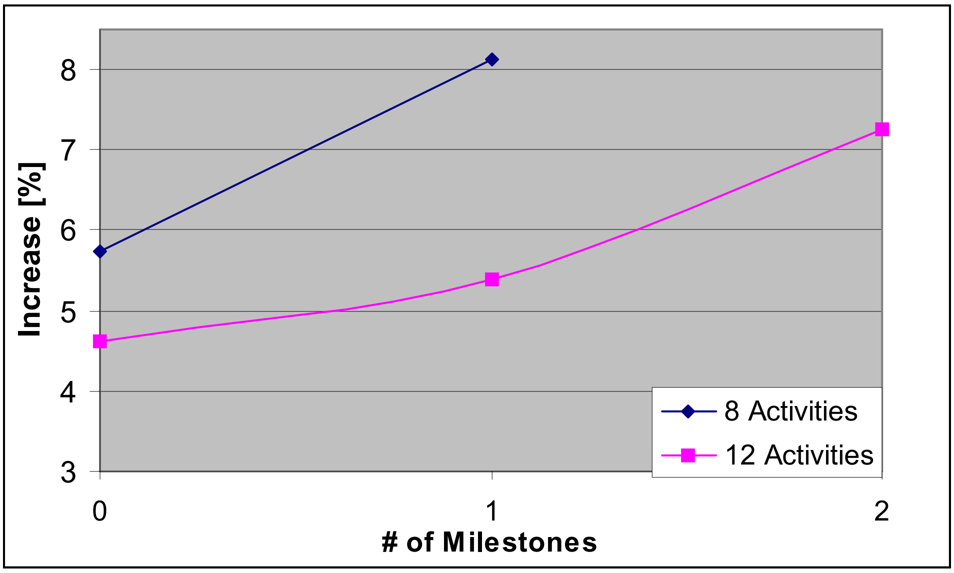


Fig. 2.12: Milestones – Comparison of the EW increase

2.4.6 Durations of the Activities

This variable falls within the group of "Partially Controlled or Uncontrolled Parameters" described previously in section 2.4.2.2. Thus, the influence of the scheduler upon it is limited. Nevertheless, the study of its effect and particularly of its combination with the previously studied parameters is interesting and contributes to the objective of this study.

Until this point, all schedules studied have had a constant duration of 2 for all the activities, thus being relatively far removed from reality. In this section, along with the parameters already studied, the activities' durations will also vary.

The research will start with basic schedule topologies, since the effect of this parameter is completely new and changes the previous framework of study, characterized by constant single activity durations.

In order to highlight any possible trends, the research will start by setting the duration of one activity much larger than the others and continue towards the progressive uniformization of the durations.

2.4.6.1 Uniformity of Durations

The effect of the uniformity of durations will first be analyzed using 3 base topologies. The first one will consist of 3 rows at 4 activities, the second of 4 rows at 4 activities and the third of 4 rows at 4 activities with maximum density of ties.

The balance of durations will evolve from a single, large activity with duration 20 and 3 activities with duration 5 (one activity significantly larger than the others), to 3 activities with duration 20 and one with duration 5 (one activity significantly smaller than the others). Finally, a full uniformization of the activities' duration at value 20 is also presented, thus enabling its comparison with the previously studied uniform cases with duration 2. Conclusions will be drawn, not only about the relative balance of durations, but also about their absolute value. The results are shown in Tab. 2.10 below.

Schedule designation	# of activities with duration 20 per row	Density of ties	DPD	EW	Increase [%]	Minimum [%]	Maximum [%]
N158	1	Min	35	38,57	10,2	-14,3	20
N159	2	Min	50	54,82	9,64	-16	20
N160	3	Min	65	70,85	9	-16,9	20
N161	4	Min	80	86,17	7,71	-10	20
N162	1	Min	35	39,26	12,17	-14,3	20
N163	2	Min	50	55,87	11,74	-16	20
N164	3	Min	65	71,87	10,57	-7,7	20
N165	4	Min	80	87,49	9,36	-10	20
N166	1	Max	35	40,92	16,91	-8,6	20
N167	2	Max	50	58,18	16,35	-16	20
N168	3	Max	65	75,58	16,28	-4,6	20
N169	4	Max	80	92,86	16,08	-10	20

Tab. 2.10: Balance of Durations – Isolated Effect

Observations:

1. In all cases the percent increase of the EW diminished with the increasing number of large activities. The minimum was obtained when all activities had duration 20, that is, in the case of uniformity of enlarged durations.

2. The curves of the EW increase – shown in Fig. 2.13 below – indicating that the behavior is similar in both cases with minimum density of ties, but changes in the project with maximum density of ties. In this last case the absolute values of the EW increase are larger, and the diminishing trend in the curve with increasing number of large activity is not as clear as in the other 2 cases.

3. However, when comparing the curves for the minimum value – shown in the upper part of Fig. 2.13 – it is visible that the similarities are now driven by the number of rows, instead of the density of ties. Comparing the 2 cases with 4 rows, the trends are more pronounced in the curve with maximum densities of ties, but the general behavior is similar.

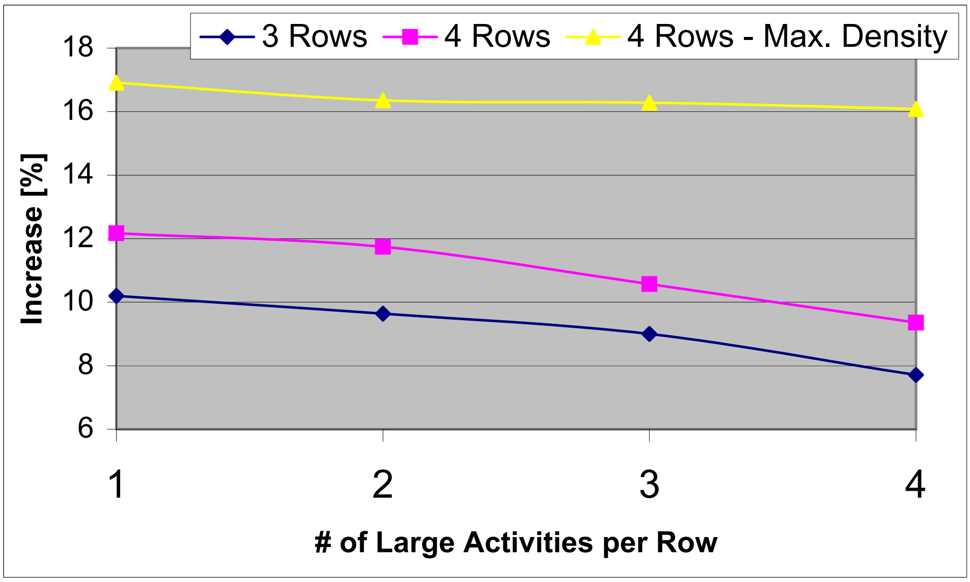


Fig. 2.13: Balance of Durations – Comparison of EW increase and Minimum Values

2.4.6.2 Combination with other Parameters

Although focusing on the isolated effect of the uniformity of durations, section 2.4.6.1 already addressed the combination of effects with the density of ties and with vertical development. Thus, this section will focus on the other parameters.

Combination with Horizontal Development

For this analysis 3 schedules at 4 rows were simulated, all with one activity with duration 20 and all other activities with duration 10. The number of activities was changed from 4 to 2, and then later to 6. The topologies of these schedules are given in Fig. 2.14 below.

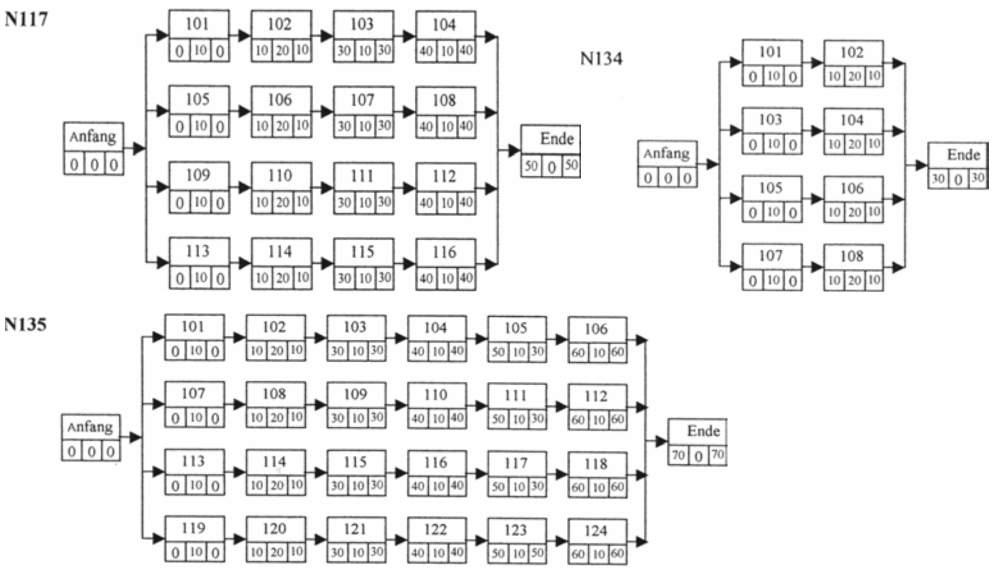


Fig. 2.14:Balance of Durations - Combination with Horizontal Development

The results obtained are given in Tab. 2.11 below.

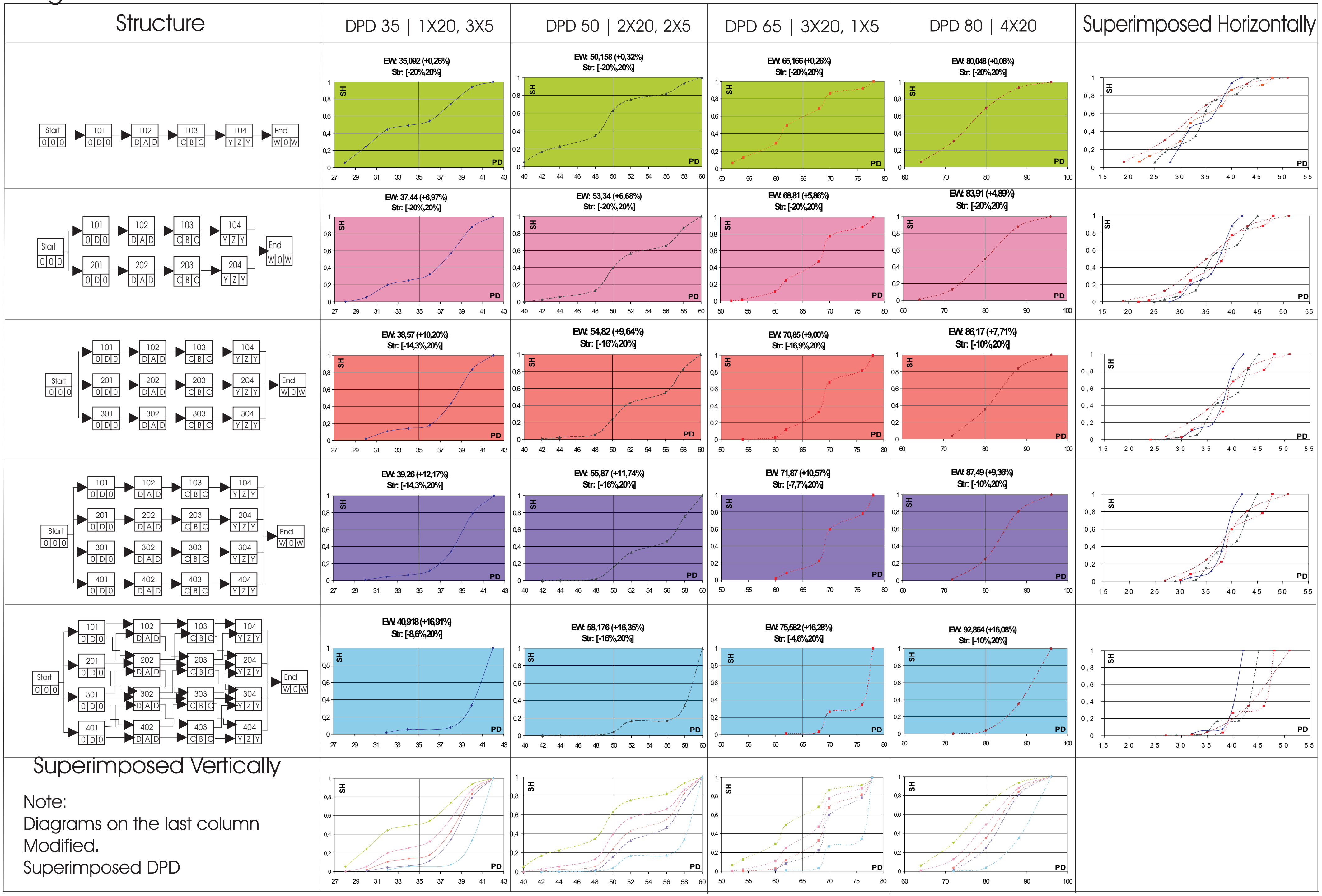
Schedule designation	# of activities per row	DPD	EW	Increase [%]	Minimum [%]	Maximum [%]
N134	2	30	34,48	14,95	-20	+20
N117	4	50	55,23	10,46	-12	+20
N135	6	70	76,34	9,06	-8,57	+20

Tab. 2.11: Balance of durations – Combined effect with horizontal development

Observations:

The resultant effect is the same as for isolated horizontal development, as described previously in section 2.4.4.1 and its subsections. Thus, the analysis of superimposed effects – shown in Fig. 2.15 below – will focus on the uniformity of durations with rows, density of ties and vertical development.

Fig. 2.15: Balance of Durations



Combination with Vertical Development and Density of Ties

This analysis has been completed implicitly in section 2.4.6.1, and points 2, 3 and 4 of the "**Observations**" can also be applied to the subject of this section. They are, furthermore, confirmed by the cases shown in rows 1 and 2 of Fig. 2.15 above.

Deviation from the Deterministic Value

Similar to the Durations of the Activities analyzed in section 2.4.6, this variable falls within the group of "Partially Controlled or Uncontrolled Parameters" (section 2.4.2.2). Furthermore, while the duration of the activities can still be partially controlled by the scheduler, this parameter represents the uncertainty associated to the activities' durations in a schedule. Therefore, it can not be set or changed by the scheduler, and is more so a fact that he has to cope with.

Its importance for obtaining a complete picture of the effect of the schedule structure on the expected total project duration is vital, since it is the source of uncertainty in the total project duration. Though, it will also be studied.

For the sake of consistency, all schedules studied until now had a fixed percent deviation of 20% for all simulations. This meant that all activities had their duration randomly increased or decreased by 20% during the simulation runs. The next sections will handle the effect of change the percent value of the deviation. The analysis procedure will be the same as the one used in section 2.4.4 (Structure), 2.4.5 (Ties) and 2.4.6 (Durations of the Activities) of the study will be utilized.

2.4.6.3 Isolated Effect

The percent deviation will now be increased from 20% to 40% and 60%. The base structure will be a one row at 4 activities schedule. The results are given in Tab. 2.12 below.

Schedule designation	Deviation [%]	DPD	EW	Increase [%]	Minimum [%]	Maximum [%]
N1	20	8	8,04	0,49	-20	+20
N170	40	8	8,04	0,49	-40	+40
N171	60	8	8,12	1,47	-60	+60

Tab. 2.12: Deviation from the deterministic value – Isolated effect

Observations:

1. The minimums and maximums have the same absolute value, which is consistent with the deviation simulated. Thus, the range of dispersion is always maximal.
2. The EW percent increase remains stable in the first 2 cases simulated (20% and 40%), but increases significantly in the last case simulated.

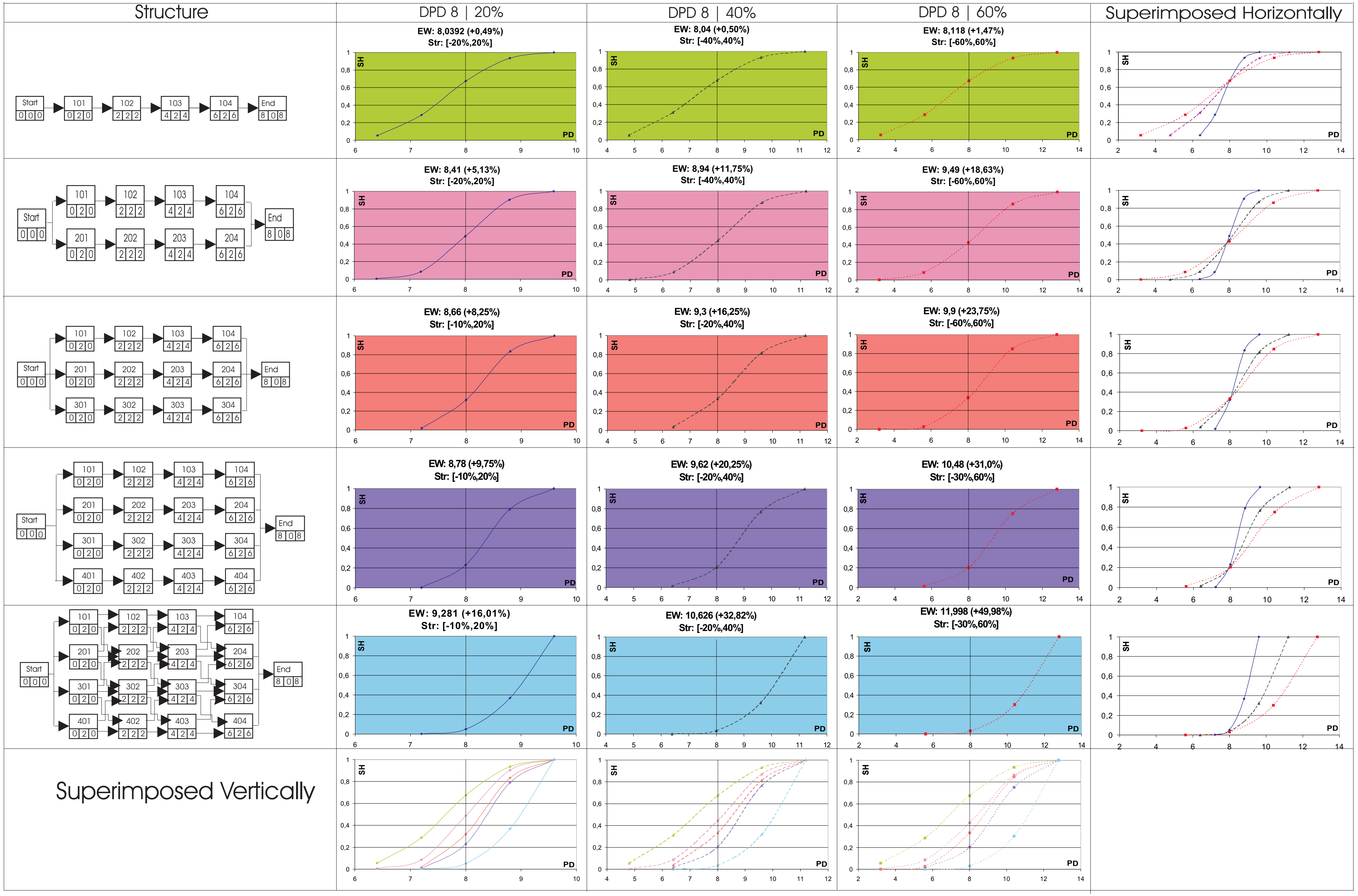
2.4.6.4 Combination with other Parameters

Fig. 2.16 below summarizes the information obtained by superimposing the effect of deviation change onto the effect of structure change and density of ties. The same format from sections 2.4.4, 2.4.5 and 2.4.6 has been used. The analysis of this figure leads to several observations:

1. When comparing the changes in the first column of Fig. 2.4 ("Vertical and Horizontal Development") with those in the 2nd and 3rd columns of Fig. 2.16, it is clear that the change trend in the minimum and maximum values is identical. The only difference is the absolute value, which changes according to the percent deviation simulated (e.g.: for a 20% deviation and 4 rows, the dispersion range goes from –10% to +20%, corresponding to a –20% to +40% range at a deviation of 40 % and a range of –30% to +60% at a deviation from 60%)
2. Similarly, the EW increase for the same base structures and deviations of 40% and 60% also approximately corresponds to multiplying the EW increase value obtained for a deviation of 20% by 2 and 3, respectively.
3. When looking at the last column of Fig. 2.16, again the enlarging effect can be seen: superimposing the curves for the different deviations simulated shows that the curves tend to become less steep with increasing deviation value, indicating

that the range of dispersion increases, as mentioned previously. The enlarged effect of the vertical development can also be seen. It is evident in the fact that the difference between the curves tends to move from the left side to the right side of their intersection point, corresponding to a decrease in the y-axis value of this point from approx. 0,65 on the first row to 0,2 in the 4^{th}.

Fig. 2.16: Percentual Variation of the Durations



Final Results

The results obtained throughout the study have been presented in the corresponding sections under the titles "**Observations**". Thus, this section will focus on their overall comparison and analysis. The attainment of the objectives proposed in the beginning of the study will then be addressed. Finally, the qualitative trends obtained will be summarized in quick reference tables.

2.4.7 Analysis

In all the schedules simulated, the EW increase was positive. This leads to the conclusion that no matter what the variables in question are, uncertainty in the single activities' durations will bring about delays in the project. Thus, when dealing with uncertainty, it is more effective and realistic to try to reduce the uncertainty of the total project duration than to try to reduce the total project duration itself. This conclusion is of paramount importance to the future direction of this work.

Although uncertainty tends to mount during the course of the schedule, section 2.4.4 has proven that the uncertainty associated with the total project duration can not only be controlled through conscious manipulation of the schedule's topology, it can even be made smaller than the uncertainty of the activities' durations themselves! This result is particularly encouraging in terms of the endeavor to assure a delivery date through schedule optimization.

Reviewing the observations presented in the subsections of chapter 2, it is clear that the effects of the variables studied are not correlated at the level of detail at which this research was conducted. The effects of the variables studied overlap and conjugate, but can always be identified and isolated when looking at a complex case. This supports the endeavour to create a body of qualitative trends, valid for all scheduling contexts, where an effect can be predicted for each of the variables present in the schedule, and the overall effect derived from the existing single effects.

There was a single occasion in this study where the effect of one variable changed the known and expected trend of others. This happened in section 2.4.6.1 (Uniformity of Durations) and is presented in Fig. 2.13. However, as mentioned in point 4 of the

Observations in that section, that change consisted of an enhancement of effects. This particular situation does not contradict the logic behind this study. Moreover, it points toward the correct way in which schedule optimization should be approached: starting with a body of knowledge consisting of qualitative trends, the scheduler should isolate the few cases that are expected to produce the best results and determine the best one of these through the appropriate simulation of that specific situation.

2.4.8 Conclusions

As indicated in section 2.4.7 above, the non-correlation of effects is valid for the level of detail utilized in the study. However, there were many indications that some effects might correlate given a higher level of detail. When dealing with the uncertainty of real-life situations, it should always be kept in mind that the level of detail made possible by present day modeling and computing technology can easily loose connection with reality, producing results of little practical relevance. A pragmatic example of this might be the rendering of results with 8 decimal digits that can be quickly and easily obtained from a pocket calculator, based on measurement input data with 2 decimal digit accuracy.

This study aimed to abide by 2 major principles: the scientific accuracy of the methodology and research procedures utilized, and the practical relevance of the results obtained.

This work deals with uncertainty. Thus, the input data utilized in this study is itself uncertain. It was concluded that the level of detail utilized was sufficient to produce results that meet the objectives defined in section 2.1 and to create a body of knowledge for the optimization research carried out later in this thesis. Specific correlation effects were not handled in great depth because they were considered of second order or minor practical importance.

However, further research in this area is possible and desirable. The results of this study are far from conclusive and objective oriented research on the second order correlation effects mentioned in the last paragraph may be the perfect starting point for a new study. The author would like to recommend that the level of detail used corresponds to the objective set, and that extra care be taken to maintain a connection with reality.

Finally, from the analysis of the results of this chapter, a set of qualitative tendencies were summarized in Tab. 2.13 and Tab. 2.14 below.

	Percent variation of EW to the DPD	Minimum Values	Maximum Values
Increasing # of activities per row	Falls moderately	Falls	Falls moderately
Increasing # of parallel rows	Rises logarithmically	Falls	Rises moderately
Increase in the density of ties	Falls moderately	Falls significantly	Always equal to the absolute deviation simulated

Tab. 2.13: Structure – Summary of Tendencies

	Percent variation of EW to the DPD	Minimum Values	Maximum Values
Increase of Uniformity of Durations	Falls moderately	Uncharacteristic	Always equal to the absolute deviation simulated
Increase of the Percentage of Variation	Rises proportionally	Falls	Always equal to the absolute deviation simulated

Tab. 2.14: Durations – Summary of Tendencies

3. Scheduling and Stochastic Simulation

3.1 STATE OF THE ART

3.1.1 Historical Background

Ever since the dawn of civilization, societies have realized that in order to carry out any complex endeavor involving joint effort, multidisciplinary teams and significant time and/or resources consumption, a system for planning, managing and controlling the execution of projects would be vital.

Thus, it is known that as far back as when the first large Egyptian pyramids were built, a method of managing the construction was devised by their constructors: the stones were numbered and delivered to the construction site according to a plan; at the right time and in the right sequence. This implies that the conditions on site were surveyed in advance, and that transportation and elevation means, as well as other resources and manpower were also planned beforehand. Such a plan could only emerge from the careful analysis of the structure of the project, its division into sub-processes, and an understanding of their interdependencies and durations. Later, during the execution phase, the plan had to be put into practice through effective management, as well as constant control and comparison between the plan and reality.

The technological capabilities of those times were limited, but those early project managers successfully erected masterpieces of construction which, thousands of years later, still impress our high-tech society.

Those management methods were modified and adapted for centuries, enabling the construction of cathedrals in the middle age and other majestic endeavors of societies, until the industrial revolution dramatically increased the need for coordination, and resource and time optimization.

In 1919, Gantt presented the bar chart schedules that still bear his name today. They consisted of a list of all the activities in a project and a y-axis with the time span of the project. Each activity is marked with a bar between its scheduled start and end dates.

This method enables contractors to manage resources easily by checking the chart directly on a day-to-day basis, overseeing the activities that needed to be carried out simultaneously.

This allowed a certain degree of resources optimization during the planning phase, since the activities could be moved backwards or forwards in time, between certain limits, in order to level the resources' needs. It also implied the careful planning and analysis of effort needed in a project, which carry with them insights and clarifications about the project's structure. However, this method did not allow a full overview of the activities interdependencies or the time span on which they could start and end without delaying the project, i.e: the activities' floats.

Recent modifications incorporated some of the advantages of network scheduling by adding arrows representing the ties between the activities and marking the floats of the activities in the bars. The output of the scheduling application MS Project represents a good example of these modified Gantt Bar Charts. Rendering the ties between activities was an important improvement to the original schedules, since it enabled a scheduler to visualize the impact of moving the activities in time on the rest of the schedule.

3.1.2 Scheduling

World War II and the impressive, large scale engineering works that were then carried out, pushed traditional empirical based methods past the edge of their limitations. The focus had shifted from careful resources management to the coordination of the works of several stakeholders and their interdependencies.

By the end of 1956, the US company Pont de Nemours & Co called for the development of an effective method for planning and controlling investments, maintenance and reparation works. In 1957, the method devised was tested on the construction of a factory, and 1959 the "Critical Path Planning and Scheduling" method, the predecessor of the famous Critical Path Method, was presented publicly.

At almost the same time, working within the context of the Polaris Rocket Program, the US Marine gave instructions to its Special Projects Office to develop a method for effectively coordinating and controlling the works of more than 10 000 stakeholders. In

1958/59, the first publications on the Project Evaluation and Review Technique (PERT) appeared. The overwhelming success of this method, saving 2 years in the total duration of the project, led the US government to make its utilization compulsory for all government contracts exceeding a total cost of a million US Dollars. This method took into consideration the fact that activities' durations can not be thought of as being deterministic. It applied a simple formula to incorporate this factor into the calculation of the durations. This formula and the limitations it has since proved to have will be discussed in further detail in section 4.2.4.1.

Network Scheduling has since rapidly earned the respect of the industrial and academic milieus. A huge amount of research and development effort has been put into this subject, resulting in innumerous improvements and variations, described in a wealth of publications over the last 40 years.

Today, network based scheduling is widely accepted as "the most evolved form of planning and calculating construction processes" (Seeling (1996), free translation from the German language by the author), enabling duration and cost reductions and the effective optimization and coordination of resources.

3.1.3 Stochastic Simulation

The latest developments in this area have increased the accuracy with which the activities' durations are determined, and attempt to accurately represent their non-deterministic and uncertain character. The recent surge in the quality of personal computers has made complex stochastic simulation, incorporating several complex and interrelated parameters, more affordable for both researchers and industry professionals.

Certain projects are unique or too expensive and complex to be tested for the sake of obtaining statistical data about their durations and the duration of their activities. Thus, stochastic simulation provides a good means for generating virtual statistical data by way of mathematical models which characterize the network based schedules.

The factor of uncertainty is simulated through the variation of some of the parameters of this model, according to a known pattern, generally a range and/or a certain statistical distribution. The stochastic character is obtained from number generators using pseudorandom algorithms. A detailed description of these algorithms can be found in the literature on the most common computer programming languages, such as C++ from Borland.

The level of complexity of the simulations has risen in parallel with the dramatic increase in the computational ability of computers.

3.1.4 Latest Developments and Trends

The major problem with stochastic simulation is the ability to guarantee the representativeness of the data obtained. If the simulation conditions, format or methods do not represent to reality accurately, the whole process is threatened with redundancy. The late 80s and the 90s saw two important trends emerge in response to this problem:

One focused on the conditions and method approach, aiming at incorporating human knowledge and experience into computer-based expert systems which would then decrease the gap between the simulation conditions and reality.

The second one focused on the format approach. It applied fuzzy arithmetic to the characterization of the activities' durations. This approach is based on the observation that stochastic methods can only be applied when the statistical distribution function of the parameters is known. This is turn implies that the processes analyzed can be repeated. Fuzzy methods, however, do not depend on distribution functions. They can therefore characterize non-stochastic uncertainty (compare with Lessmann et al. (1994)).

Thus, the discussion now focuses on whether the processes in question can be characterized using distribution functions. Although conclusions with regards to this subject are far from certain, it is the author's opinion that a case-by-case analysis of the nature of activities' uncertainty has to be done and the appropriate format chosen accordingly. However, the author further holds that the majority of the activities' durations in construction industry can in fact be characterized stochastically, being non-stochastic cases rather the exception. This opinion is backed by the author's own practical experience, on-site construction scheduling, and by the many examples of the successful appliance of non-deterministic network scheduling to all sorts of projects over the last 40 years.

The number of non-stochastic cases is increasing rapidly with the introduction of new technology and internationalization of the construction companies. Construction companies nowadays frequently bid jobs more in countries where their known parameters no longer apply. The Fuzzy based methods offer a large research and development potential that should by all means be explored in order to come close to a commercial alternative to the widespread stochastic methods based software applications.

Rabetge (1990) focuses on fuzzy methods and his description is particularly illustrating. In his approach, the ties between activities, as well as the durations, are quantified using fuzzy numbers. In their article, Mon et al.(1995) also include economic considerations and cost factors into a Fuzzy/PERT cost approach.

The latest developments go one step further and include the uncertainty of the schedule structure itself in the simulation, applying the same principles of conditioned simulation to the interdependencies between activities. This subject was presented and discussed by Prof. Valadares Tavares and his team from IST/TU Lisbon at the "Conferencia Especializada Gestao de Projectos 1999", a Project Management Conference held yearly at IST/TU Lisbon. Unfortunately, the proceedings of the conference just include an abstract of this presentation.

3.2 SCHEDULING

"The objective and task of Network Scheduling is to safely plan the preparation and progress phase of production or projects, achieve their coordination and management on an objective oriented manner, as well as their control." (Petzschmann (1992/93), free translation from the German language by the author).

This implies a previous analysis of the project structure and its division into individual, time and resources demanding sub-processes or activities. Thus, the whole process has to be thought through, from the planning phase (concept, dimensioning and design) to the delivery of the completed object to its users.

This effort brings up interrelations, constraints and requirements, finally portraying them on a clear network scheme. Another advantage of this method is the possibility it offers to optimize the schedule for time, resources and/or cost.

There are two major approaches to the drawing of the network schedule, depending on whether the planner is focusing on the activities with their durations, start and end dates, or on important events during the project. These two different approaches divide Network Scheduling into two groups, namely, activity-oriented scheduling or event-oriented scheduling.

The first group can be further divided into two types of representation; Activities on the Arrows (AoA) and Activities on the Nodes (AoN) network based schedules. As their names suggest, the difference between the two types of representation lies in the way in which the activities are represented. The Critical Path Method (CPM) – one of the most widely used Network Scheduling methods – belongs to the first sub-group, while the less widely used Metra Potential Method (MPM) belongs to the second sub-group.

The event-oriented network based schedules are represented through Events on the Nodes (EoN) methods. The Project Evaluation and Review Technique (PERT), which is also widely known and applied, belongs to this group.

The 3 main methods mentioned above were all developed independently and almost simultaneously during the 50s and 60s. They have since evolved under several modifications and improvements.

Innumerous works have been published on this subject since then, and the basic Network Scheduling Technique can nowadays be considered common knowledge in higher education engineering. Thus, a detailed explanation of this technique and its mathematical basis would be redundant in this work. Interested readers can, however, refer to several books by Prof. Reinhard Seeling on the matter indicated in chapter 11, as well as Rabetge (1990), Zimmermann (1971), Petzschmann (1992/1993) and Han (1997).

3.3 STOCHASTIC METHODS

In the construction industry, the concept of stochastic methods for planning is almost equivalent to PERT. Non-deterministic planning is the exception in construction, rather than the rule, and PERT has become a standard for this type of scheduling approach.

PERT is a stochastic model characterized by deterministic dependencies between activities and stochastic activity durations. The stochastic variable activity duration follows a Beta-distribution, as shown in Fig. 3.1 below.

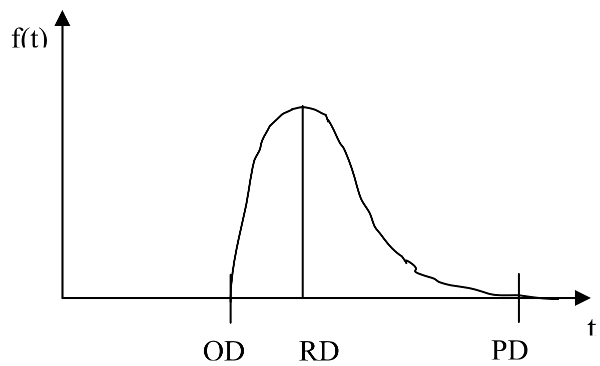


Fig. 3.1 PERT - Distribution function for the activities' durations

The PERT model constructs its time planning based on the Beta-distribution which can be represented with sufficient accuracy by the expected value and variance. These secondary parameters are derived from the primary parameters "optimistic duration", "pessimistic duration" and "most likely duration", also called "realistic duration".

This work utilizes a modified version of the traditional PERT model, replacing the realistic duration with a tendency, ranging from 1 (very optimistic) to 5 (very pessimistic). This concept was used in the Monte Carlo Simulation by its author, Dr. Han, for the purposes of his PhD thesis, resulting in a software prototype for stochastic simulation-aided construction scheduling. The following 3 subsections characterize the theoretical background of this work and describe Dr. Han's prototype which, together with the proposals of further research and improvement stated in Han (1997), serve as the starting point for the author's method and research described in this thesis.

3.3.1 Monte-Carlo Simulation

The analysis of the actions within a complex system is carried out through a system model. The modelling of the system in question means the substitution of that system with something simpler or easier to analyze (compare with Mitrani (1982)). Thus, the system model is a descriptive form of a real event or system, which contains the information necessary for the study of the system.

The model utilized can be classified according to its technical or mathematical nature. Examples of technical models might be the cars used in crash tests or the prototypes studied in wind tunnels. Examples of mathematical model might be the description of the flight behavior of a plane through mathematical equations and the analysis of their different parameters, such as speed and fuel consumption. In a similar vein, a model of a construction project is an execution plan where all the activities and processes of the project and their interdependencies (ties) are indicated and quantified.

Simulation is the replacement of the conditions in reality by a model, whose characteristics are then subjected to experimental study. In a stricter sense, simulation is the study of mathematical problems using experimental methods. This work will always use the term simulation in this strict sense.

In a mathematical model the fundamental components of a real system or process are represented by mathematical values. The dependencies between these components are replaced by equations. If we consider the input data represented by a vector Z and the output data represented by a vector X, then the simplest way to represent the relationship between input data and results is an equation like

$$X=f(Z) \tag{3.1}$$

However, the functional relationship between Z and X can rarely be represented in a simple way. It generally consists of several complex dependencies between the different variables involved.

Most processes simulated evolve over time, so a dynamic model has to be used. If the variables that describe the system (X and Z) only change or are observed at discrete, integer-value points in time, equation 2.1 for a certain time point t is represented as

$$X_t = f_t\,(Z_t, Z_{t-1}, \ldots, Z_{t-k}, X_{t-1}, \ldots, X_{t-k}) \qquad (3.2)$$

In the equation above, the Z components are labelled exogenous and the X components are labelled endogenous.

Thus, vector X_t represents the status of the system at a given time point. The simulation of the system in a computer would then have to consider a discrete, period-oriented characterization. In this type of simulation, the system is observed at pre-defined, generally periodic time points, and the values of its endogenous variables are calculated.

Another simulation possibility is event-oriented simulation, where the system is only observed when the values of endogenous or exogenous variables change, flagging a endogenous or exogenous event. A counter – also called a simulation clock – provides the event time values in the event-oriented simulation, or determines the next time point for the system to be observed in the time-oriented simulation.

Another distinction that needs to be made in simulation is that between deterministic and stochastic simulations. If at least some of the components of vector Z are random values, then the simulation will be considered stochastic, otherwise it will be classified as deterministic. Thus, optimization problems dealing with uncertainty are an example of stochastic simulation, while the calculation of the orbit of a satellite, for example, is considered to be a deterministic simulation of a stochastic problem.

Fig. 3.2 below summarizes the different types of system models.

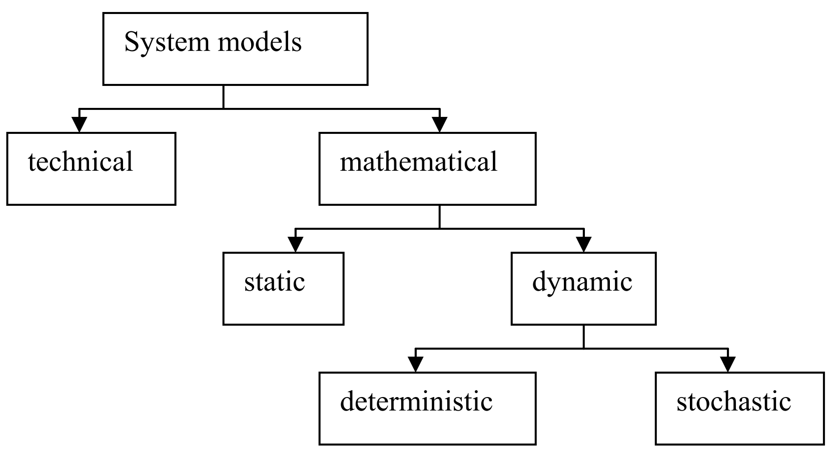


Fig. 3.2 Types of system models (Han (1997))

The utilization of stochastic simulation to solve problems is also known as the Monte-Carlo Method, or Monte-Carlo Simulation, due to the similarities it shares with the random nature of gambling and its association with the famous casino and gambling area of Monte Carlo in Monaco.

Further details on the subject of Simulation and its classification can be found in Neumann (1975).

3.3.2 Computer Simulation of Activities' Durations with Beta Distribution

This section describes the mathematical, statistical basis for obtaining Beta-distributed activity durations through the back transformation of the Beta-distribution density function, replacing the classical utilization of a modal value for the definition of the curve by the assignment of tendency factors.

It then develops to calculate the functions and parameters needed for its utilisation in computer simulation, resulting in the definition of an algorithm for this purpose.

3.3.2.1 The Density Function and its Characterizing Parameters

As mentioned in section 3.3, the PERT method utilizes the Beta-distribution for the activities' durations. The density function within a finite interval [a,b] is defined as:

$$f(x) = \begin{cases} \dfrac{\Gamma(r+s)}{(b-a)^{r+s-2}\Gamma(r)\Gamma(s)}(x-a)^{r-1}(b-x)^{s-1} & \text{for } a \le x \le b \\ 0 & \text{else} \end{cases} \qquad (3.3)$$

with r,s >0, r+s-2 $\neq$ 0

where: a – optimistic activity duration

b – pessimistic activity duration

r,s – parameters from the distribution function

$\Gamma(\alpha)$ - Gamma function

The Gamma function is defined as

$$\Gamma(\alpha) = \int_0^\infty x^{\alpha-1} e^{-x} dx \qquad \textbf{for } \alpha > 0 \tag{3.4}$$

The expected value E(X) and the variance D(X) will be:

$$E(x) = a + (b-a)\frac{r}{r+s} \tag{3.5}$$

$$D(X) = (b-a)^2 \frac{rs}{(r+s)^2(r+s+1)} \tag{3.6}$$

Shape Parameters

Since r = s = 0 would lead to a [a,b] uniform distribution, and given that the parameters a and b represent optimistic and pessimistic durations, respectively, the parameter values with practical relevance are r,s >0 and b > a$\geq$0.

Apart from the optimistic and pessimistic durations a and b, the PERT method also considers a most likely duration, or *modal value*. The modal value corresponds to obtaining a maximum for the distribution curve. Thus, the solution is obtained through

$$\frac{df(x)}{dx} = 0 \quad \text{and} \quad \frac{d^2 f(x)}{dx} < 0 \tag{3.7}$$

Applying in (3.3),

$$\frac{df(x)}{dx} = \frac{\Gamma(r+s)}{(b-a)^{r+s-2}\Gamma(r)\Gamma(s)}(x-a)^{r-2}(b-x)^{s-2}\left[(r-1)(b-x)-(s-1)(x-a)\right] \quad (3.8)$$

Substituting (3.8) in (3.7) we have three solutions:

$x_1 = a$

$x_2 = b$

$x_3 = \dfrac{b(r-1)+a(s-1)}{r+s-2}$

Since the first two solutions don't make sense in practice, the modal value adopted will be $m = x_3$.

This leaves just one degree of freedom left for the estimation of parameters r and s, still undefined. However, since these parameters do not have an obvious physical meaning, their direct estimation would certainly bring about errors. Thus, it is preferable to consider the common, expedite PERT equations for the definition of the expected value and the variance $\sigma^2_{D_{i-j}}$ of the duration of an activity i-j:

$$\mu = \frac{a+4m+b}{6} = E(D_{i\text{-}j}) \quad (3.9)$$

$$\sigma^2 = \frac{(b-a)^2}{36} = \sigma^2_{D_{i-j}} \quad (3.10)$$

Considering the equations (2.9), (2.10), (2.5) and (2.6), we have:

$$\frac{a+4m+b}{6} = a + (b-a)\frac{r}{r+s} \quad (3.11)$$

$$\frac{(b-a)^2}{36} = (b-a)^2 \frac{rs}{(r+s)^2(r+s+1)} \quad (3.12)$$

Thus, the solutions obtained are:

$$r = s = 4 \quad (3.13)$$

$$r = 3 + \sqrt{2}\,,\ s = 3 - \sqrt{2} \quad (3.14)$$

$$r = 3 - \sqrt{2}\,,\ s = 3 + \sqrt{2} \qquad (3.15)$$

Applying these solutions to the standard Beta distribution Beta – [0,1]:

$$m = \frac{r-1}{r+s-2} \qquad (3.16)$$

Substituting parameters r and s we have:

(1) $m_1 = \dfrac{4-1}{4+4-2} = \dfrac{3}{6}$

(2) $m_2 = \dfrac{3+\sqrt{2}-1}{(3+\sqrt{2})+(3-\sqrt{2})-2} \approx \dfrac{5}{6}$

(3) $m_3 = \dfrac{3-\sqrt{2}-1}{(3-\sqrt{2})+(3+\sqrt{2})-2} \approx \dfrac{1}{6}$

The Gamma Function

The Gamma function was previously mentioned in (2.4). It is part of the baseline for the computer simulation of Beta-distributed activities' durations. (2.4) will be calculated through the approximate Gauss-Laguerre formula:

$$\int_0^\infty x^{\alpha-1} e^{-x} dx \approx \sum_{i=0}^{n} A_i F(x_i) \qquad (3.17)$$

Han (1997) defines Ai as

$$\mathbf{A_i} = \frac{(n!)^2}{L'_{n+1}(x_i)L_n(x_i)}, \qquad (3.18)$$

and proposes the utilization of n = 4 to correspond to the necessities of practical appliance in construction. Thus, he proposes the utilization of the following Laguerre polynomial

$$L_5(x) = 120 - 600x + 600x^2 - 200x^3 + 25x^4 - x^5 \qquad (3.19)$$

Substituting equation (2.19) in (2.17) and (2.17) in (2.4), the following approximate equation for the Gamma function is obtained:

$$\begin{aligned}\Gamma(\alpha) = {} & 0{,}2635603^{\alpha-1} \times 0{,}5217556 + 1{,}4134031^{\alpha-1} \times 0{,}3986668 + 3{,}5964258^{\alpha-1} \\ & \times 0{,}0759424 + 7{,}0858100^{\alpha-1} \times 0{,}0036118 + 12{,}6408008^{\alpha-1} \times 0{,}0000234\end{aligned} \qquad (3.20)$$

3.3.2.2 Generation of Random Numbers

The first step in generating Beta-distributed random values is to generate uniformly distributed random numbers which are then transformed to match the distribution desired. For the sake of simplicity, it is common to use uniformly distributed random numbers in the interval]0,1[. The density and distribution functions f and F of a uniformly distributed Variable X are:

$$f(x) = \begin{cases} 1 & 0 \le x \le 1 \\ 0 & \text{else} \end{cases} \qquad F(x) = \begin{cases} 0 & x < 0 \\ x & 0 \le x \le 1 \\ 1 & x > 1 \end{cases} \qquad (3.21)$$

Period length is also important in the computer generation of random numbers. Since computers can only utilize finite algorithms, the numbers in the sequence generated will be repeated according to a finite period. Thus, these numbers are better called pseudorandom numbers (PRN). Generally, a sequence Ni of PRN can be described as (Bauknecht(1976)):

$$\underbrace{N_0, N_1, \ldots, N_S}_{0\,period}, \underbrace{N_{S+1}, \ldots, N_{S+L}}_{1^{st}\ period}, \underbrace{N_{S+L+1}, \ldots, N_{S+2L}}_{2^{nd}\ period}, \ldots \tag{3.22}$$

where: L – period length

The numbers N_0 to N_{S+L} will all be different, whereas

$$N_{S+1} = N_{S+L+1} = N_{S+2L+1} = \ldots \tag{3.23}$$

The usual strategy for overcoming this limitation involves choosing the largest possible period length L. For simulation purposes, the following condition must apply:

$$N \le L \tag{3.24}$$

where: N – number of simulation runs needed

L – period length of the PRN generated

The generation algorithms utilized generally follow congruence methods, which are described in the literature as being particularly simple and effective. A detailed description of these methods can be found in Han (1997).

3.3.2.3 The Rejection Method as Basis for the Final Algorithm

All the necessary "tools" for the back transformation of the Beta-distribution function have been defined. Thus, it is now necessary to define an algorithm that makes effective use of them.

Han (1997) proposes an algorithm based on the rejection method. This approach is often used to transform [0,1] uniformly distributed random numbers into numbers for random variables with [0,1] non-uniform distribution.

The rejection method assumes that the random value X, which is to be obtained from the random numbers, has a limited density f and only can assume values within the finite interval [a,b].

Let M be a maximum from f, Z and Y two uniformly distributed values respectively in the intervals [a,b] and [0,M]. According to the definition of conditioned probability:

$$P(Z \le x \mid Y \le f(z)) = \frac{P(Z \le x \wedge Y \le f(z))}{P(Y \le f(z))} \tag{3.25}$$

Is can be shown in Fig 2.3 below that:

$$P(Z \le x \wedge Y \le f(z)) = \frac{\int_a^x f(t)dt}{M} \tag{3.26}$$

Besides,

$$P(Y \le f(z)) = \frac{\int_a^x f(t)dt}{M} = \frac{1}{M} \tag{3.27}$$

Finally, considering F is the distribution function from X, we have:

$$P(Z \le x \mid Y \le f(z)) = \int_a^x f(t)dt = F(x) = P(X \le x) \tag{3.28}$$

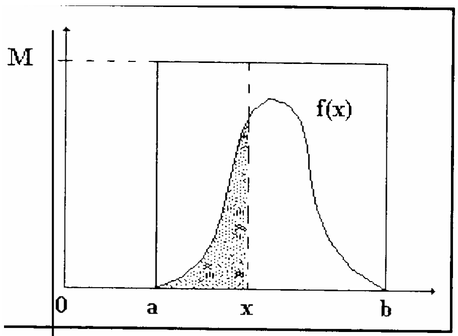


Fig. 3.3: Density curve f(x) of the random variable X (Han (1997))

Let u_1 and u_2 be two [0,1] uniformly distributed random numbers, generated one after the other. y = Mu_2 and $z = (b-a)u_1 + a$ will be two values of the random variables Y and Z. z will be considered as belonging to the distribution density when $y \le f(z)$, i.e.:

$$u_2 \le \frac{1}{M} f[(b-a)u_1 + a] \tag{3.29}$$

Due to the characteristics of the Beta-distribution density curve, the maximum value M can be obtained through the formula of the third solution of equation (3.8). Thus:

$$M = \frac{b(r-1)+a(s-1)}{r+s-2} \tag{3.30}$$

Hence, the final algorithm follows the 3 steps below:

Input: limited distribution density f:[a,b] $\in$ R^{+}, M is a maximum of f

Generate two random numbers u_1 and u_2

If $u_2 \leq \frac{1}{M} f[(b-a)u_1 + a]$ then let $z = (b-a)u_1 + a$ and go to 2., else go to 1.

Z is a random number of distribution function f, Stop.

This method is known as the rejection method because when $u_2 > \frac{1}{M} f[(b-a)u_1 + a]$, the random number u_1 is rejected.

3.3.2.4 Tendencies and their Characterizing Parameters

As mention previously in section 3.3, Han (1997) suggests modifying the traditional PERT model by replacing the realistic duration by a tendency, ranging from 1 (very optimistic) to 5 (very pessimistic). Thus, when generating Beta-distributed random numbers, the effect of this tendency on the definition of the shape of the Beta density function has to be taken into consideration. Fisz (1989) et al . propose a factor k for the analysis of the curve shape, defined as

$$k = \frac{E([X-E(X)]^3}{\sigma^3} \tag{3.31}$$

Hence, for a Beta distribution density function within a finite interval [a,b]:

$$k = \frac{2(s-r)}{r+s+2}\sqrt{\frac{r+s+1}{rs}} \tag{3.32}$$

When k = 0, the curve is symmetrical, whereas k < 0 will correspond to a curve shifted towards the right and k > 0 corresponds to a curve shifted towards the left. Considering the solutions given by equations (3.13), (3.14) and (3.15), we derive the solution (3.13) k equals to 0, whereas in solutions (3.14) and (3.15) k is respectively negative and positive. Thus, the values of parameters r and s given in these 3 solutions can be thought to characterize 3 tendencies; neutral (symmetrical curve, k = 0), pessimistic (k < 0) and optimistic (k >0), respectively.

In order to obtain parameters r and s for the remaining 2 tendencies, the distribution of the 3 modal values can be obtained by applying the solutions given by (3.13), (3.14) and (3.15) to the standard Beta distribution Beta – [0,1] in the 3rd solution of equation (3.8). They are, respectively,

$$m_1 = \frac{4-1}{4+4-2} = \frac{3}{6} \qquad (3.33)$$

$$m_2 = \frac{3+\sqrt{2}-1}{(3+\sqrt{2})+(3-\sqrt{2})-2} \approx \frac{5}{6} \qquad (3.34)$$

$$m_3 = \frac{3-\sqrt{2}-1}{(3-\sqrt{2})+(3+\sqrt{2})-2} \approx \frac{1}{6} \qquad (3.35)$$

Thus, aiming at the uniformed distribution of the modal values for the 5 tendencies, the following 2 extra solutions were considered:

$$m_4 = \frac{2}{6} \qquad (3.36)$$

$$m_5 = \frac{5}{6} \qquad (3.37)$$

Solving equations (3.11) and (3.12) for the parameters r and s, while still considering the [0,1] Beta distribution, we obtain:

$$r_4 = \frac{5+2\sqrt{3}}{3}, \quad s_4 = \frac{7+4\sqrt{3}}{3} \qquad (3.38)$$

$$r_5 = \frac{7+4\sqrt{3}}{3}, \quad s_5 = \frac{5+2\sqrt{3}}{3} \qquad (3.39)$$

In this way, parameters for two solutions with negative k and two solutions with positive k can be utilized, totaling the 5 tendencies desired. Thus, a distinction can be drawn between **very** pessimistic and pessimistic, as well as between **very** optimistic and optimistic tendencies by comparing their respective k values.

The 5 tendencies and their respective parameters r and s are listed in tab. 3.1 below. A visual representation of the 5 density curves corresponding to the 5 tendencies is given in fig. 3.4 below.

Tendency	**Parameter r**	**Parameter s**
Very optimistic	$3-\sqrt{2}$	$3+\sqrt{2}$
Optimistic	$\frac{5+2\sqrt{3}}{3}$	$\frac{7+4\sqrt{3}}{3}$
Neutral	4	4
Pessimistic	$\frac{7+4\sqrt{3}}{3}$	$\frac{5+2\sqrt{3}}{3}$
Very pessimistic	$3+\sqrt{2}$	$3-\sqrt{2}$

Tab. 3.1: Parameters r and s for the 5 tendencies (compare with Han (1997))

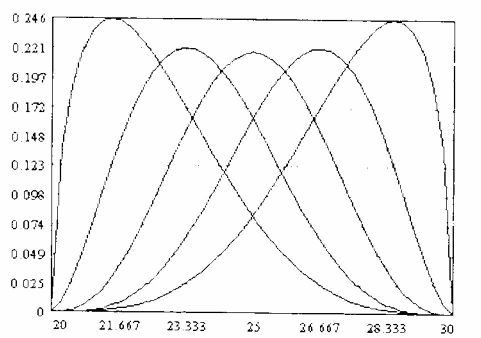


Fig. 3.4: Density curves of the 5 tendencies for a = 20 and b = 30 (Han (1997))

3.3.2.5 Final Algorithm

Given that all of the components and methodology defined, the algorithm proposed in Han (1997) for the back transformation of the Beta distribution function is given in

Fig. 3.5 below.

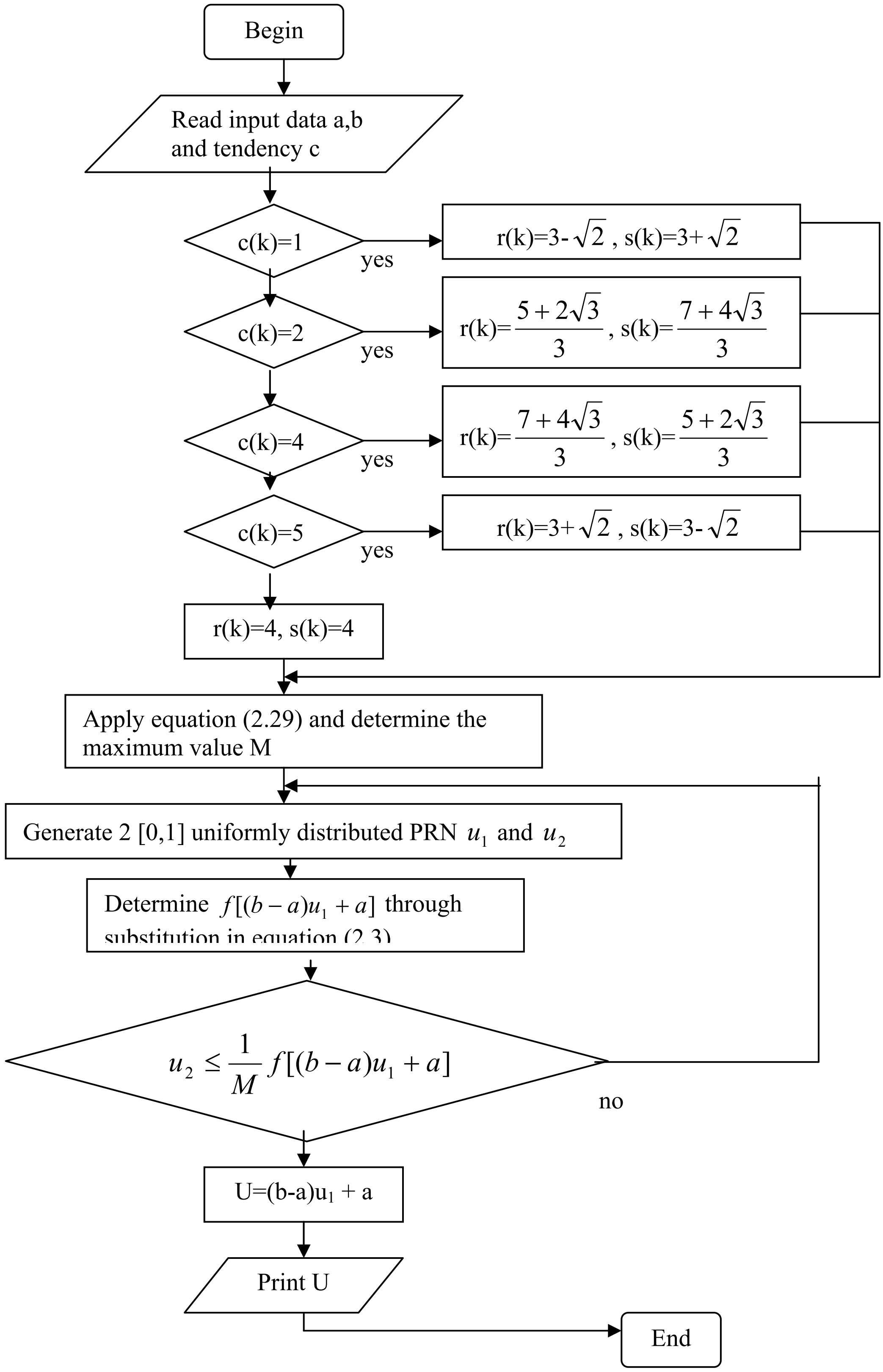


Fig. 3.5: Flowchart for obtaining Beta distributed activity durations applying the rejection method (compare with Han (1997))

3.4 THE SIMUNET PROTOTYPE FOR SIMULATION OF SCHEDULES

Based on the algorithm for back transformation of the Beta distribution function shown in fig. 3.6 above, Han (1997) produced Simunet, a prototype for computer-aided stochastic simulation of schedules. Simunet was used by the author in the simulations described in chapters 5 and 6 of this work.

3.4.1 Features

Simunet is a Borland C++ coded software application for the simulation of schedules based on a modification of the PERT method, which consists of the substitution of the traditional “realistic duration” by a tendency. It also includes two Visual Basic coded macros for information exchange with MS-Project. It was developed by Dr. Han as a practical result of his Ph.D work. Simunet provides the user with the mean duration of each activity and its variance, its critical degree, the mean project total duration and its variance, and the usual schedule print-outs from MS-Project 4.0 based on the mean activities’ durations. The concept of critical degree represents a modification of the traditional activity scheduling proposed by Han (1997) and as described in section 3.4.1.3 later on.

The prototype interfaces with MS-Project 4.0 on an interactive basis through two Visual Basic coded macros, Input and Output. MS-Project is basically used as a user-friendly I/O (input/output) interface, where the data concerning the activities is entered and the results of the simulation, values and graphs, are displayed. This has the practical advantage of providing the user with a work surface he/she is familiar with, since MS-Project, in its various versions, is one of the most widely used scheduling applications worldwide. On the other hand, the stochastic simulation of network schedules goes beyond the capabilities of MS-Project, and is hence carried out by Simunet itself.

Macro Output accepts the input data entered into MS-Project by the user, converts it for the sake of simulation, starts the simulator and feeds it with the input data. Macro Input reads the simulation results, converts them to MS-Project format and transfers the information to MS-Project. Both macros control MS-Project over Borland C++ DDE (dynamic data exchange) EXECUTE commands.

Simunet does the simulation work and saves the results to a .dat format file, which can be edited with conventional editors. This file, "result.dat", includes the variance of the mean activities' durations.

The MS-Project work surface is adapted for this specific utilization, including columns for the optimistic and pessimistic durations, as well as the tendency, instead of the traditional deterministic duration column. It also includes columns for the mean Beta-duration of each activity and for their critical degree. Besides, the environment is adapted so that it can be read the mean Beta-durations of the activities and build the corresponding mean network schedule and mean bar chart.

A detailed description of the MS-Project software application can be found in its Microsoft reference book. A case specific description of the features utilized within the Simunet system can be found in Han (1997).

The structure of the application and its components is shown in Fig. 3.6 below.

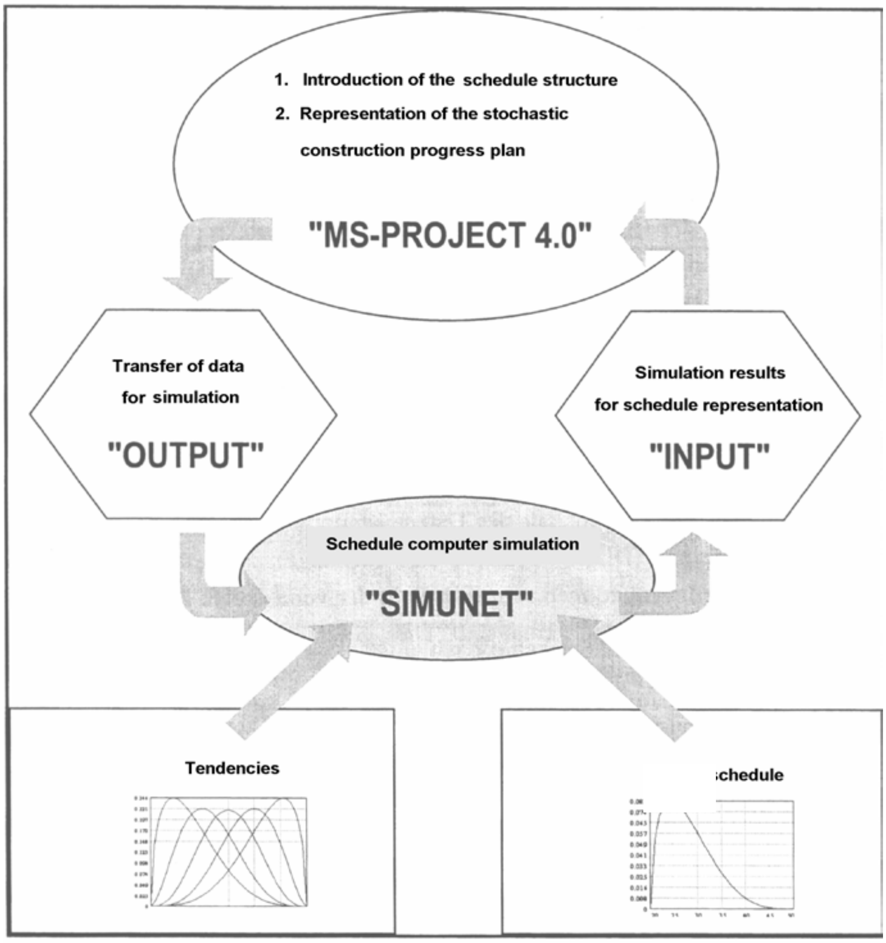


Fig. 3.6: Data flow between MS-Project and Simunet (compare with Han (1997))

3.4.1.1 Input Data for MS-Project

The system requires the input of the following data:

Activity number

Activity name

Activity's duration parameters a (optimistic duration), b (pessimistic duration) and c (tendency).

Activity's predecessors and successors, and tie type (finish-to-start, start-to-start, end-to-end)

Particular attention has to be paid to the numbering of the activities. The simulator identifies the activities by this number, and duplicate or missing activity numbers will cause the simulator to produce errors, abort the simulation or make the feedback of the simulation information through macro Input impossible. There is no means of checking the numbering entered, thus the user has to be particularly attentive.

Another peculiarity is that all but one activity must have at least a successor. Besides, the simulator does not consider the last activity in the activities' list entered. Thus, a zero duration activity (milestone) for the end event always has to be included. All activities without a successor must be tied to this end activity.

There is no point in entering lagged ties (e.g.: finish-to-start + 5, start-to-start +3, end-to-end+2). MS-Project does display them in the graphs and in the start and end dates of the activities, but the Simunet simulator version that was supplied to the author did not consider the lag (+5, +3, +2) in the calculations. In these cases, a lag time activity with deterministic duration (5, 3 or 2) should be entered.

After entering the input data and before starting the simulator by activating macro Output, the user has to make sure that files "h_pert_2.exe" and "start.bat" are in the same directory as the MS-Project (.mpp) file with the input data entered. Otherwise, the simulator will not run.

3.4.1.2 Output Data

When activating macro Output, a "data.dat" file is created. It contains the necessary and converted data for the simulator. This file will remain in the same directory as the files needed for activating macro Output. It will be overwritten each time macro Output is activated.

The simulator then performs 300 project simulation runs, storing the data concerning the duration of the activities, their start and end date. Finally, it calculates the mean duration of the activities, as well as the mean and variance of the activities' start and end dates, and of the total project duration. It also calculates the critical degree of each activity according to the statistical method described in section 3.4.1.3 below. Two new files are created in the same directory as the others up to this point: "result.dat", with the editable results of the simulation, and "temp.dat", with the converted data for back transposition to MS-Project.

The minimum number of simulation runs was obtained from statistical considerations, observing the normal distribution, the Student distribution and the Tschebyschew equation, comparatively. Detailed information on this topic can be found in Han (1997).

Macro Input does the back transposition of the simulation results to MS-Project, filling the respective columns with:

The critical degree

The Beta mean duration

The mean start and end dates of the activities

MS-Project then prepares the respective lists, graphs and bar chart.

3.4.1.3 Critical Degree

This parameter is based on the Probability of Path from simulation.

According to the CPM, the critical path corresponds to the longest sequence of activities in terms of duration. Since each simulation run generates its own duration parameters, the durations of the activities are likely to change, and with them the critical path of the project for that simulation.

Let m be the number of different critical paths $L_1, L_2, \dots, L_m$ in N simulation runs and n_i ($i = 1, 2, \dots, m \quad m \in \mathrm{IN}$) be the number of times the path L_i becomes critical. The probability of the path L_i is then defined as:

$$P_{L_i} = \frac{n_i}{N} \qquad 0 \le n_i \le N \qquad 1 \le i \le m \tag{3.40}$$

Hence, the higher the probability P_{L_i} of the path L_i, the likelier it is that the path will become critical. The path with the highest probability is frequently called the main critical path, and the others, subcritical paths.

Any path in a network schedule consists of a sequence of activities. The network of ties often includes forks or junctions, where one sequence splits into another or into several others. Looking at the main critical path of a project, it is clear that changes in the durations of the schedule activities might exclude parts of its sequence from the critical path, following an alternative ones after its junctions. In extreme cases where a schedule has a junction after each activity, it is possible that each activity has its own probability of belonging to the critical path.

Thus, the changes in the activities' durations are responsible for the changes in the critical path, which leads to the conclusion that "Criticality" is an inherent characteristic of the activities, and that is where it should be assessed.

Let n_j (j = 1, 2,…, N N $\in$ IN) be the number of times the activity A_j becomes critical in N simulation runs. The probability of the activity A_j is then defined as:

$$P_{A_j} = \frac{n_j}{N} \qquad 0 \leq n_j \leq N \qquad 1 \leq j \leq N \tag{3.41}$$

The higher the probability P_{A_j} of the activity A_j, the likelier it is that this activity will become critical. "This is why it can be said that the probability of activity describes the level of indirect influence of that activity in the project duration" (Han (1997), free translation from the German language by the author). Han (1997) calls this variable Critical Degree, and acknowledges that it is a parameter of major importance because it influences the progress of a project. Furthermore, Han (1997) proposes a paradigm shift from the concept of critical path to the concept of critical activity, assessed by its critical degree. This variable is labelled "K. Grad" or K within Simunet. Thus:

$$K = P_{A_j} \tag{3.42}$$

The concept proposed by Han (1997) underlies the intrinsic uncertainty of an activity and its impact in the total project duration, both proposed and described by the author in chapter **4** of this work.

3.4.1.4 Other Features

Simunet includes other interesting features. However, since they will not be used in the scope of this work, their description here would be of limited relevance and, shall therefore, only be mentioned briefly. Their complete listing and description can be found in Han (1997).

3.4.2 System Requirements

The Simunet prototype can be run on any IBM compatible personal computer with a 486Mhz processor or higher (compare with Han (1997)). However, the author recommends the use of a 266MHz Pentium II processor or higher as experience has shown that the simulation speed can become very slow otherwise. A minimum of 8MB RAM and 20MB hard disk free space are also required.

The operating system has to be either DOS 5.0 or higher, or Windows 3.1 or higher.

As mentioned before, Simunet works in conjunction with MS-Project 4.0, thus the minimum requirements of MS-Project also have to be taken into consideration.

3.4.3 Limitations

Simunet is a computer program developed within the framework of a PhD work. Although a lot of effort has been made to making it useable for field construction professionals and to keeping it as practical and as user friendly as possible, Simunet is still a prototype. Thus, it does not measure up to applications coming from big software houses in terms of visual and utilization appeal.

It puts some constraints on the user, such as the obligatory placement of files h_pert_2.exe and start.bat in the same directory as the .mpp source file. This creates some problems when trying to save project files (.mpp files) in different directories. Besides, the name of the .mpp source file is fixed, thus the Output macro will always read the source data from the same file. The user circumvent this problem by saving project files with other names for future reference, while always using the same name for the file to be simulated. However, this often creates confusion about what files really are, especially when resuming work after an interruption.

The instability of the input interface mentioned in section 3.4.1.1 also needs to be addressed, especially which respect to the inflexibility of the activity numbering and the fact that all activities must have a successor for the simulator to work. This is particularly important, since the progress of the simulation will be interrupted without any given reason. Sometimes the data will be transferred back to MS-Project, but fill the wrong fields without warning or program abortion. However, the program does abort, the user will always be sent to the same line of the Visual Basic code of one of the macros.

While running, the program shows a dark screen with a number indicating the number of the simulation in progress. This generally takes a long time and has no visual appeal.

The critical path marked by MS-Project in the network schedule graph or bar chart does not necessarily gather the activities with the highest critical degree. MS-Project's work surface should be further adapted to include this feature. Otherwise, the schedule print out might mislead a user familiar with the conventional features and format of MS-Project who did not read Han (1997). This limits the use of Simunet on the field.

A specific limitation noticed by the author when utilizing the simulator for his own research was the fact that the total project duration and its variance are not transferred back to the MS-Project surface. Thus, in order to store these values, they have to be copied from the screen at the end of each simulation separately, demanding extra concentration.

In conclusion, it can be said that the simulator is limited by its non-windows nature, that is, it is typical of MS-DOS based computer applications in terms of flexibility, interactivity, error detection and warning, and visual appeal. However, the application gives technically correct results and performs the function it was designed for.

4. Uncertainty in Construction Scheduling

4.1 INTRODUCTION

As Peter Wakeling, director of procurement policy in the British Ministry of Defense, wrote it in his foreword to Chapman and Word (1997): “ All projects involve risks – the zero risk project is not worth pursuing.”. This is not purely intuitive but also a recognition that acceptance of some risk is likely to yield more desirable and appropriate levels of benefit for the resources committed to the project. Risk always involves both threat and opportunity.

Large and technological advanced projects are full of uncertainty and risk, especially at their inception. The very size creates uncertainty, new technology multiplies it. A wide variety of necessary project ingredients, such as regulatory agencies, community relations, changing political demands and timely delivery, further compound the uncertainty. When a schedule lags and cost estimates grow, it is perfectly normal to question the project management’s ability to manage. While the major reasons for such changes in the direction of the project are often caused by uncontrollable forces, this perception has been unwittingly nurtured by our tendency to characterize the project by single valued measures – a single cost – a single start update – which gives the illusion of certainty.

The present trends in the construction industry follow the general economic trends at the end of this century: mergers and globalization. Construction projects become bigger, more complex, more interdisciplinary. The owner wants to yield maximum revenues in the shortest possible time. This is not only due to the large financial amounts invested in the larger and larger projects being adjudicated, but also to the fact that clients are becoming increasingly demanding in terms of the performance and range of services of the project management team.

A survey of 40 U.S. construction managers and owners covering projects of an average total cost of US$ 5,000,000 – mentioned by Mulholland and Christian (1999) – reveals that, from a scope and design objectives perspective, the overwhelming majority of the construction projects have medium to very high uncertainty at the beginning of the construction. 65 % of the projects considered had medium to very high uncertainty. A more recent report by Laufer and Howell (1993), however, put this figure at around, thus confirming the trend indicated above.

4.2 UNCERTAINTY

Increased complexity necessarily carries with it increased uncertainty. A schedule is always a prediction and, therefore, subject to uncertainty. Moreover, given that no two construction projects are exactly the same, previous experience does not necessarily guarantee future success. As Mulholland and Christian (1999) argue, however, that "[t]here is a lack of accepted method of risk assessment and management among professionals in the construction industry compared with the financial and health professions. The construction industry also does not seem to recognize, nor accept, that risk should be addressed formerly and given more serious attention."

4.2.1 Definition

In Microsoft's ENCARTA (1999) Bookshelf 99 (Chamber's Dictionary), the adjective *uncertain* is defined as "**uncer'tain** *adjective* not certain (with *of* or *about*); not definitely known or decided; subject to doubt or question (in no uncertain terms unambiguously); not to be depended upon; subject to vicissitude; hesitant, lacking confidence."

More specifically, Zimmermann (2000) defines uncertainty as implying that "in a certain situation a person does not dispose about information which is appropriate to quantitatively and qualitatively describe, prescribe or predict deterministically and numerically a system, its behavior or other characteristica".

4.2.2 Human Perception

The very first question that arises when attempting to model or quantify uncertainty is how this concept should be regarded. Zimmermann (2000) argues that uncertainty is a "phenomenon, a feature of real world systems, a state of mind or a label for a situation in which a human being wants to make statements about phenomena (i.e. reality, models, theories)". When producing a schedule, the planner is trying to plan, thus predict the future, based essentially in assumptions, historical data and models. Thus, although based on the objective fact that one cannot predict the future, its subjective nature can't be ignored.

Construction scheduling has traditionally modelled uncertainty in terms of probability theory based prediction of activities' durations. The scheduler has to cope with several causes of uncertainty:

- Lack of information – prediction of the future
- Conflicting evidence – depending of third party information
- Ambiguity – Typically linguistic information
- Belief – the scheduler is himself involved in the process, be it as direct stakeholder or as external consultant

Ultimately, the scheduler will enter a combination of interval and linguistic information into a model that he thinks best fits the description of the situation, thus not perceiving "the information about the phenomenon directly, but only after it has been "filtered" by the uncertainty theory used" (Zimmermann, 2000).

4.2.3 Areas of Manifestation

Uncertainty is part of every step in life, and construction is no exception. Construction is simply one area in which uncertainty has to be dealt with on a daily basis.

Schedules define the work sequence and duration of specific and, generally, unique projects. They are completed during the work preparation, and involve decisions and choices about:

- duration of activities
- ties between them

The process of defining these two points is itself a common source of uncertainty for the scheduler and, therefore, where the greatest gains in reducing uncertainty can be won.

4.2.4 Traditional Solutions

4.2.4.1 Present Situation

Construction scheduling has used quantitative, network-based modelling processes ever since the 60s . These have had good results and have since become standard methods. Traditional scheduling processes, however, have tended treat uncertainty and risk as though they do not exist. Laufer and Howell (1993) argue that while network-based planning processes, such as CPM, provide deterministic durations for activities and give rise to seemingly precise predictions, they have also frequently produced unrealistic project performance times in the past. Knowing these limitations, schedulers have used down-to-earth precautions to counteract this problem .

The traditional approach to reducing uncertainty when preparing a schedule mainly consists of adopting the following measures:

- Involvement of experienced schedulers
- Storing productivity rates from previous works to improve deterministic duration assessment in the future
- Updating the process and reorganizing the schedule at regular intervals during the construction phase

Seen technically, statistical and semi-statistical methods have been created to tackle the problem. PERT is one of the best known. It considers an optimistic (a), a pessimistic (b) and a most likely (m) duration, generating activity durations by using a simplification of the Beta distribution. The formula used is

$$\mu = \frac{a + 4m + b}{6} \tag{4.1}$$

This method has been subject to a lot of criticism as a result of its inaccuracy. The value with the highest contribution to the definition of average duration m, is most difficult to estimate and hence most likely to be inaccurate. Furthermore, given that m is a discrete value, its probability in a continuous distribution such as Beta equals to zero.

It is not the aim of this work to provide a complete description of this method. A description can, however, be found in the large body of literature that has been published about PERT since its inception in the 60s.

These procedures have proven to be insufficient on several occasions in the past.

The major problem that these methods face is in adapting to the dynamic, ever changing character of the construction business. A new project involves new crews, equipment, different owners and local authorities, and poses different problems with communication, relationship, performance levels and expectations. The fringe conditions, such as soil, accesses, design and others also change, making all previous experience and the data its produces insufficient in assuring the greatest possible reduction in uncertainty.

4.2.4.2 Consequences

Uncertainty frequently leads to situations that disadvantage all the stakeholders in the construction process. Some of the consequences are as follows:

Stakeholder	Consequence
Project manager	Loss of Prestige[1] Loss of professional credibility[2]
Owner and Project manager	Financial penalties[3]
Contractor	Extra costs[4]

Tab. 4.1: Uncertainty – Consequences for Construction Stakeholders

[1] Increasingly demanding clients force the PM team to respond with improved technical means and solutions, as well as with the increased competence of their staff. It is only by doing this that a company can survive in the highly

competitive market of large scale Project Management. For this, prestige is vital. It is the business card of a company when bidding for a project. It, therefore, has to be preserved at all costs.

[2] Loss of credibility due to innumerous schedule changes("schedule updates" and "recovery plans")

[3] Globalization, operational integration, increased speed of process and the financial amounts involved force the stakeholders to protect themselves financially by recovering some of the cost of delays in the form of heavy financial penalties for schedule overruns. Moreover, delays cause the loss of prestige, not only to the PM team, but also to the owner himself. This is particularly important in large scale jobs, often called prestige projects.

[4] Constant changes to the schedule lead to extra costs in terms of reorganizing resource assignments and work sequence.

4.2.5 Recent Solutions

Other methods have recently been used to improve the response to uncertainty. Their basic principle involves trying to gather as much information, both historical and virtual, as possible. The most important ones are:

- Monte Carlo Simulation
- Expert Systems
- Neural Networks

The first method generates virtual statistical data about a project by simulating it using loose parameters which are known to describe the situation at hand. The project model is calculated n number of times, chaing the parameters affected by uncertainty with each run. The relevance of the values obtained increases, since this procedure simulates the assignment of parameter values by n experts. This work, as well as the simulator developed by Han (1997) (see chapter 3), are based on this approach.

The second method gathers and organizes the experience of several experts, enabling decisions based on close approximations of the problem to be analyzed.

The third method typically consists of a network of software routines in a way that it can learn from training information, adjust itself and function automatically according to a certain pattern.

4.3 UNCERTAINTY QUANTIFICATION

The pressure on the planner is daunting. If he has to manage uncertainty, then three categories of uncertainties are to be measured and monitored. They are:

1. Knowns: They have no associated uncertainty
2. Known-Unknowns: A variable whose value is known to be unknown.
3. Unknown-Unknowns: Factors which cannot be imagined and, hence, cannot be predicted. History shows that such factors do not frequently arise, however, when they do arise, their consequences are as unpredictable as their very existence and chaos is to be expected.

Plans mostly fail because of known-unknowns. If a few of them, with significant weight, shift in the wrong direction, the bottom line will be pushed over the edge. These factors are best measured by a range. The crucial issue in an element's variability is its magnitude. Most of the elements in a plan are known-unknowns, but not all of them have the potential to change the bottom line. Those known-unknown that have the potential to change the bottom line can be called critical elements, and they typically have adverse consequences and thus spoil the plan.

As mentioned in 4.2.3, the assignment of durations to single activities and the ties between them is the major area of uncertainty when preparing a schedule. Thus, any effort to reduce or limit uncertainty in scheduling will necessarily depend on its quantification in these fields. The present work will focus on the analysis of stochastic uncertainty for both activities' durations and project durations.

4.3.1 Structure

The German Industry Norm DIN 69 900 Part 1 (p. 4) defines structure and schedule structure as follows: "Wholeness of essential relationships between the components of a system. It describes its constitution and the way it works.", "Structure of a schedule, whose relationships are essentially obtained from the ties between activities" (free translation from the German language by the author). The set of ties between activities builds the structure of the schedule. The importance of this structure has been much highlighted in the literature over the past thirty years. The very concept of the critical path, which led to the critical path method, CPM, highlights the importance of the schedule structure in controlling Uncertainty in Scheduling.

The analysis of the relationship between uncertainty and schedule structure will be addressed in detail in chapters 5 and 6.

4.3.2 Duration

The duration assigned to the activities is of major importance when preparing a schedule. PERT allows for three possible durations (a,b and m). In his work, Han proposes the substitution of m by a tendency C, which ranges from very optimistic (1) to very pessimistic (5), as mentioned in 3.3.2.4. The value of the tendency is easily and more accurately estimated by an experienced scheduler.

Uncertainty in the duration of activities, therefore, can be quantified by the evaluation of the range of duration between a and b, and by the tendency assigned.

Following on from classical Network Scheduling Theory (PERT/CPM) and Han's proposals about its further development, the author proposes 2 quantification ratios for the assessment of each activity's contribution to the uncertainty associated to the project delivery date.

4.3.3 Quantification Expressions

Every endeavor has a motivation, without one it would be senseless. The uncertainty assessment carried out in this chapter aims to achieve a minimal level of uncertainty in the project delivery date, measured by the variance of the project total duration after Monte-Carlo Simulation. Therefore, all uncertainty quantification will be carried out with reference to this. Mulholland and Christian (1999) argue that "[v]ariance implies uncertainty; it can be used as an objective measure of the ability to predict a reliable performance time for a project. The larger the variance the greater the risk associated with the performance time of a project. Indeed, variance often has been used by the financial community to measure the riskiness of investment options". This approach has been supported by other authors, such as Keller et al. (1994).

In their work, Mulholland and Christian (1999) argue that "(…) The variance of each critical path activity Vi can be used to determine the amount that activity contributes to the local product performance time risk Vt . Thus , to reduce the project performance time risk Vt , you would be necessary to reduce the variance Vi on the critical path activities ." Further on, they also write that " The activity with the highest relative risk is subject to larger proportional change in duration and therefore is considered at higher risk than other critical path activities. The proportionat measure of variability of an activity is determined by calculating its coefficient of variation, which is equal to its standard deviation divided by its expected performance time.".

The concepts of *relative risk* and *the amount of contribution of each activity to the total project duration risk* are ground breaking principles warranting further discussion. This approach, however, does not consider the structure uncertainty, since it focuses on deterministically defined critical path activities. It doesn't take into consideration that the very same uncertain single activities durations that influenced by Vi, might also place activity i in or outside the critical path.

Uncertainty in the duration of activities can be quantified by the evaluation of the range of duration between a and b, and by the tendency assigned.

a) Range

Uncertainty is directly proportional to the span of the range between OD and PD

b) Tendency

Assigning a tendency to the duration actually reduces uncertainty, since it means that the simulator with focus on generating durations on a given part of the range. However, confronted with high uncertainty in determining the duration of an activity (due, for instance, to a lack of information), the scheduler will, as a defensive measure, typically assign a rather pessimistic tendency. Hence, the author proposes two concepts for two different approaches to the tendency assignment

<u>Effective</u> – focuses on a part of the range of likely durations, hence decreasing the uncertainty

<u>Defensive</u> – exercises caution in the face of a lack of information, thus producing an increased level of uncertainty

The following 2 examples illustrate this idea:

In an area of reputed good bus service, a bus is scheduled to arrive at a bus stop at 10:00. From his previous experience and the historical records of the bus company, the scheduler would define a range of arrival times from an optimistic 9:57 to a pessimistic 10:03. This narrow range reflects the low level of uncertainty about the arrival time. It is relatively easy to define. The tendency assignment, however, reveals a lot more about the scheduler's attitude and has interesting repercussions for the data generated by Han's prototype:

Optimistic tendency (C < 3) left part of the curve (values: 9:57, 9:58 and 9:59)

Pessimistic tendency (C > 3) right part of the curve (values: 10:01, 10:02 and 10:03)

Medium tendency (C = 3) center of the curve (10:00)

A medium tendency assignment, corresponding to a single value, reveals a low degree of uncertainty.

In an area known for its unreliable bus service, a bus is also scheduled to arrive at 10:00. The same procedure for generating a range of likely arrival times is applied. The scheduler would then obtain a range from an optimistic 9:30 to a pessimistic 10:30. The range, much larger than in the case given above, is revealing. Knowing that buses generally arrive late, the scheduler would assign a rather pessimistic tendency (C > 3). This could have two meanings:

The scheduler is focusing on the right part of the curve, thus diminishing the level of uncertainty (effective assignment). Practical experience shows that this is seldom the case: assigning a large range implicitly implies pessimism or caution.

Having little or unreliable information about the arrival time, the scheduler assigns a large range and a pessimistic tendency as a conservative, protective measure. This corresponds to a defensive tendency assignment and is common practice in construction scheduling.

Thus, the author proposes two expressions for the quantification of uncertainty of activity durations and for the level of seriousness of its impact on the project duration.

They were obtained from the study, simulation and analysis of more than 25 schedules. The equations were improved iteratively through progressive comparison and adjustment.

The values obtained for the different activities were compared with an uncertainty ranking which was based on the previous practical experience of the author and on common-sense. The formulas were fine-tuned by comparing particular activity pairs.

Uncertainty ratio (UR)

This value is obtained before simulation. It quantifies the uncertainty of an activity. It is based on defensive tendency assignments, which best correspond to the common practice in the construction industry.

$$UR = \frac{PD}{OD} \times C \qquad (4.2)$$

Where

PD – pessimistic duration

OD – optimistic duration

C – tendency, ranging from 1 to 5 (very optimistic to very pessimistic)

Practical examples:

Case 1:

Let us consider the steel reinforcement works of a large concrete slab. These works are to be carried out by a sub-contractor of questionable reliability, and hard weather conditions cannot be ruled out. Based on this information, the planner assigned the following values to the variables:

OD = 8 days

PD = 16 days

C = 5 (very pessimistic)

Case 2:

The same works are now to be carried out by a reliable contractor and good weather conditions are expected. The values assigned are:

OD = 8 days

PD = 11 days

C = 2 (optimistic)

	OD	PD	C	UR
Case 1	8	16	5	10
Case 2	8	11	2	2,75

Tab. 4.2: Comparison of Uniformity Ratios

When comparing both cases and their UR values, it is clear that a larger gap between OD and PD creates a larger value, which is then amplified by a pessimistic tendency.

Duration Uncertainty Seriousness (DUS)

This value is obtained after simulation and takes into consideration the duration, the structural uncertainty, and its seriousness in the context of the whole schedule. It is a deterministic value expressed as a real number. It gives the expected value for the contribution to the total project duration of the activity it concerns in units of time. Thus, it will be used to define a ranking for the activities with the highest impact (seriousness) to the project total duration.

$$DUS = \frac{PD}{OD} \times C \times BD \times K^3 = UR \times BD \times K^3 \qquad (4.3)$$

Where

BD – average duration of the activity, obtained through simulation

K- critical degree of one activity, obtained through simulation and according to Han's paradigm described previously in section 3.4.1.3.

Practical examples:

Case 1:

Let us take the same values as given in case 1 above. After simulation with Han's prototype, the results obtained were:

BD = 14,5 days

K = 0,3

Case 2:

The same can be done for case 2 above, with the following simulation results:

BD = 9,5 days

K = 1

Case 3:

Same as case 1 above, with K = 1

Case 4:

OD = 4
PD = 8
C = 5
BD = 7,25
K = 1

Case 5:

OD = 24
PD = 33
C = 2
BD = 28,5
K = 1

	OD	PD	C	BD	K	UR	DUS
Case 1	8	16	5	14,5	0,3	10	3,915
Case 2	8	11	2	9,5	1	2,75	26,125
Case 3	8	16	5	14,5	1	10	145,000
Case 4	4	8	5	7,25	1	10	72,500
Case 5	24	33	2	28,5	1	2,75	78,375

Tab. 4.3: Comparison of Uncertainty Ratios and Duration Uncertainty Seriousness Values

The table shows that, although case 1 has a significantly larger intrinsic uncertainty and simulated average duration (BD), its presence in the critical path in just one third of the simulated runs (K = 0,3) diminishes its expected impact in the total project duration, thus its DUS. However, when (case 3) its K rises to the same value as case 2, the higher intrinsic uncertainty causes the DUS to increase dramatically.

The importance of the duration magnitude is obvious: a small percent deviation of a large number causes a considerable deviation in absolute terms, affecting the project total duration. This is taken into consideration by the proposed formula, as one can see when comparing cases 2 and 5: while both have the same intrinsic uncertainty (UR value), an increase in the simulated average duration causes a proportional increase in the potential impact in the project total duration (DUS value).

4.3.4 Stability of the DUS Expression for Different K Powers

The DUS expression was proposed to take into consideration the intrinsic uncertainty of an activity, its duration size and the structure of the plan network through the K value. This last parameter varies between 0 and 1, thus having the lowest absolute value in the expression. However, this does not reflect its real importance. Thus the author proposes

K value powered to 3. This increases the importance of K in the equation despite its low, absolute value. Nevertheless, other powers are also possible and were studied. Tab. 4.4 shows the cases studied and the values obtained. This information is displayed graphically in Fig.4.1.

							K^1	K^2	K^3	K^4
	OD	PD	C	UR	BD	K	DUS			
Case 1	8	16	5	10	14,5	0,3	43,500	13,050	3,915	1,175
Case 2	8	11	2	2,75	9,5	1	26,125	26,125	26,125	26,125
Case 3	8	16	5	10	14,5	1	145,000	145,000	145,000	145,000
Case 4	4	8	5	10	7,25	1	72,500	72,500	72,500	72,500
Case 5	24	33	2	2,75	28,5	1	78,375	78,375	78,375	78,375
Case 6	8	16	5	10	14,5	0,4	58,000	23,200	9,280	3,712
Case 7	8	16	5	10	14,5	0,5	72,500	36,250	18,125	9,063
Case 8	8	16	5	10	14,5	0,6	87,000	52,200	31,320	18,792
Case 9	4	8	5	10	7,25	0,6	43,500	26,100	15,660	9,396
Case 10	4	8	5	10	7,25	0,5	36,250	18,125	9,063	4,531
Case 11	4	8	5	10	7,25	0,4	29,000	11,600	4,640	1,856
Case 12	24	33	2	2,75	28,5	0,5	39,188	19,594	9,797	4,898
Case 13	24	33	2	2,75	28,5	0,6	47,025	28,215	16,929	10,157
Case 14	24	33	2	2,75	28,5	0,7	54,863	38,404	26,883	18,818
Case 15	8	11	2	2,75	9,5	0,3	7,838	2,351	0,705	0,212
Case 16	8	11	2	2,75	9,5	0,4	10,450	4,180	1,672	0,669
Case 17	8	11	2	2,75	9,5	0,5	13,063	6,531	3,266	1,633
Case 18	8	11	2	2,75	9,5	0,6	15,675	9,405	5,643	3,386
Case 19	8	11	2	2,75	9,5	0,7	18,288	12,801	8,961	6,273
Case 20	8	11	2	2,75	9,5	0,8	20,900	16,720	13,376	10,701
Case 21	4	8	5	10	7,25	0,7	50,750	35,525	24,868	17,407
Case 22	11	22	5	10	19,15	0,8	153,200	122,560	98,048	78,438
Case 23	22	44	5	10	38,1	0,3	114,300	34,290	10,287	3,086
Case 24	22	30	2	2,73	19,1	0,9	46,882	42,194	37,974	34,177
Case 25	8	16	5	10	14,5	0,5	72,500	36,250	18,125	9,063

Tab. 4.4: Stability of the DUS Expression for Different K Powers – Cases Studied

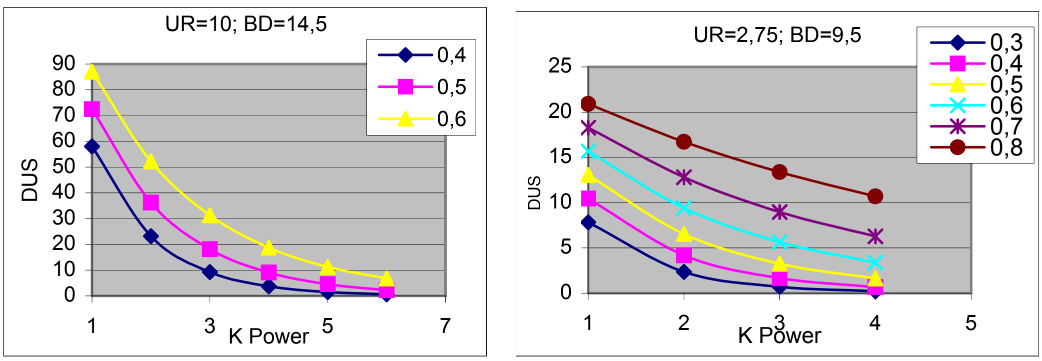


Fig.4.1: Comparison for Cases with Constant UR and BD, and different K Values and Powers

4.4 CONCLUSIONS AND PREDICTIONS

The ability to quantifying uncertainty represents a major step towards its assessment and a stepping stone for its eventual control. Any quantification must be done with a specific point of reference. This implies a center, objective or target. The ratios proposed made it possible to assess the uncertainty of each single activity, taking into consideration, not only their intrinsic uncertainty, but also their potential impact in the project total duration. This information is, nevertheless, constrained to single activities, and does not enable any direct statement about the uncertainty total project duration *per si*. This can only be achieved if the influence of the schedule structure in the propagation of single activity's uncertainty is known.

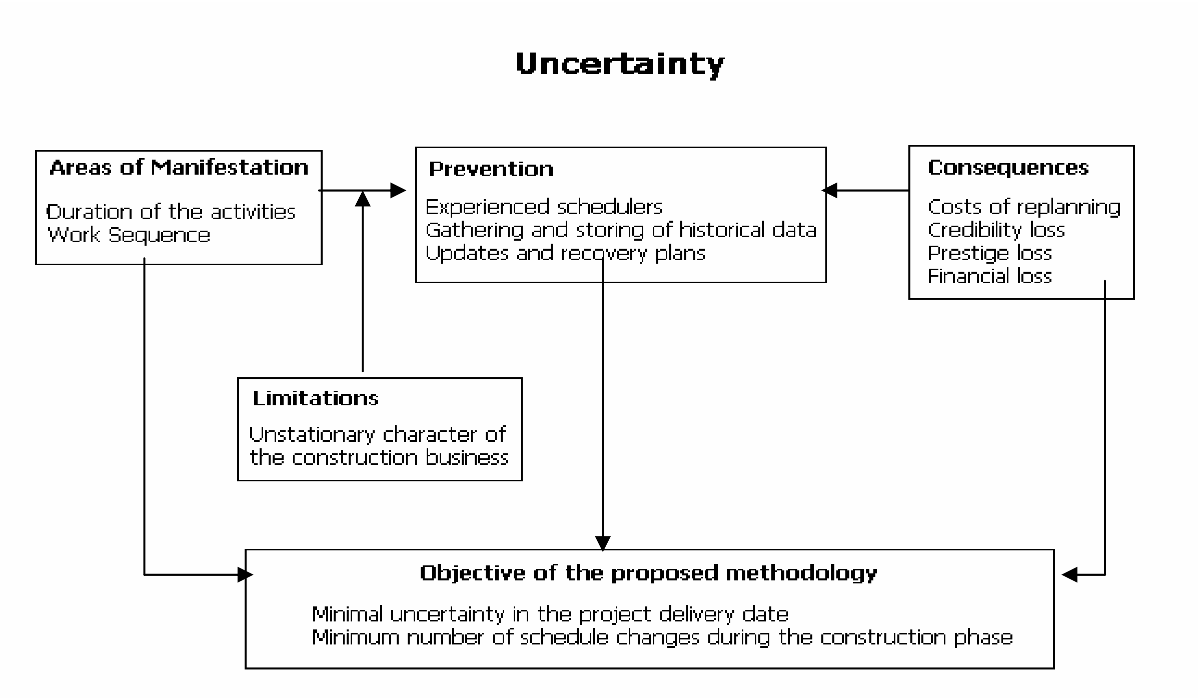


Fig. 4.2: Overview on the Concept of Uncertainty

5. Uncertainty Robustness Following the Design of Experiments Process

5.1 INTRODUCTION

When the product fails, one must replace it or fix it. In either case, one must track it, transport it and apologize for it. Losses will be comparatively greater than the costs of manufacture and these expenses will not necessarily restore the reputation lost.

Taiichi Ohno of the Toyota Corporation suggests that "[w]hatever the executives think the losses of poor quality are, they are actually six times greater" (quoted in Juran, 1993).

Most of the managers and engineers in developed countries have long since realised that quality losses are equivalent to the costs absorbed by a factory when it builds defective products – the squandered value of product that can not be shipped, the added costs of rework, and so on. It is also understood that losses are low when a factory ships pretty much what it builds (Juran (1993)).

Customers do not care about a factory's record of staying 'in spec' or minimizing scrap. For them, the proof of a product's quality is in its performance (Juran (1993)).

Therefore, in Construction, the whole life cycle comes into the picture. It is now evident that quality can't be achieved exclusively through inspection. Designing quality is cheaper than trying to inspect it after the product hits the production floor or even worse, after it reaches the customer.

The Taguchi method belongs to the class of approaches that attempt to ensure quality through design.

5.1.1 Background

The Japanese telephone system was in an extremely poor condition after World War II and unable to fulfil Japan's medium and long term communication needs. The allied command recommended that Japan establish a research facility in order to develop a state of the art communication system. Electrical Commission Laboratories (ECL) was set up and Dr. Genichi Taguchi was put in charge of improving R&D productivity and enhancing product quality.

Finding deficiencies in the traditional trial-and-error approaches to identifying design problems, he eventually developed his own complete, integrated methodology for designing experiments. His greatest contribution to the progress of science lies, not in the formulation of the design of experiments, but rather in the accompanying philosophy he inspired (compare with Roy (1990)). In 1982, the American Supplier Institute (ASI) introduced the method developed by Dr. Taguchi to the US markets. Since that time, companies have been adopting these techniques and philosophy.

Dr. Taguchi has been awarded the renowned Deming prize on three different occasions for his contribution to the field of quality. He has also received the Willard. F. Rockwell Medal and the Blue Ribbon Award, being widely acknowledged as a leader in the US industrial quality movement.

5.1.2 Method Description

- It is a system of cost driven quality engineering that emphasizes the effective application of engineering strategies.
- It efficiently utilizes small scale experiments to reduce the variability and find cost effective, robust design.
- Deals with complex and interrelated problems.
- Aims at making the product or the process robust.
- Provide techniques for rational decision making and for prioritizing the problems.
- Leads to economy of experimentation which speeds the entire process of decision making.
- Determines the ideal function of a system.
- Determines the optimum control factor levels while maintaining or reducing the cost.

5.1.3 The Concept

The method is based on three very simple and fundamental principles (Roy (1990):

1. Quality should be designed into the product not inspected after it has been made
2. Quality is best achieved by minimizing the deviation from a target. The product should be designed in such a way that it is immune to uncontrollable factors.
3. The cost of quality should be measured as a function of its deviation from standard and the losses should be measured system-wide.

It is often said in the industry that 85% of poor quality is attributed to the manufacturing and only 15% to the worker. Similarly, the time spent on planning in the construction industry is proportionately small given the amount of the total performance and cost it saves. This observation is intrinsic to Taguchi's idea. Its principles lead to what is called robustness of the product or the process. In other words, the insensitivity of the process to uncontrollable factors like, for example, daily or seasonal variations in the climate.

Through the proper design of a system, its process can be made robust, thus avoiding costly situations where products need to be rejected or reworked. In order to determine and minimize the factors that cause variation, the design phase is divided into:

- System Design
- Parameter Design
- Tolerance Design

System Design focuses on determining appropriate working levels for design factors. Also called "Primary Design", it includes designing and testing a system based on an engineer's choice of selected materials, process parameters based on customer needs, and current technology.

Parameter Design consists of determining the factors that produce the best performance of a product or a process under study. Also called ' robust design', it is the most important phase in the design.

Tolerance Design is used to fine-tune the results of parameter design. This is done by tightening the tolerance of the factors that have significant effects on the product or a process.

Fig. 5.1 below portrays the Design Phase.

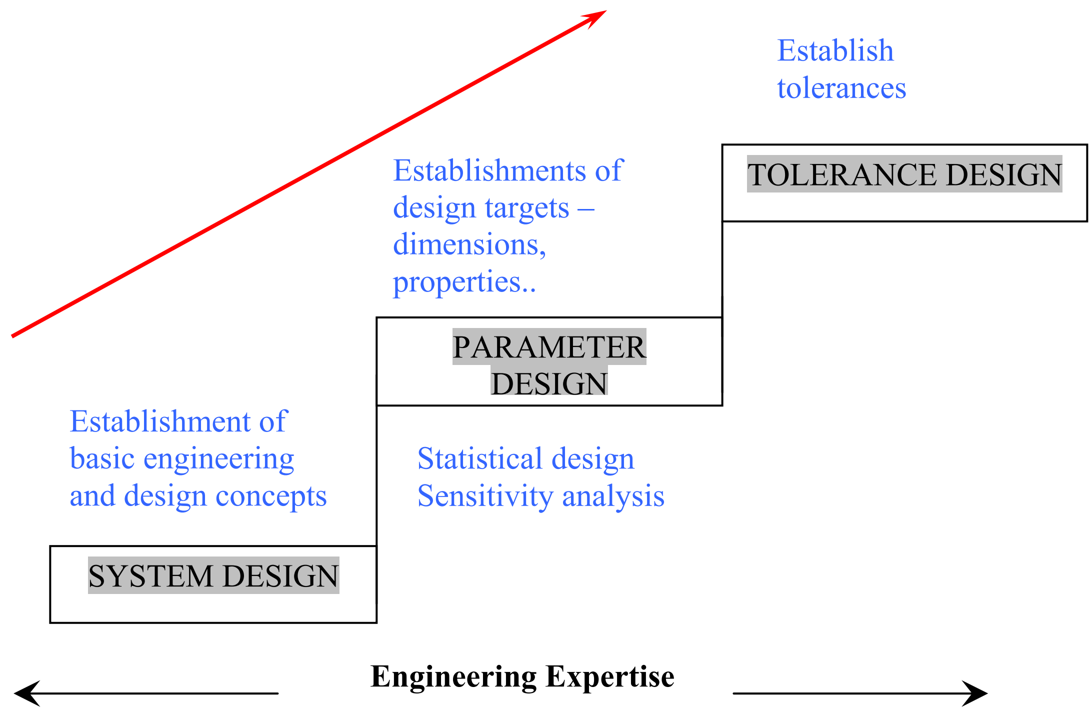


Fig. 5.1: Design Phase (compare with Karbhari (1994))

5.1.4 The Quality Characteristic

Every product is designed to perform a specific, desired function. A measurable characteristic, generally referred to as a Quality Characteristic, is used to express how well the product or process performs this function. In the majority of cases, the quality characteristic may be a single measurable characteristic, such as weight, length, time, etc. In other cases, subjective measurements, such as good, bad, high or low, may also be used. In other cases still, subjective and objective evaluations may be used in combination to produce an overall evaluation criteria.

No matter how the quality of the product is measured, whether it be by using a single criterion or a combination of criteria, the measure is rated according to one of the following three criteria:

1. *Higher is Better*
2. *Lower is Better*
3. *Nominal is Best*

5.1.4.1 Variation as a Quality Benchmark

Variation is part of nature. No two objects are absolutely identical in nature. While superficial observation of both man- and machine-made objects may lead to the conclusion that the parts look and function alike, closer examination often reveals that even machine-made products also show some degree of variation.

Variation in nature is often obvious to the human eye (Roy (1990)). Generally, the quality characteristic of the product varies in two ways:

1. It differs from another product of the same kind
2. It differs from the desired target value

The first kind of variation can be seen by comparing one item to another, whereas the second type of variation is often more important. This idea is represented in Figs 5.2 to 5.4.

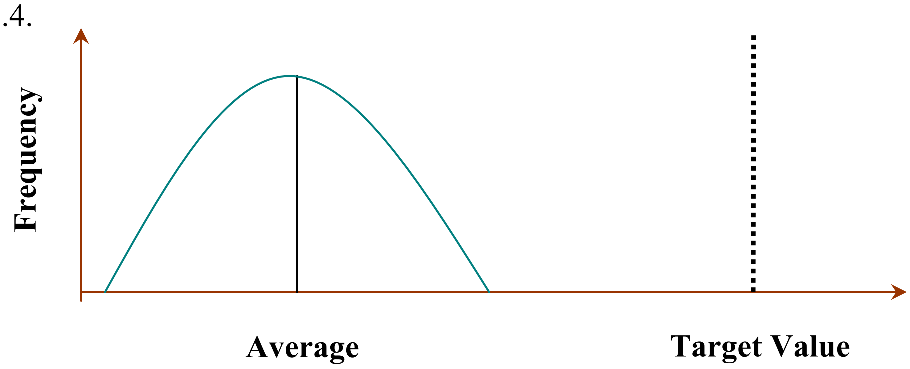


Fig. 5.2: Average Value off target and Excessive Variation Around the Average Value

In Fig. 5.2 the average value of the parameter deviates from the target value and the range of variation is excessive. In Fig. 5.3, the average is on target but the variation is still excessive.

Fig. 5.4 portrays the desired characteristics – the parameter is on target and has narrow variation

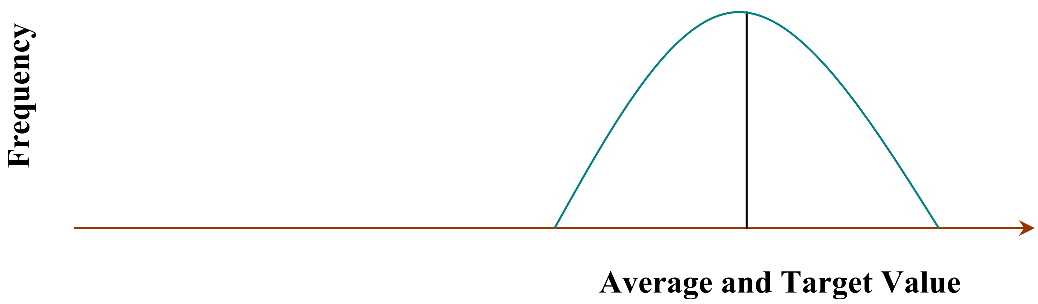


Fig. 5.3: Average value on target - Excessive variation around the target

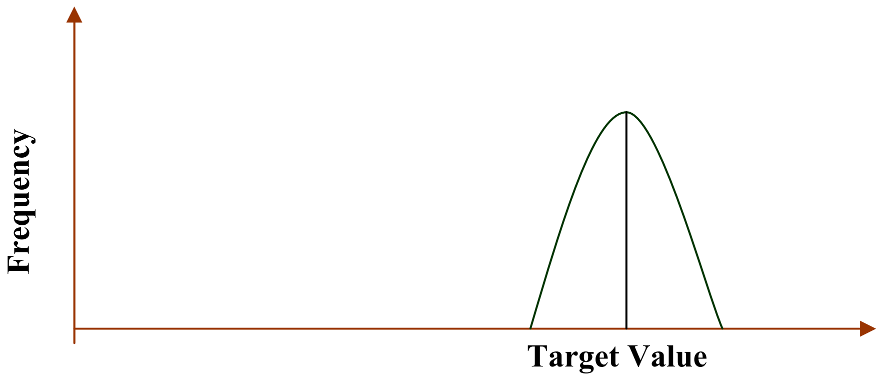


Fig. 5.4: Average value on target and with narrow variation

5.1.4.2 Cost of variation

Early in his research, Taguchi observed that variation is common to all manufacturing processes and that variation was a primary cause for the rejection of parts. Parts were rejected upon inspection when they did not comply with the predefined specification.

Rejection increases the cost of production. The complete inspection of all products produced is often too expensive or impractical, thus a defective part may reach the customer and lead to warranty costs and customer dissatisfaction. Taguchi, therefore, argues that the variation costs even extended beyond immediate factory production cost and that excessive variation causes a loss of quality. He pointed out that quality loss can be reduced by reducing the level of variation (Roy (1990), Juran (1993)). He, therefore, recommends that efforts be aimed at zero variation instead of simply maintaining production within fixed tolerance limits. Variation is viewed as representing a lack of consistency in the product, giving rise to poor quality. Taguchi developed a methodology aimed at reducing both elements of variation:

- Deviation from the target
- Variation to the others in the group

5.1.4.3 The Desirable Quality

Quality is ultimately defined by the customer's perception. Thus, it varies from product to product and from customer to customer. The criteria that customers use to judge the quality of the product are related to the satisfaction they get from the product itself.

Research has shown that a lack of product consistency is a major factor in the perception of poor quality. Consistency (reduced variation) positively affects most of the common elements of quality. For customers, quality may include service after delivery, ease of assembly, product performance, frequency of maintenance, etc (Taguchi (1990)). The core of the method proposed by Taguchi lies in perceiving quality as a reflection of product performance.

The methodology for reducing variation is a two step process:

1. Making the product/process consistently perform in the best manner (less variation from the target)
2. Making all products perform as identically as possible (less variation between the products)

5.1.4.4 The concept of Loss Function

This method highlights the fact that quality is best achieved by minimizing the deviation from the target. The process should be insensitive to uncontrollable factors. In other words, it should be robust.

The main reason behind integrating this methodology into the field of project management can be understood in terms of the Loss Function. The Loss Function takes into the consideration the consequences of uncertainties mentioned earlier.

The basic principle of the method is that quality is defined as the total loss borne by society after the product is shipped to the customer (compare with Taguchi (1990)). This loss should be measured in monetary terms and includes all costs which exceed the cost of a perfect product. It quantifies the consequences of variability associated with the process.

According to the "Goal Post Syndrome" – described by Ross (1996) – any process or the product is acceptable if the value of the specified parameter is within a specific range of tolerance, as shown in Fig. 5.5. No loss is registered if it occurs within this range. However, outside of this range, 100% functional deterioration occurs. This view does not reflect reality in an effective manner.

Taguchi argues that such limits do not exist. Performance, and therefore the customer satisfaction, gradually deteriorates as a function of its deviation from the target. Instead of fixed limits, there is a continuous function. Contrary to traditional methods, these methods are driven by customer satisfaction, not by the producer.

The Taguchi Loss function (shown in Fig. 5.5) quite accurately portrays the cost-time relationship in construction: costs sky-rocket once an effort is made to compress the schedule or when the project overruns the time.

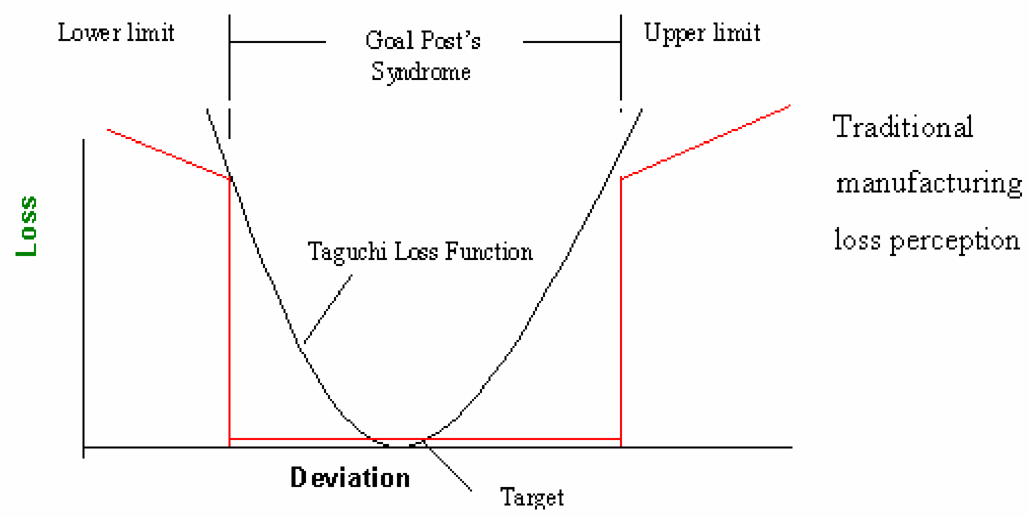


Fig. 5.5: Goal Post Syndrome vs. Taguchi Loss Function (Compare with Ross (1996))

5.2 THE ROBUST DESIGN METHODOLOGY

Robust Design can be defined as the process of choosing the product or process parameters' settings that reduce response variation from target. Because it involves parameter settings, Robust Design, as mentioned earlier, is also called "Parameter Design" by Taguchi (1979). Fig. 5.6 below shows a block diagram representation of a simple robust design problem. The block represents the product or the process under study. The responses of that product or process are determined by a large number of variables. Some of these variables are under the control of the designer and are called *control parameters*. Other responses are also influenced by variables which are difficult or expensive to control. These are called *noise variables.* Examples of noise variables include typical manufacturing variation, such as non-uniformity of raw materials, deviation of components from their nominal specifications, variation in the customer's environment, and deterioration or wear in component parts.

In theory, some of these noise variables could be controlled. For example, the designer could control raw material variation by specifying a higher grade of raw material or more expensive components with tighter tolerances. Taguchi (1979) calls this activity tolerance design. However, efforts to reduce the response variation by controlling noise variables increase the cost of each product unit produced.

In contrast, Robust Design reduces response variation by using controllable parameters to dampen the effects of the hard-to-control noise variables. This approach does not increase the cost of the product (Kacker (1988)).

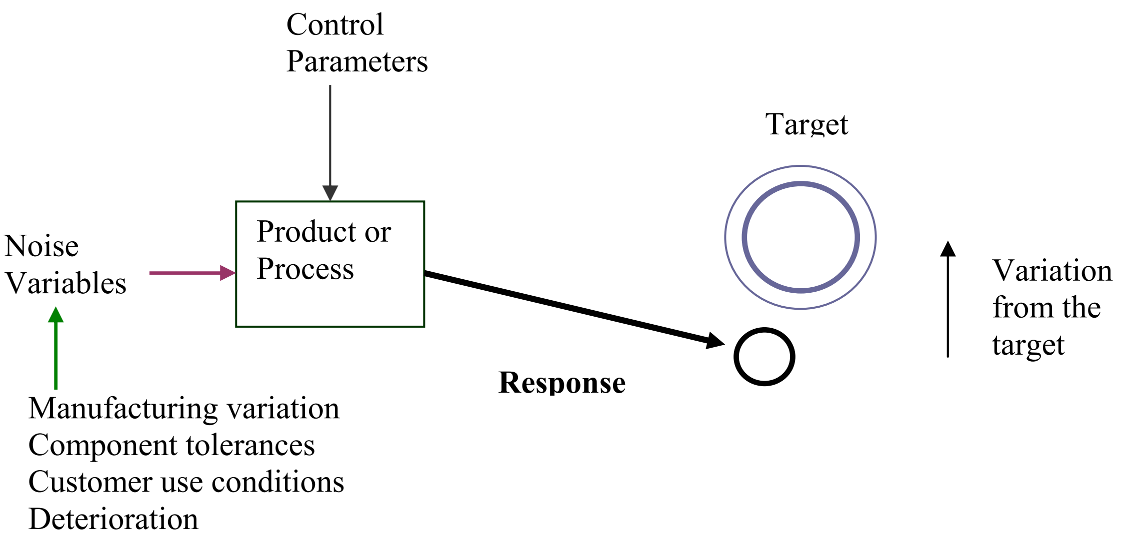


Fig. 5.6: Response Variation and Robust Design (Compare with Kacker (1998))

The Taguchi Method offers two new and powerful advantages. First, it is a disciplined way of developing a product or investigating complex problems. Second, it provides a means of investigating the available alternatives in a cost effective manner.

Although the Taguchi Method was established on well-developed and widely-accepted concepts of optimization through the design of experiments, its philosophy regarding the value of quality and the procedures for carrying one experiments were new.

Ross (1996) puts it this way: "The purpose of process development is to improve the performance characteristics relative to the customer needs and expectations. The purpose of experimentation should be to understand how to reduce and control variation of a product or a process; subsequently, decisions must be made concerning which parameters affect the performance of a product or a process."

A designed experiment is the simultaneous evaluation of two or more factors in terms of their ability to affect the resultant variability of a particular process characteristics.

To accomplish this in an effective and statistically accurate way, the levels of the factors are varied in a strategic manner. The results of the particular test combinations are observed and the complete set of results is analyzed to determine the influencing factors and preferred levels, as well as whether increasing or decreasing those levels will lead to further improvement. The major steps in this methodology are shown in Fig. 5.7.

The Design of Experiments (DOE) process is divided into three main phases which gather all experimentation approaches. The three phases are (Ross (1996)):

1. The Planning Phase
2. The Conducting Phase
3. The Analysis Phase

5.2.1 The Planning Phase

The Planning Phase is by far the most important phase for enabling the experiment to provide the expected information. An experimenter will always learn something from any experiment, regardless of whether the information observed is positive or negative. Positive information indicates which factors and which levels lead to improved product or process performance. Negative information, on the other hand, indicates which factors do not lead to improvement, but does not provide any indication of which factors do.

If an experiment includes the real, yet unknown influential factors and appropriate levels, it will tend to yield positive information. Factors and levels are selected in the Planning Phase.

Moreover, the correct selection of factors and levels is non-statistical in nature and more dependent on the product and process expertise. Brainstorming is a necessary and important step in this context. The nature and content of the brainstorming exercise depends on the type of the project under study. No specific guidelines exist. Taguchi recommends the participation of all functionally relevant persons and organizations.

The purpose of the brainstorming session (Roy (1990)) is to:

- Identify the factors and levels and other pertinent information about the experiment
- Develop consensus on the selection and the determination of the items which are objective and those which are subjective in nature.

The same author proposes the inclusion of the following topics in the agenda for the brainstorming session:

1. Objective of the Study

- What is the characteristic of quality? How can it be evaluated objectively?
- How can the quality characteristic be measured? What are the units of measurement?
- What are the criteria (attributes) for the evaluation of the quality characteristic?
- When many criteria or several attributes of the quality characteristic exist, how can they be combined into a single set of overall evaluation criteria?
- How are the different quality criteria weighted?
- What is the sense evaluation of the quality characteristic (The Lower the Better, The Higher the Better or Nominal is Best, as described in section 5.1.4)?
- What is the competitive benchmark information concerning the problem?
- What is the customer information concerning the problem?

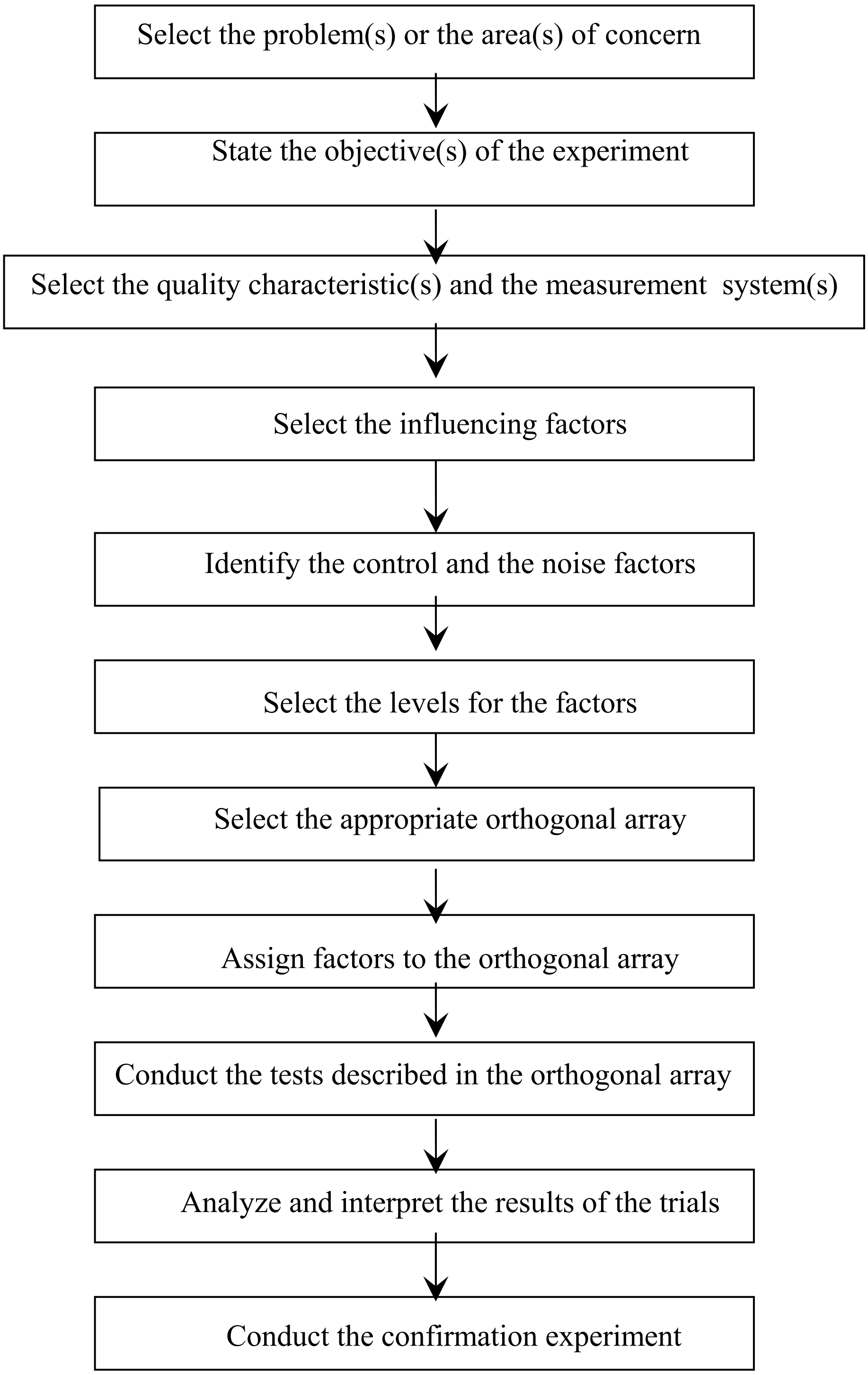


Fig. 5.7: Taguchi Method - Flowchart

2. Design Factors/Variables and their Levels

- What are the possible factors or control variables?
- Which factors or variables are more important than others?
- How many factors should be included in the study?
- What level should be selected for the factors?

- What is the trade-off between the levels and the factors?
- How urgent are the results? Should the design be aimed at a fast response with only a few factors, or is there enough time available to investigate more factors?

3. Noise Factors

- What are the factors that are most likely to influence the objective or the outcome but cannot be controlled in the experiment?
- How can the sensitivity to these noise factors of the product or the process under study be reduced, that is, how can a robust design de obtained?
- How are these factors included in the study?

4. Interaction study

- Which are the factors that are most likely to interact ?
- How many interactions can be included?
- Should an interaction be replaced by an additional factor?
- Is there a real need to study the interactions at all?

5.2.1.1 Selection and Utilization of Orthogonal Arrays

Engineers and scientists are usually faced with two product or process development situations. One development situation involves finding the parameter that will increase some performance characteristic to an acceptable or optimum value. The second situation involves finding a less expensive, alternative design, material or method which will provide equivalent performance (compare with Ross (1996)).

Depending on the situation, different test strategies may be used. Taguchi utilizes sets of orthogonal arrays to define the test strategies. The concept of Orthogonal Array (OA) will be addressed in detail at a later stage.

5.2.1.2 Typical Test Strategy

The most common test plan is to evaluate the effect of one parameter on product performance. When the first parameter does not work, the approach typically progresses by evaluating the effect of several other parameters on product performance one at a time. In urgent and desperate cases, the experimenter may be forced to evaluate the effect of several parameters on the overall performance at the same time.

A one factor experiment evaluates the effect of one parameter on the performance while intentionally holding other factors constant. If the factor studied happens to interact with there happens with some other factor, then this interaction cannot be observed.

This strategy makes limited use of the test data when evaluating the factor effects. Given a case with given 10 data points, only two data point are compared with two others, with the remaining six data points being temporarily ignored. If an attempt is made to utilize all the data points, then the experiment will not be orthogonal. Orthogonality means that factors can be evaluated independently of one another; the estimation of one factor does not affect the estimation of the effect of another factor (compare with Roy (1990)).

	Factors				
Trial no.	A	B	C	D	
1	1	1	1	1	
2	2	1	1	1	
3	1	2	1	1	Factor Levels
4	1	1	2	1	
5	1	1	1	2	

Tab. 5.1: Example of a Non-orthogonal Array

For example, the data set in Tab. 5.1 is clearly non-orthogonality. If the data is obtained when the factor A is at level 1 (A1) and all the data under A2 is averaged, then this will not represent the fair comparison of A1 and A2. The factor effects are only orthogonal when the levels utilized for the factors in trial 1 are compared to other levels, one at a time.

This situation makes separation of any of the main factor effects impossible, let alone any interaction effects. Some factors may contribute positively and other negatively, but this fact is not hinted at in the comparison (compare with Ross (1996)).

This can be avoided by utilizing either full factorial or fractional factorial experiments, which require the utilization of strategic orthogonal arrays.

5.2.1.3 Better Test Strategies

Highly detailed and intricate problems are most frequently tested using full factorial experiments. Full factorial experiments are orthogonal and have an equal number of test data points under each level of each factor.

This is illustrated in Tab. 5.2 below.

Trial no.	A	B	C	
1	1	1	1	
2	1	2	1	Factor Levels
3	2	1	2	
4	2	2	2	

Tab. 5.2: Example of an Orthogonal Array (Compare with Ross (1996))

Given this balanced arrangement, factor A does not influence the estimate of the effect of factor B and vice versa. Such an arrangement is used when just a few factors are to be studied, but is not sustainable when many factors are studied.

When a full factorial experiment is used, a minimum number of 2^f possible combinations must be tested, where f is the number of factors at two levels each.

5.2.1.4 Fractional Factorial Experiments

Statisticians have developed more efficient test plans, called fractional factorial experiments (FFEs). FFEs use only a portion of the total possible combinations to estimate the main factor effects and some of the interactions.

Certain treatment conditions are chosen to maintain the orthogonality among the various factors and interactions. However, substantially less information is generated from these small experiments when compared with the information obtained from a full factorial experiment.

Taguchi has developed a family of FFE matrices, called orthogonal arrays (OA), which can be utilized in various situations. Such techniques are not only used to simplify the experiments, but also to save a considerable amount of effort and time. They require rigorous mathematical treatment, both in designing the experiment and in analyzing the results.

		Number of Experiments Needed	
Factors	Levels	Factorial Design	Taguchi Method
2	2	$4(2^2)$	4
3	2	$8(2^3)$	4
4	2	$16(2^4)$	8
7	2	$128(2^7)$	8
15	2	$32.768(2^{15})$	16
4	3	$81(3^4)$	9

Tab. 5.3: Taguchi Method Compared with Full Factorial Experiments - Number of Experiments Needed

The OA is a mathematical inventions which can be traced back to the writings of French mathematician Jacques Hadamard in 1897. The usefulness of these arrays was, however, not fully explored until World War 2 when Plackett and Burman, British statisticians, first started to used the saturated approach previously mentioned. The Hadamard matrices are mathematically identical to the Taguchi OAs, but the columns and the rows are arranged differently. Although this shortcut method is well known, there are no general guidelines for its application or for the analysis of the results obtained by performing the experiments (compare with Ross (1996)).

The Taguchi Method elaborates on these two important areas. First, it clearly defines a set of OAs (a set of tables that define the experimental condition maintaining the orthogonality), each of which can be utilized in many experimental situations. Second, it sets a standard method for the analysis of the results. The combination of standard experimental design techniques and analysis methods in the Taguchi approach guarantees a level of consistency and reproducibility rarely found in any statistical approach.

Standard OAs satisfy most experimental design needs in cases involving a fixed number of levels for all factors is involved and where the interactions are less important. A modification of the OA becomes necessary, however, when mixed levels and significant interactions are present.

5.2.1.5 Selection of Orthogonal Arrays

The selection of OA predominantly depends on the following items in order of priority (Ross (1996)):

1. The number of factors and interactions of interest
2. The number of levels for the factors of interest
3. The desired experimental resolution or cost limitation

The first two points determine the smallest orthogonal array that can be utilized. However, this will also automatically be the lowest resolution and the lowest cost experiment possible. The experimenter may choose to run a larger experiment with higher resolution but which will most probably be more expensive to complete.

The arrays which are most commonly utilized can be categorized as two-level and three-level arrays. The L4, L8, L12, L16 and L32 are the two level arrays, while the L9, L18 and L27 are three-level arrays. Thus, when the factors studied occur on two levels, one could select L4 to L32 arrays, depending on the number of factors. Similarly, when the factors studied occur on three levels, the experimenter can employ L9 to L27 arrays, again depending on the number of factors.

The L8 array has 8 trials and the L27 array has 27 trials. The entries in the OA have the value 1, 2 or 3, representing the level assigned to the corresponding factor and level (column) in that specific trial (row). An overview of this information is provided in Tab. 5.5.

Roy (1990) and Ross (1996) provide deeper insight into this subject.

OA	Number of factors	Use column nos.	Resolution number*
L4	1–2	1,2	4 high
	3	1–3	1 low
L8	1–3	1,2,4	4 high
	4	1,2,4,7	2
	5–7	1,2,4,7,(3,5,6)†	1 low
L12	1–11	1–11	1 low
L16	1–4	1,2,4,8	4 high
	5	1,2,4,8,15	3
	6–8	1,2,4,7,8,(11,13,14)	2
	9–15	1,2,4,7,8,11,13,14,(3,5,6,9,10,12,15)	1 low
L32	1–5	1,2,4,8,16	4 high
	6	1,2,4,8,16,31	3
	7–16	1,2,4,8,16,31,(7,11,13,14,19,21,22, 25,26,28)	2
	17–31	1,2,4,7,8,11,13,14,16,19,21,22,25, 26,28,31,(3,5,6,9,10,12,15,17, 18,20,23,24,27,29,30)	1 low

*Resolution number is a measure of the amount of confounding in a column; see Table 7.4
†Column numbers in parentheses may be assigned in any order to achieve the indicated resolution; column numbers not in parentheses must be used first.

Tab. 5.4: Two-Level Orthogonal Array Factor Assignment (Ross (1996))

OA	Number of factors	Use column nos.	Resolution number*
L9	1–2	1,2	4 high
	3–4	(1,2,3,4)†	1 low
L18	1–8	1–8	1 low
L27	1–3	1,2,5	4 high
	4	1,2,5,(9,10,12,13)	2
	5–13	1,2,3,4,5,(6–13)	1 low

*Resolution number is a measure of the amount of confounding in a column; see Table 7.4
†Column numbers in parentheses may be assigned in any order to achieve the indicated resolution; column numbers not in parentheses must be used first.

Tab. 5.5: Two-Level Orthogonal Array Factor Assignment – L9, L18, L27 (Ross (1996))

The resolution of the experiment plays a vital role in the expedient and successful utilization of the methodology. In the first round of experiments, the recommended strategy is to group the typically large number of factors under evaluation. This means that the resolution will be relatively low in the first round of experiments. This strategy minimizes the number of tests to be carried out but will nevertheless produce meaningful results.

However, if the effort and cost associated with the tests are relatively low, a higher resolution experiment can be employed.

Roy (1990) and Ross (1996) provide detailed accounts of how to deal with interaction and assigning columns of OA for the interaction under study. They also provide information on how to develop OAs for special conditions, where the level of one factor differs from the rest.

Once the list of factors and the levels have been determined, the next major step is to determine the actual experimental test combinations that will evaluate the factors at different levels. This involves two parts:

First, selecting of the orthogonal array, considering the number of factors, their levels, and the resolution desired. Second, assigning factors to the chosen array. When factors are assigned to positions in an OA, this automatically dictates all the possible combinations of factors and levels which will be tested.

5.2.2 The Conducting Phase

The trial test conditions are given by the rows. Referring back to the L4 OA given in Tab. 5.2, the conditions for the first trial consist of factors A, B and C, set at level 1. Similarly, for trial three, the factors A and C are at level 2 and the factor B is at level 1.

The trial description, as well as the output data sheets, should translate these combinations into operational terms.

Two statistical considerations have made when conducting the experiments. They are (Ross (1996)):

- The statistical validity of the sample size
- The randomization strategy

Sample Size determination

The type of quality characteristic under consideration, variable or attributed, has a great impact on the sample size required for the experiment. Generally, when compared to attributed data, variable data require considerably fewer tests to obtain the same the same level of statistical confidence.

Variable data

Variable data has a continuous format which means that an infinite number of values can occur anywhere between very low and very high values. The discrimination between two experimental results depends on the accuracy of the measurement system. Examples of such type are, time, pressure, temperature, weight, length etc.

A minimum of one test result for each trial is required to maintain the sample size balance (orthogonality), though more than one test per trial can be used. This will increase the sensitivity of the experiment, enabling the detection of small changes in averages of population. The choice of the number of trials will typically be based on a cost-benefit trade-off analysis.

Attributed Data

Attributed data, on the other hand, has a discontinuous format which means that the experimental results can only be discrete values such as, good and bad, off and on, or 0 and 1. Binary attributed data provides much less discrimination than variable data. When a part is classified as bad, no measure on how bad is provided.

Because of this reduction in discrimination, many pieces of attributed data are required to provide equivalent information about the one obtained from one piece of variable data. As a guideline, the sample size of the type of data where occurrences and nonoccurrence are known should be set such that the class with the least frequency consists of least 20 samples.

For example, if the past performance has been 10%, then the total sample size of the experiment should be 200, thus producing an expected 20 defectives. These defectives should be spread over all trials to provide information as to which factors were influencing the quantity of defectives (Ross (1996)).

On the other hand, when the attributed data is of a type where only occurrences are known, the expected number of occurrences per trial should range from 2 to 5.

Randomization Strategy

The order in which various trials occur should also be examined, ensuring randomization.

Randomized trial-order protects the experimenter from any unknown and uncontrolled factors that may vary during the entire experiment, influencing the results (Ross (1996). Random order should not match any of the patterns of the columns, like, for instance, testing all odd-numbered trials first and even-numbered trials next. This assured, any unknown or uncontrolled factor effects will be spread evenly over the entire experiment. This will prevent biased interpretations of which factors and interactions cause a change in the average of the quality characteristic considered.

Randomization can take many forms. The most widely used approaches are:

1. Complete - all tests have an equal chance of being selected as the first of the remaining tests. In other words, each one has an equal opportunity of being selected for the next test.

2. Simple repetition – all tests have an equal opportunity of being selected for the first test, but once that trial is selected, all repetitions are tested for that particular test.

3. Complete within the block- This strategy is utilized when changing the test set up for one factor is very difficult or expensive in comparison to the others. The tests for that factor at level 1 are conducted first and level 2 follows.

Characteristics of Good and Bad Data Sets

Simply by observing the output data from the experiments, especially when looking at an OA structure, the experimenter can predict the type of information that may be obtained from the analysis.

Good data sets will typically generate positive information about which factors make a difference in the quality characteristic of interest. Bad data sets will typically generate negative information about which factors do not make a difference in the quality characteristic of interest (compare with Ross (1996)). These respective data sets can be characterized as follows:

Good Data Sets:

- All trials and repetitions are complete and the data is balanced
- Consistent results and/or low variation within a trial
- Large differences in results from trial to trial

Bad Data Sets:

- Missing trials and /or repetitions
- Inconsistent results and/or high variation within a trial
- Small differences in results from trial to trial

5.2.3 The Analysis Phase

The final phase in this methodology consists of analyzing and interpreting the experimental results. This is done in order to improve the performance characteristics of the product or process in light of customer needs and expectations.

After all the tests are conducted, it is necessary to decide which parameters affect the performance. Various analytical techniques are available to assist in making this decision. Among them are (Ross (1996)):

- Observation Method
- Ranking methods

- Column Effects Method
- Plotting methods
- Analysis of Variance

Some of these decision-making tools are used when dealing with influential factors that are subjective in nature, while others as aimed at objective decision-making. The primary statistical method used to interpret experimental data and to make the necessary decisions will be Analysis of Variance (ANOVA) as it is the most objective. Other methods used should be regarded as supporting and reinforcing techniques (Ross (1996)).

It should be kept in mind that the determination of influential factors and their relative strengths is based on the levels chosen for these factors. Regardless of the analytical method, any factor can be made to look less important if the levels chosen are closer together and any factor can be made to look more important if the levels chosen are farther apart (Ross (1996)). Thus, it is of paramount importance to choose the right levels.

The Observation Method

This is a preliminary method of interpretation. It can be utilized when the response is a "Nominal is Best" situation, but it works best with "The Lower the Better" or "The Higher the Better" characteristic, as described previously in section 5.1.4.

The method is very simple and provides the easiest means of interpreting of the results. The analysis effort is focused on the trials with the most similar and technically appealing results. This is best described in terms of a concrete example:

Two trials in an experiment provide the best results, thus the common levels for the factors in those trials are investigated. Then, those trials are compared with the remaining trials in the experiment; if a change in the levels of those factors is evident, then the factors are contributing to the result. On the other hand, if the results do not differ significantly when the factors are at different levels, then the factors in question do not contribute significantly to the result.

The interpreter is, in this way, provided with insight into which factors are key players in an experiment. This might lead to the exclusion of a few factors when it comes to planning the experiment, thus affecting the course of further interpretation and action.

The Ranking Method

This represents an extension of the observation method. Following the ranking method, all the results are ranked from best to worst, along with the trial conditions under which they occurred. This make the consistency analysis of the levels at the extremes of the best to worst scale possible. Thus, if there is a strong relationship between any given factor and the target quality characteristic, all the first levels will fall on one of the extremes of the scale, while all the second levels will fall on the opposite extreme. This method does not, however, allow the evaluation of interactions.

The Observation Method and the Ranking Method reveal an interesting property of using two level OAs as an experimental basis (i.e., when dividing the results into groups which are consistent within the group); if one factor really is important, two groups of data will tend to appear. One group that is associated with the low level will appear, as will another which is associated with the high level.

Furthermore, if the results of an odd number of trials appear in one of these groups, this may be an indication that either the measurement system makes an important contribution to the total variance or that other strong factors have not been included in the experiment and are changing the results in a random manner.

The Column Effects Method

This is the approach used by Taguchi. It involves a simplified analysis of variance (ANOVA), allowing the experimenter to manually point out columns which have large influences on the response. The sum of the data associated with the first level is subtracted from the sum of the data associated with the second level for each column in an OA. The information generated in this process is:

- Which factors make a difference

- The relative importance of those factors
- The direction in which the levels of those factors should be changed in order to yield further improvements

The magnitude of the differences is compared to find the effects that are large relative to others. The relative magnitudes, where a plus or minus sign shows positive or negative correlation with the level numbers, respectively, indicate the relative ability of those factors to affect the results. Thus, the strongest factors or interactions will have the largest differences.

The technically most appealing level sum will indicate whether the lower or the higher levels of the factors considered have the highest potential of leading to better results.

Plotting Methods

The most commonly used method involves plotting across levels, as shown in Fig. 5.8 below.

This implies the previous calculation of the averages of effects for each level. This calculation is made by obtaining the sums of the data associated with each level in the OA columns and dividing them by the number of tests (data entries) for the respective level. The plots will then visual represent the way in which factors change the response.

Similarly, graphs can be plotted to show which factors interact by setting the x-axis as base for the factor levels. If the lines obtained are parallel, no meaningful interaction exists. The greater the skew between the lines, the stronger is the interaction.

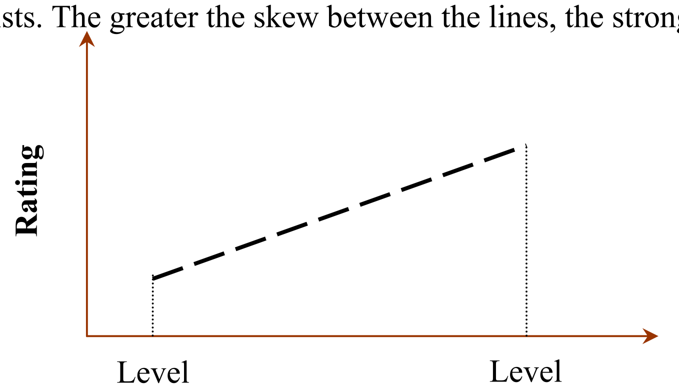


Fig. 5.8: Plotting Methods – Example

Analysis of Variance (ANOVA)

Taguchi replaces full factorial experiment with streamlined, less expensive, faster, partial or fractional factorial experiment. His design is based on specially developed OAs.

Since the partial experiment is only a sample of the full experiment, the confidence that can be placed in the results must be evaluated. ANOVA can be used to this effect, providing a measure of confidence for the results obtained.

The method was developed by Sir Ronald Fisher in the 1930s as a way of interpreting the results from agricultural experiments. ANOVA is a statistically based, objective decision making tool for detecting differences in the average performance of the groups of items tested (compare with Roy (1990)). Instead of using pure judgment, the decision takes variation into account. This analysis provides the variance of the controllable and noise factors. By understanding the source and magnitude of the variance, robust operating conditions can be predicted.

Roy (1990) and Ross (1996) both provide very comprehensive and practical descriptions of the ANOVA for different cases and situations. The analysis described in the next chapter follows this method. It should be noted that, following the conclusions obtained in chapter 2, the interaction between the four controlled parameters was considered irrelevant for this level of detail.

5.2.4 Confirmation Experiment

A confirmation experiment is the final step in the first iteration of the process. It is performed by carrying out a test using the specific combination of the factors and levels previously evaluated. The main objective is to determine the best combination of the factor levels that are have proven to be significant according to analytical methods. That is, it aims to validate the conclusions drawn during the analysis phase.

This is a very important step when dealing with small fractional factorial experiments with low resolution. When a small fractional factorial OA experiment is used and several factors contribute to the variation observed, the best combination of factors and levels may not be one of test combinations considered in the OA. Hence, the confirmation experiment can also be used to test particular combinations in question. The conclusions of a fractional factorial OA experiment should, therefore, be considered preliminary until they are validated by the confirmation experiment.

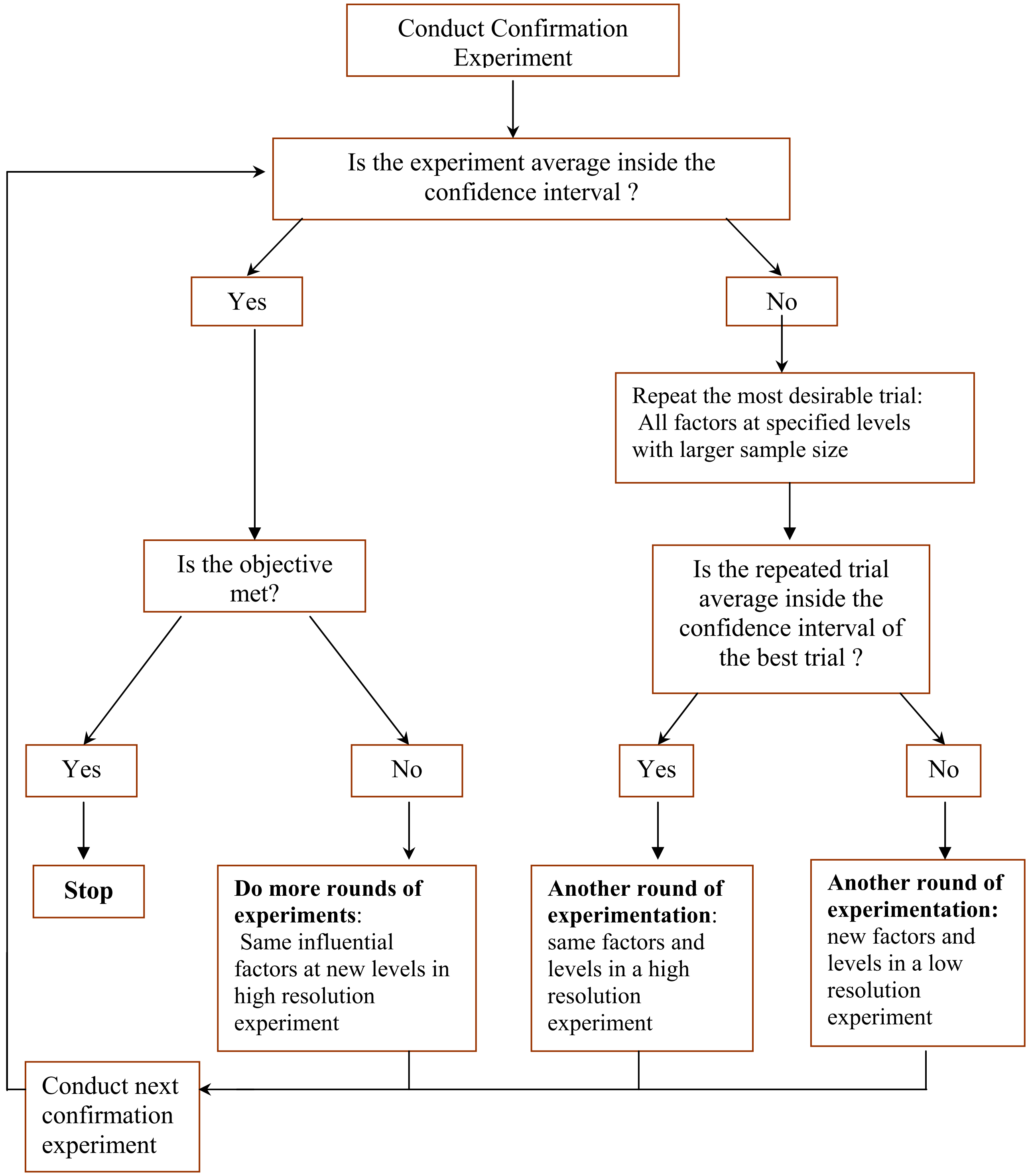


Fig. 5.9: Confirmation Experiment Flowchart (compare with Ross (1996)

5.3 THE DESIGN OF EXPERIMENTS PROCESS FOR SCHEDULE ROBUSTNESS

5.3.1 Introduction

As highlighted in the first sections of chapter 4, it is very important to meet the planned delivery date of a project. Large projects involve many stakeholders, and carry with them high risks.

One of the major characteristics of large scale projects is that resource constraints are not physical but financial. Large scale projects involve large scale stakeholders who have the financial and logistical capability to provide resource if they are deemed needed and financially rewarding. Thus, resource constraints are of relative less importance in large scale projects and the focus is shifted to other financial issues, such as cost optimization and, in particular, avoiding financial penalties resulting from delays.

The importance and attention given to project and construction management, and to the companies that offer their services in this area, has grown together with the importance given to finishing jobs on time. This issue has been so expanded that is has become common to hear about cost overruns as a result of recovering delays, but less common to hear about delayed delivery dates themselves. The predicted penalties for delivery delays in large scale projects have become so inflated that delays are now out of question. That is, it is now preferable to recover delays by boosting the investment to previously unthinkable levels than to risk overruns.

Thus, when analyzing the problem of completing a large scale construction project on time, it should be kept in mind that the objective is to avoid the disproportionately high costs of recovering a delay, more so than it is to avoid a delay in the project delivery date itself. In light of this, the author uses this chapter to propose the concept of Delivery Date Assurance and a methodology that can be used to achieve it.

5.3.2 Review and Objective

The PERT modification proposed in Han (1997) was described in section 3.3, and in section 3.4 the utilization methodology of its simulation software was explained. Thus, the conditions for achieving the effective stochastic simulation of projects have been summarized and presented. Simunet, the simulator proposed by Han (1997), has proven to be an effective tool for determining the project total duration and its variance.

Chapter **1** explained why scheduling can and should be considered when assessing quality. It also provided an means in which this task can be carried out.

Chapter 2 examined the relationship between the schedule topology and the impact of the intrinsic uncertainty of activities' on the uncertainty of the project total duration. Lastly, it also provided a body of knowledge which made up a set of qualitative tendencies.

Chapter 5 describes an optimization methodology for designing experiments in such a way as to deliver manufacturing products which are variation insensitive, thus robust to their noise factors.

This section follows the methodology described in the previous sections of this chapter. It regards the schedule of a project as its final product, and the intrinsic uncertainty of its activities as noise factors.

Thus, the results obtained in the previous chapters are implemented in this section and an autonomous methodology is developed for obtaining optimized, robust schedules, which have the lowest variance for the fundamental structure entered (precedences and intrinsic uncertainty of the activities). This provides schedulers with a systematic, structured and objective tool which can be used to minimize the uncertainty of their projects' delivery dates, by moving away from some of the subjective intuition and previous experience that is commonplace nowadays.

To achieve this, the results obtained in chapter 2 were confirmed. They were then utilized to minimize the variance of the total project duration in 3 work schedules. The results were then validated by applying them to 4 real schedules.

5.3.3 Definition of Concepts

The methodology and tools developed are based on a few innovative concepts which first need to be defined.

Delivery Date Assurance

The author proposes this term for his transfer of the Process Approach to achieve Quality Assurance to Planning, specifically to the delivery date of projects. This transfer follows the principle of Process Approach Quality Assurance instead of the Result Approach of *a posteriori* Quality Control. Thus, *A posteriori* progress updates and recovery plans, which correspond to patching, repairing and substituting in the manufacturing industry production, are reduced to a minimum.

Optimized Schedule Topology

The author uses the term “Optimized Schedule Topology” to characterize the structure of the schedule obtained after its has been optimized using to his *Computer Assisted Procedure for Delivery Date Assurance (DDA)*, described later in this chapter. Thus, it includes the *optimization precedences*. Optimized schedules have the lowest variance possible given the fundamental structure of the original schedules.

Fundamental Structure of a Schedule

This term, proposed in Han (1997), describes the elements that contain the whole of the network schedule structure and the stochastic information of all the activities it contains. The author has slightly modifies the concept, defining it as the set of information that defines the physical precedences and the intrinsic uncertainty of the activities, hence the fundamental input data for the optimization process. This data cannot be changed because it defines the basic structure of the schedule. The term “Intrinsic Uncertainty” was described previously in section 4.3.

Total Duration Uncertainty of a Schedule

The author uses this term to characterize the "amount of uncertainty impact" in the total duration of a schedule. The "amount of uncertainty impact" is defined as being the sum of the DUSs for its activities. The comparison of different schedule topologies for the same project is only relevant if the value of this sum remains constant. This is because a reduction or increase of in value will cause a reduction or increase in its respective variances, thus biasing the conclusions.

Physical Precedences

This term describes the set of activity precedences that are set by intrinsic constraints, such as the laws of nature. An example would be precedences in the form-cast-strip or columns-slabs construction processes. This set of precedences includes all those, and just those, precedences that cannot be changed. It only includes precedences of resources limitations if they cannot be surmounted. Otherwise, precedences due to resources limitations are not considered.

Resource Management Precedences.

From the definitions given above, the author proposes the following classification of precedences:

1. Fundamental or physical
2. Resource management
3. Optimization

Given the scope of large scale projects, as described in section 5.3.1, resource management precedences can be changed and should, therefore, not be considered when defining the fundamental schedule structure that is to be optimized using *DDA*.

The optimization precedences are added by *DDA* to achieve the optimized schedule topology.

5.3.4 Justification of the Research Methodology

The Taguchi Method fits the objective proposed in section 5.3.2 for many reasons.

1. Loss in construction scheduling can be represented by a continuous function with a single zero value on the target quality; the smallest delay carries with it penalty costs, and ending a project unnnecessarily early also creates unnecessary expediting costs. Thus, the costs of not meeting the delivery date can be described by a continuous loss function with a single zero value at the contractual delivery date. This corresponds exactly to the concept of Loss Function described by the Taguchi Method.
2. It further states that quality is best achieved by minimizing the deviation from a target, and that the product should be immune to uncontrollable factors. This can be directly applied to scheduling. The schedule assumes the role of the product and the intrinsic uncertainty of the activities' durations corresponds to the uncontrollable or noise factors. Morevoer, the Simunet simulator provides the variance of the total project duration, which is precisely a parameter for assessing variation.
3. For the appliance of the Taguchi Method, control factors must be identifiable. This is guaranteed by the study described in chapter 5, which isolated schedule topology parameters that influence the impact of the intrinsic uncertainty of the activities in the total project duration.
4. Having defined control factors, the Taguchi Method can be used to derive their level of interaction (see chapter 5). It was also mentioned in chapter 2 that, at a practical level of detail and excluding specific second-order effects, the parameters provided for control factors during the first steps of the Taguchi method can be considered non-correlated. Thus, this step has also been covered in the results of the preceding chapters.
5. The parameters that are to be used as control factors can be assigned 3 levels easily. This also favors the Taguchi method, since it makes applying of the orthogonal arrays easier.
6. The study described in chapter 2 set a body of knowledge from which further research can be begun. Accordingly, the objective of the research described in this chapter aims to apply the knowledge and tools gathered in this work in a

concrete and practical manner. Thus, although the objectives of chapter 2 and 5 are similar, they are not the same. The set of parameters needed for the research described in chapter 5 might also go beyond the one obtained in chapter 2, including parameters still unidentified. With most optimization methods, this would cause a problem that is difficult to solve. The parameter design phase of the Taguchi method, however, takes this problem into consideration and provides solutions.

7. Experimentation using full factorial experiments for 4 control factors at 3 levels would imply 81 experiments just for the final phase, (see Tab. 5.3.). The Taguchi method, however, can achieve the same results with only 9 experiments. Moveover, this example only takes the final phase of experimentation into consideration and does not count all of the experiments necessary to establish the right control factors and levels in the first place. Hence, the advantages of Taguchi method just in terms of simplicity is far greater than evidence here. This is even more true given that other methods also do not provide the same feedback on the correctness of the factors and levels chosen that the Taguchi method does. Provided that 3 schedules were utilized in the experimentation phase and 4 in the validation, the economy in experimentation and simulation effort is obvious and weighing.
8. Contrary to other optimization methods, the Taguchi method considers discrete levels for the factors. This makes it significantly easier to apply its results in practice, since continuous values for the control factors, such as, “64% of duration uniformity”, do not have any practical meaning. Moreover, changing the results obtained so that they better suit real-life application still involves changing the results, that is, introducing an error. The Taguchi method, on the hand, provides the results can be directly applied in practice since the discrete levels utilized – for example, “full uniformity” or “one activity larger than the others” – do not need to be adapted and, thus, retain whatever inherent errors they may contain.

5.3.5 Experiment Design

5.3.5.1 Factors and their Levels

As covered in greater depth in section 5.3.6.2 below, the pre-experimentation phase included several experiments in order to obtain the right factors and their levels. The study described in chapter 4 provided the knowledge basis. Thus, considering the information contained in Tab. 2.13 and Tab. 2.14, three factors were considered initially:

1. Uniformity of Durations

Gives the relationship between the durations of the activities, i.e., whether the activities' duration are approximately uniform or whether one or more activities are significantly longer than the others.

2. Parallelism

Gives the degree of parallelism between activities in the schedule, i.e., the extend to which the schedule has activities which are planned in parallel.

3. Density of Ties

Enables the progressive inclusion (or elimination) of ties, e.g., an increase in the density of ties through the inclusion of optimization ties, as defined in section 5.3.3.

During the pre-experimentation phase, a fourth factor was found to be necessary; the relative location of the center of mass of the Duration Uncertainty Seriousness (DUS) of the activities within the schedule time-line as defined in section 4.3.3. Thus, a 4th factor was defined.

4. Location of the DUS's C.M.

Thus, if the location of the DUS's center of mass fell within the 1st, 2nd or 3rd third of the total project duration, it was defined as being in the beginning, middle, or at end of the project, respectively. Its corresponding level was assigned.

The DUS value of all activities was calculated when constructing the stochastic information table of the project. Based on these values, the center of mass of the DUS was calculated as follows:

1. Take the average AL of the mean start- and end-dates of the activity after a complete simulation.
2. Take the DUS value for the activity in question.
3. Consider only the target activities (see section 5.3.6.2 for definition and justification).
4. Add the DUS values of the target activities (total duration uncertainty value of the project TDU).
5. Calculate the percent value of each activity's DUS in the TDU value.
6. Calculate the first area moment, thus taking the mean of the AL values for the target activities, weighted according to their percent value in the TDU. This value will be a time point along the project time-line, given by the time-span between the mean project start- and end-dates obtained after one full simulation.

The process for defining levels is represented in Tab. 5.6 below.

Levels	Uniformity	Parallelism	Density of ties	Loc. of DUS's C.M.
1	All activities uniform	Full	Low	Beginning
2	One activity bigger than the others	Zero	Medium	Middle
3	More than one activity bigger than the others	Half lagged	High	End

Tab. 5.6: Factors and their Levels

The description of the research process used to create these levels, as well as the way in which they were realised in the experiments, will be dealt with in sections 5.3.5.1 and 5.3.6.2.

5.3.5.2 Selection of the Orthogonal Array

The selection of the most appropriate orthogonal array (OA) must be preceded by the definition of the quality characteristic. In section 5.3.2 the objective was to minimize the variance in the total project duration obtained from the simulation experiments. Thus, the appropriate quality characteristic was of the order *Lower is Better*.

Therefore, having 4 factors at 3 levels, the orthogonal array L9 was chosen.
Tab. 5.7 below illustrates the trial conditions of an L9 orthogonal array. The table entries correspond to the level of the respective factor (column) for that trial (row).

Trial no	Factors			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Tab. 5.7: Trial Conditions for an L9 OA (Taguchi (1979))

5.3.6 Conducting Phase

The research was divided into pre-experimentation, experimentation and validation phases. In the pre-experimentation and experimentation phases, 3 close to genuine projects from the practical experience of the author were used. These were simple projects, called work projects, which made it possible to change and highlight specific topological characteristics.

5.3.6.1 Description of the Work Projects

These schedules were chosen because their activities had physical and practical meaning, and thus incorporated precedences which reflect strategic options in scheduling, such as resource management or optimization precendences. In order to generate the different levels of factors, “Density of ties” and “Parallelism”, it is necessary to include and change ties. This only has practical significance if the ties have real-life meaning.

Project Plant

This project involves the construction of two 70m x 20m prefabricate frame and cladding industrial units, as well as the construction of a storage yard for the production of prefab concrete panels, including vibration tables and batch plants.

The construction is scheduled to take place during the rainy season and, therefore, the fundamental structure shows a pessimistic outlook toward the success of ground works. The project consists of 39 activities, divided in 2 parallel bodies of 19 activities, with a mean total duration of 132 work days.

Project Towers

This second work project involves constructing two 5 stories high office towers with a plant area of approximately 600 m^2. The towers have each a reinforced concrete core, steel beams and reinforcements, and mixed-structure slabs. The steel elements are fire-proofed in accordance with Eurocode (2 hours).

The envelope consists of glazed cladding on aluminum frames.

The fundamental structure of the schedule is made up of 25 activities, divided into 2 groups of 12 activities, with an original mean total duration of 372 work days.

Project Tanks

This third and last work schedule involves the construction of two water storage tanks, elevated 15m above ground-level. The tanks have a total capacity of 2 × 565 m^2 and are to be erected on a rural area, at risk for termites.

The fundamental structure of the schedule is made up of 25 activities, divided into 2 groups of 12 activities, with an original mean total duration of 114 work days.

5.3.6.2 Pre-experimentation Phase

As mentioned before, the experimentation phase was preceded by a pre-experimentation phase, where the work projects were already utilized. The aim of this phase was to derive the formulation and materialization procedures for the factors and their levels in the schedule, as well as to obtain the best characteristics for the work schedules and adapt them accordingly.

This phase turned out to be of major importance, since it established the baseline and procedures for applying Taguchi's Experiment Design concept to scheduling. Thus, although the points in this section describe the work projects utilized specifically, they go beyond the bounds of the projects themselves, defining the baseline for applying Taguchi's experimental design to scheduling.

Several factor/levels relations were equated and the best-suited orthogonal array were chosen from Tab. 5.4 and Tab. 5.5, respectively. Preliminary simulation tests were also conducted.

Scope of Analysis – Activities Ranking by DUS

During the pre-experimentation phase, the DUS ratios of the activities were originally only used to determine the location of the DUS's center of mass. However, during the course of the experimentation, the question arose as to how many activities need to be considered in order to define the levels of the factors, i.e., how many and which activities should be considered when:

- defining the location of the DUS's C.M.
- observing and setting the level of parallelism
- splitting the activities in order to obtain uniformity

Three factor levels arose from the process of defining which activities should be linked when increasing the density of ties.

This question is of particular practical importance because it is extremely stime consuming to have to consider all the activities in the analysis. Moreover, the number of activities with low DUS – that is, which have little or no impact of the total uncertainty of the project total duration – was found to be significantly higher than the number of activities with high DUS. This can be seen in the stochastic information tables of all the work and validation schedules simulated, that is, for a total of 7 projects. An example is given in Tab. 9.1.

Since most of the uncertainty potential is concentrated in a relatively small number of activities, limiting the number of activities that need to be considered for simulation and optimization, while maintaining the significance of the results obtained, seemed to be possible and useful.

This result is in line with the classical definition of the Critical Path which holds that the activities in the critical path provide the best means of monitoring the project's progress and assessing delays. The number of activities in the critical path is, moreover, usual relatively low in comparison to the total set of activities.

Repeated observation of activities lists, including their DUSs, led to the conclusion that there are generally a few activities with significantly higher DUSs than the others. When looking at projects with parallel processes or groups, if we regard the same activities in different groups as belonging to one pair or trio, this number decreases further. This process therefore reduces the focus most of the uncertainty impact in the total duration of the schedule to a few key activities.

The experimentation strategy adopted in order to compare the significance of the simulation results obtained to the number of activities considered, involved observing only those activities which gathered more than 50% of the total sum of the activities' DUS. Thus, the number of activities observed decreased when the DUS was concentrated and increased when it was dispersed. It was concluded that it is sufficient to take 4 to 6 pairs/trios of activities into consideration and still obtain the expected effects.

Hence, it was established that the first step of the experimentation procedure should involve limiting the scope of the observation by:

- Calculating the DUS value for all activities
- Observing the DUS distribution
- Ranking the first 4 to 6 activities/activity pairs or trios by DUS

The first step can be done easily with the assistance of a spreadsheet program, such as MS-EXCEL. Once concluded, a stochastic information table of all the activities with the indication of OD, PD, C, UR and DUS is printed out, making step 2 an easy task.

Changing the Level of Parallelism

It was concluded that the factor parallelism should be considered at the three levels indicated in Tab. 5.6. Intermediate levels, such as "Activities overlapped by $1/4$" or "Activities overlapped by $3/4$" were also tested, but were found to give less conclusive results. Moreover, the realisation of these levels in practice is less effective.

A procedure was created so that the level of parallelism could be easily increased and decreased. If two activities A and B need to be lagged a start-to-start tie is introduced between one of the activities, say A, and a buffer activity that precedes the other activity (B) to be lagged. The buffer activity has a finish-to-start tie with the activity (B) it lags. The different levels of the Parallelism factors are then created by assigning the buffer a duration of 0, $1/2$ duration of B, or full duration of B.

It was also found that, when assigning durations to the buffers, it should be kept in mind that all the activities in the same construction process or schedule body will eventually also be lagged. Thus, the visual inspection of the schedule print-out is critical to verify whether or not the desired topology was achieved. Only then should the simulation trials be carried out and their results considered.

Changing the Location of the DUS's C.M.

The DUS's C.M. levels are obtained by shifting its original location at the fundamental structure. A procedure for shifting the location of the DUS's C.M. also had to be developed. As mentioned before, the work schedules use fundamental structures with practical meaning.

The higher the intrinsic uncertainty of a schedule, the bigger the variance of its total duration will be. Thus, a schedule in which all activities have definite, deterministic durations (OD = PD and C = 1, hence UR = 1) will have zero total project duration variance, and this value will grow in direct relation to the increase of the UR of the activities. This was confirmed in a small experiment displayed in Fig. 5.10 below. As mentioned before, the impact of the activities' intrinsic uncertainty has to be taken into consideration. This was achieved by creating the Duration Uncertainty Seriousness (DUS) formula.

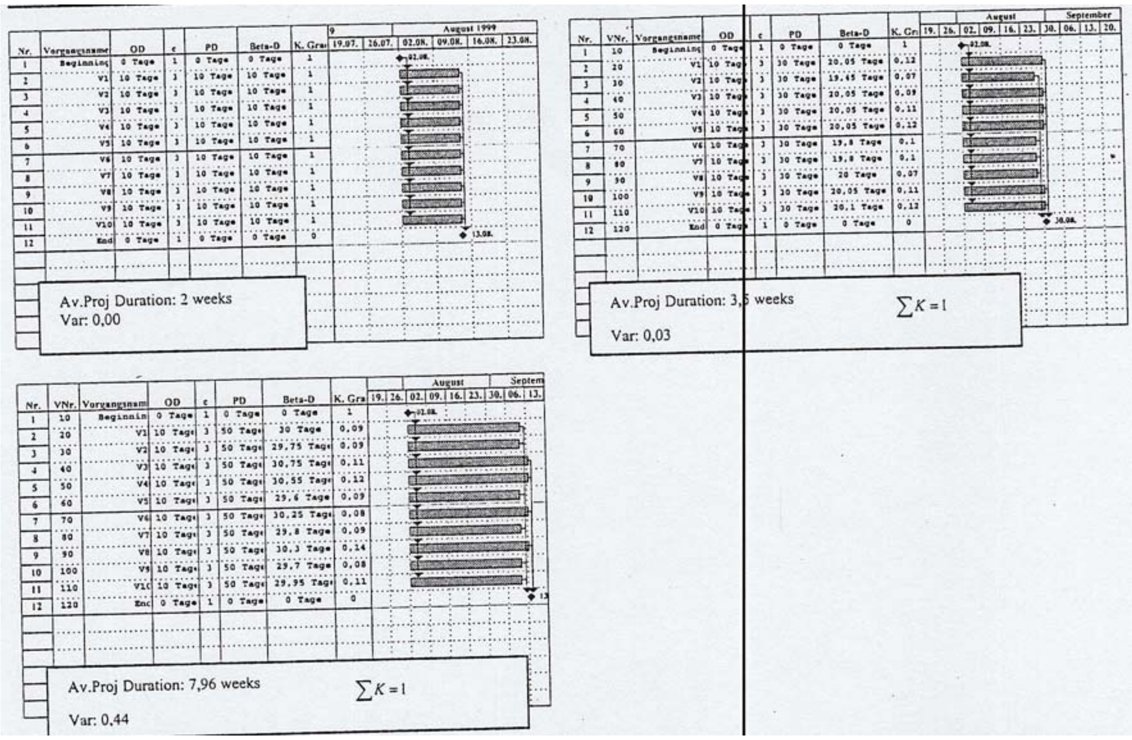


Fig. 5.10: Relationship between Total Duration Uncertainty and Project Duration Variance

Shifting the location of the DUS's C.M. is a delicate procedure and creates several problems:

Adding activities will change the fundamental structure of the schedule, thus making comparisons impossible.

Changing the stochastic information of the activities may lead to unrealistic activity durations and/or duration ranges.

Altered activity stochastic information may change the total duration uncertainty of the schedule (as defined in section 5.3.3), thus biasing the process of comparing the different schedule topologies.

Taking these three points into consideration, the best procedure for achieving the location shift was found to be to directly exchange the stochastic information of two activities with comparable critical degrees. This generates some activities with unrealistic durations and/or duration ranges, but the total duration uncertainty of the schedule is maintained, thus guaranteeing a legitimate comparison between the variance values of the different schedule topologies obtained.

The procedure obtained consists of three steps:

1. Look at the schedule (graph and activities' information list) to determine which activities could be shifted. The aim of this step is to note the location of activities along the time-line, as well as their critical degrees.
2. Exchange of the OD, PD and C values of the two activities chosen
3. Carrying out a simulation and confirm that:

- The location of the DUS's C.M. occurred as desired
- The K-degrees of the activities remained the same

Since all stochastic information is exchanged, the only way in which a different total duration uncertainty for the schedule could be obtained is if an unwanted change of the K-degrees occurred due to the tie network. In classical terms, it would correspond to a change in the critical path, leaving out one or both the activities changed.

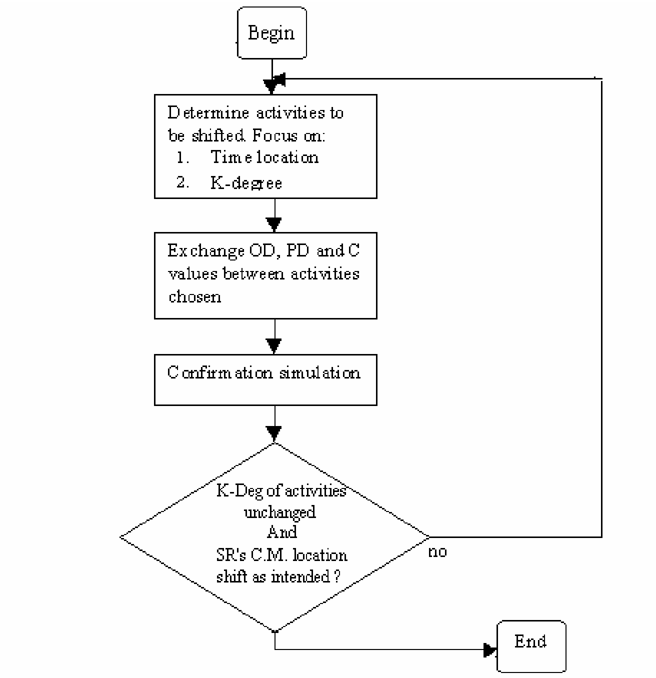


Fig. 5.11: Procedure for Shifting the Location of the DUS's C.M. – Flowchart

Changing the Density of Ties

Another conclusion of this study concerns the amount of ties that need to be added to change from one level to the next highest. It was concluded that at least 3 extra ties and 2 extra pairs of ties should be added in schedules with respectively 2 or 3 parallel bodies.

Definition of a Fourth Factor

However, the results from most of this phase did not fully agree with the expectations of the author, as they did not always coincide with the results previously obtained in chapter 5. This discrepency indicated the existence of another factor which was not being taken into consideration. Further experimentation led to the conclusion that this factor was the relative location within the schedule time-line of the center of mass of the Duration Uncertainty Seriousness (DUS) of the activities.

Once this 4th factor was included, the results of the simulation did agree with the results obtained in chapter 2. Thus, the results obtained in chapter 2 could be validated and the pre-experimentation phase was deemed over.

5.3.6.3 Experimentation Phase

In this phase, the simulation tests defined by the trial conditions of the orthogonal array L9 (see

Tab. 5.7) were conducted and the results were recorded for analysis.

The experimental method was adapted in several rounds, where subsequent rounds of experimentation were optimized based on the results of previous rounds. This is not required by the Taguchi method. However, it should be kept in mind that one of the objectives of this work is the practical and effective appliance of this method to scheduling and, given its innovative characteristic, this process is itself subject to research and experimentation.

Thus, while applying the Taguchi method for achieving the objectives stated in section 5.3.2, a continuous effort was made to find the procedure that best suits the specific needs of scheduling. Given the interactive nature of this process, the boundary between pre-experimentation phase and experimentation phase is not clear. Most of the points and conclusions mentioned in section 5.3.6.2 were obtained once the author thought that the experimentation phase had already begun. Thus, for the sake of clarification, the experimental phase will be defined as including only the last and final set of 9 simulation trials per project.

Particular care was given to the way of the factor levels for each trial were transposed to the schedule. It is very important to look at a print out of the schedule topology after transposing the trial conditions to confirm that they are correct. After the procedures for materializing the level of one factor, which were developed during the pre-experimentation phase, have been carried out, its impact on the other factors needs to be examined. Two situations occur frequently:

1. Interference between factors Uniformity and Location of DUS's C.M.

Given the nature of the DUS equation (see equation 4.3), an activity with a large duration is likely to have a high DUS. Thus, when splitting one large activity into several sub-activities in order to achieve uniformity of durations, the location of DUS's C.M. might shift in proportion to the change in the level of factor D (Loc. of DUS's C.M.).

2. Interference between factors Density of Ties and Parallelism

When adding ties to obtain a higher level for factor C, activities later along the time line which were parallel might become partially or even fully lagged. The opposite affect may also occur, giving activities previously not parallel a certain degree of parallelism. Thus, the level of the factor B (Parallelism) might be altered.

Another point to be kept in mind is that the procedure for setting the level of parallelism between activities, which was described in section 5.3.6.2, always adds ties, thus increasing their density. In the experiments carried out here, the number of ties added for this purpose was kept below 3. This level was experimentally proven not to alter the results.

5.3.6.4 Analysis Phase

In this phase, the results obtained from simulation were sorted and analyzed. The *Lower is Better* quality characteristic in question, together with the fact that interactions between factors should be continuously observed, indicated that the plotting methods previously described in section 5.6.1.3 should be used for the analysis of the results. It was not necessary to label the X-axis of the graphs with ratings; the X-axis could instead be labelled with the value of the variance obtained.

These methods have the advantage that they show the interactions between factors through parallel lines in the graphs. They are also particularly simple to prepare and analyze.

The percent contribution of each factor was also calculated, both for the purpose of achieving the objectives set in section 5.3.2 and in terms of the levels for the best solution determined. These were validated using a confirmation experiment, as shown in Fig. 5.9.

It proved to be unnecessary to determine the optimal solution or confirm the experiment in order to define the optimization method. This is because the optimization method is instead based upon the comparison of trends and the percent contributions of the factors and their levels. It is, furthermore, validated in 4 real schedules. However, in order to fully demonstrate the Taguchi method, these two steps are presented for the first work project (Plant).

A comparison of the percent contribution of the different factors and their levels was also carried out, also using plotting methods and bar charts. The purpose of this comparision was to evaluate the relative importance of each factor in different topology scenarios in order to determine:

1. If, and under what circumstances, their weights are relevant in practical utilization
2. If their importance depended of the topology scenario, i.e., whether their effect was global (scenario independent) or local (scenario dependent)

Finally, the results and conclusions obtained were gathered in the *DDA* schedule optimization method. This method is characterized by a first improvement step, consisting of a body of scheduling conception and analysis principles and rules, and a second optimization step, consisting of the definition of a focused simulation scope and procedure, allowing a simple and expedite application in practice. A detailed description of *DDA* is given later in section 6.2.

5.3.7 Results

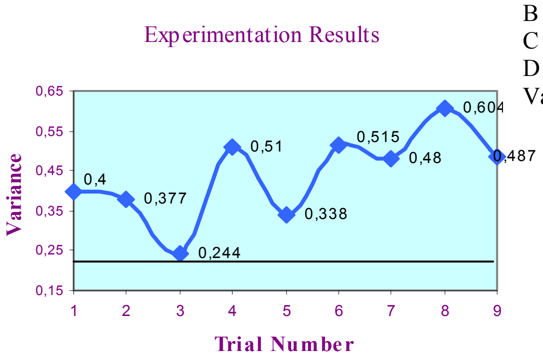
This section presents the final results of the experimentation phase, that is, those from which final conclusions concerning the experimentation with the work projects can be drawn. It does not include the results of the validation phase. The average effect of the factors at their different levels, represented in the graphs below, was calculated as described in Ross (1996).

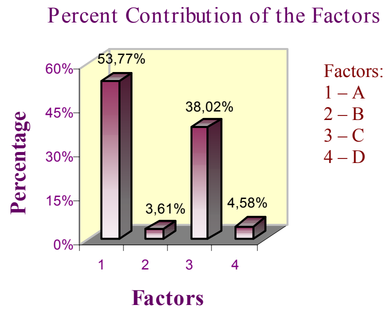
Project Plant

Optimal solution:

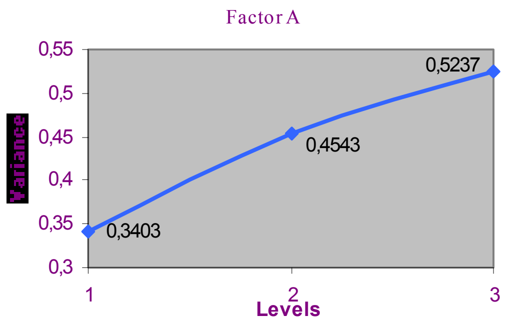
Factor	Level
A	1
B	3
C	3
D	1

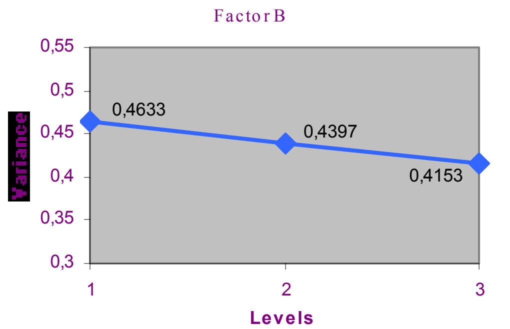
Variance: 0,226

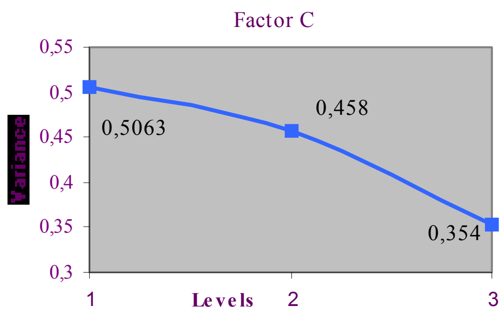




Average Effect of the Factors at their Different Levels:







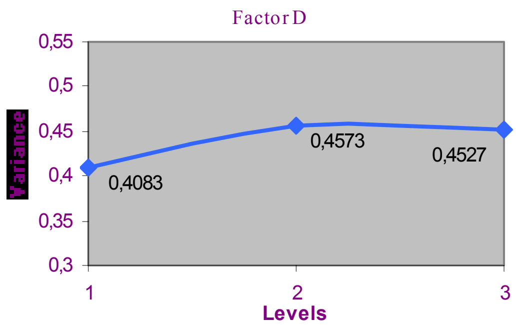
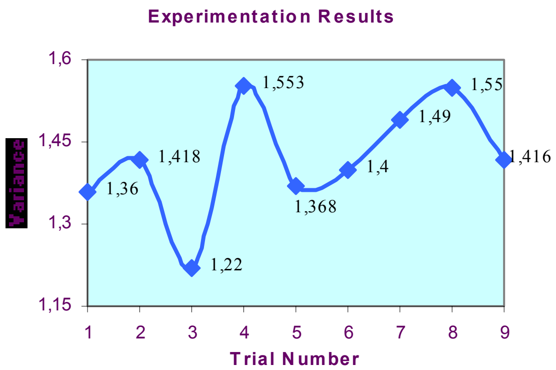
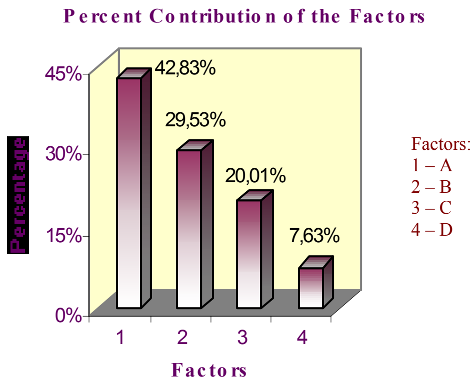


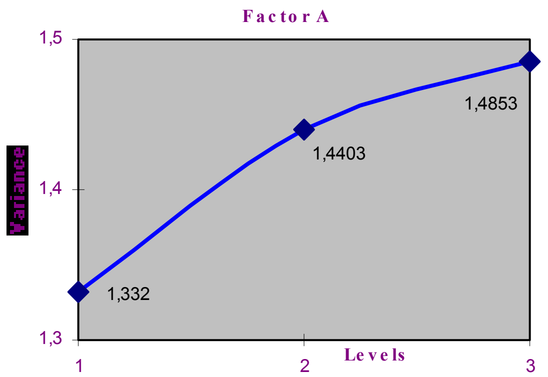
Fig. 5.12: Project Plant – Experimentation Results

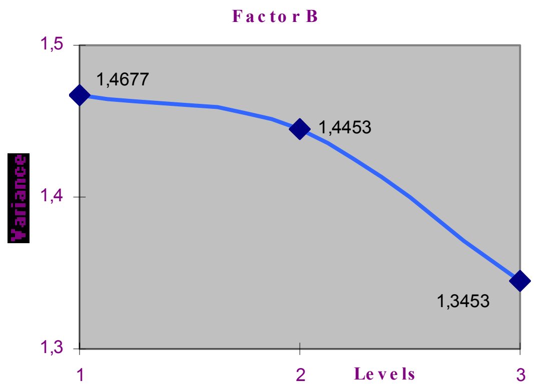
Project Towers

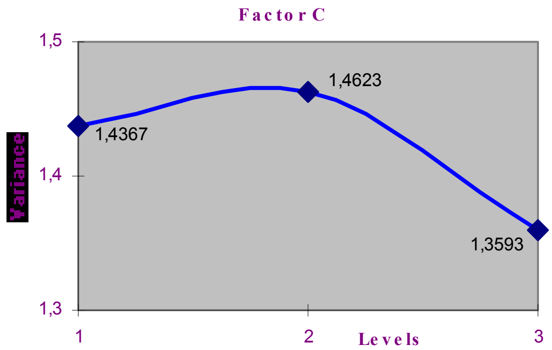


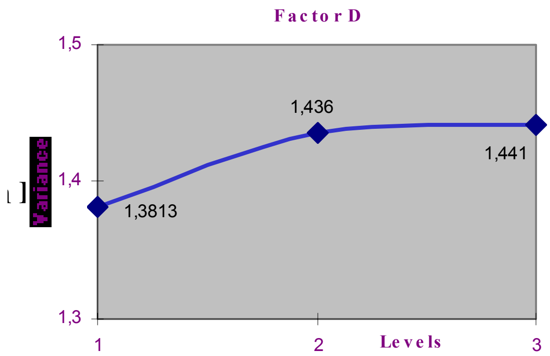


Average Effect of the Factors at their Different Levels:

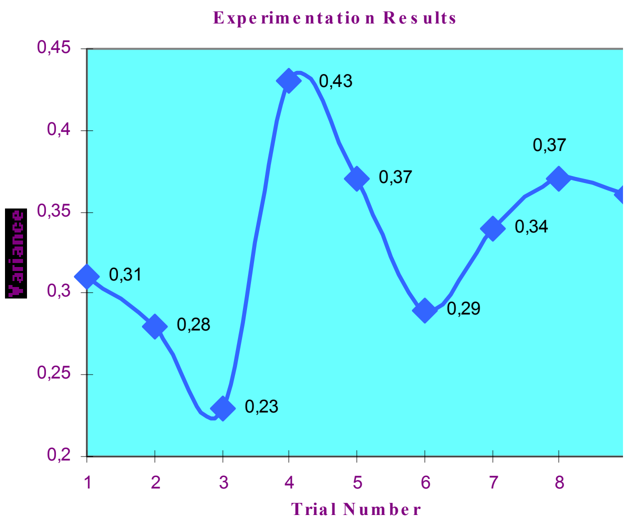


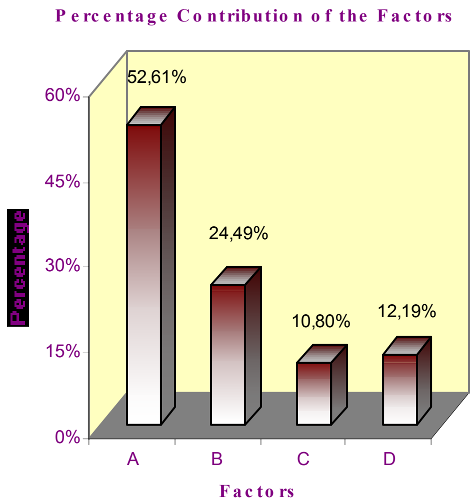




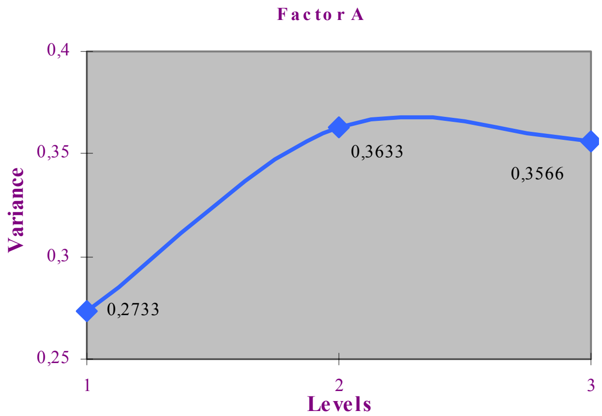


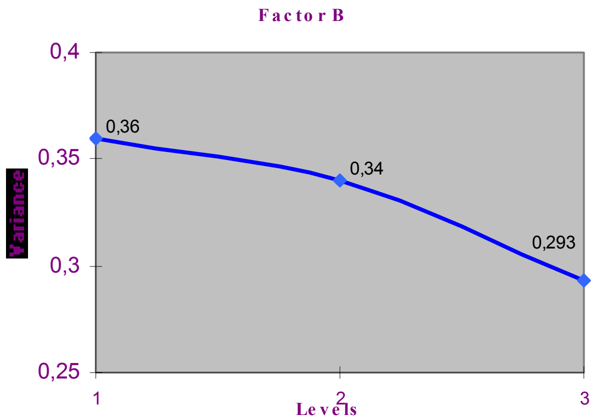
Project Tanks

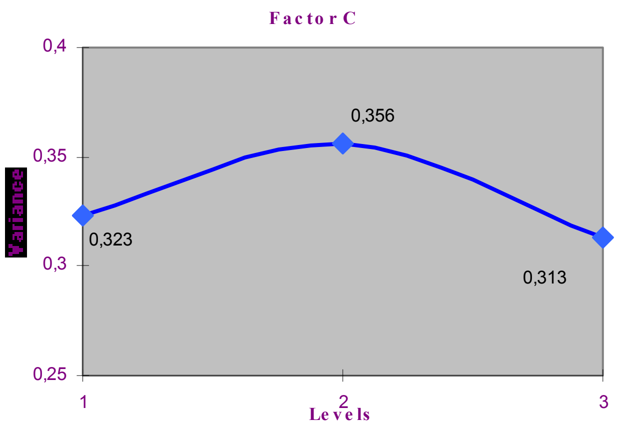


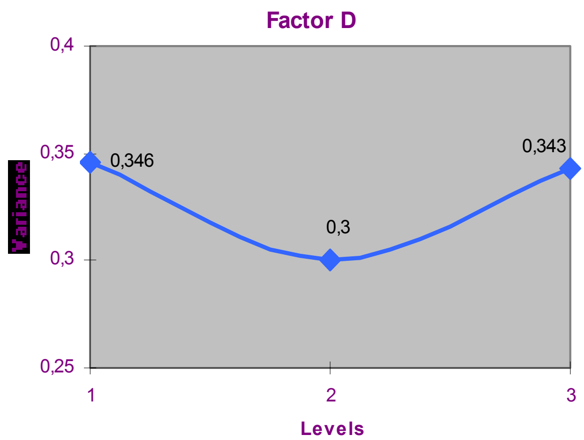


Average Effect of the Factors at their Different Levels:









The percent contributions indicated underneath and further on were calculated according to Ross (1996), (p.146 ff.). So that they can be better seen, the values obtained were summarized in the graphs below.

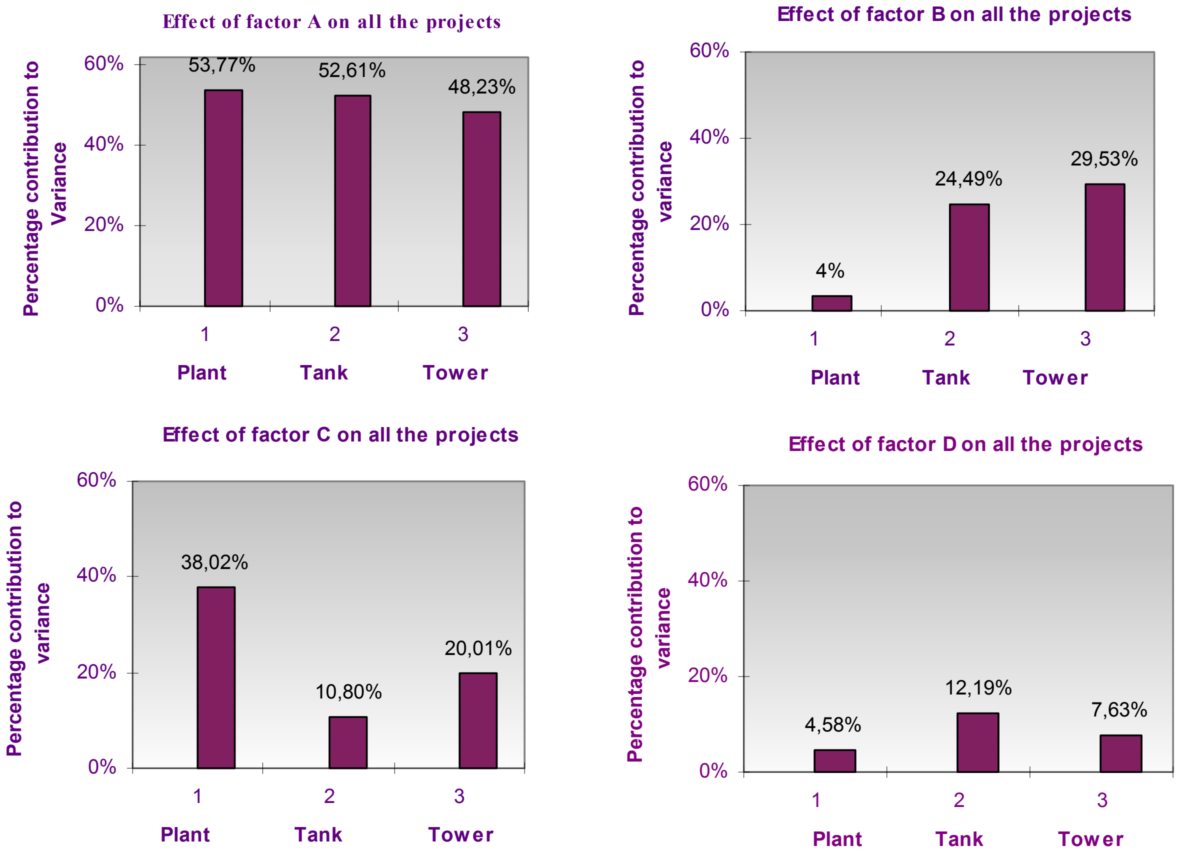


Fig. 5.15: All Projects – Comparison of Factor Effects

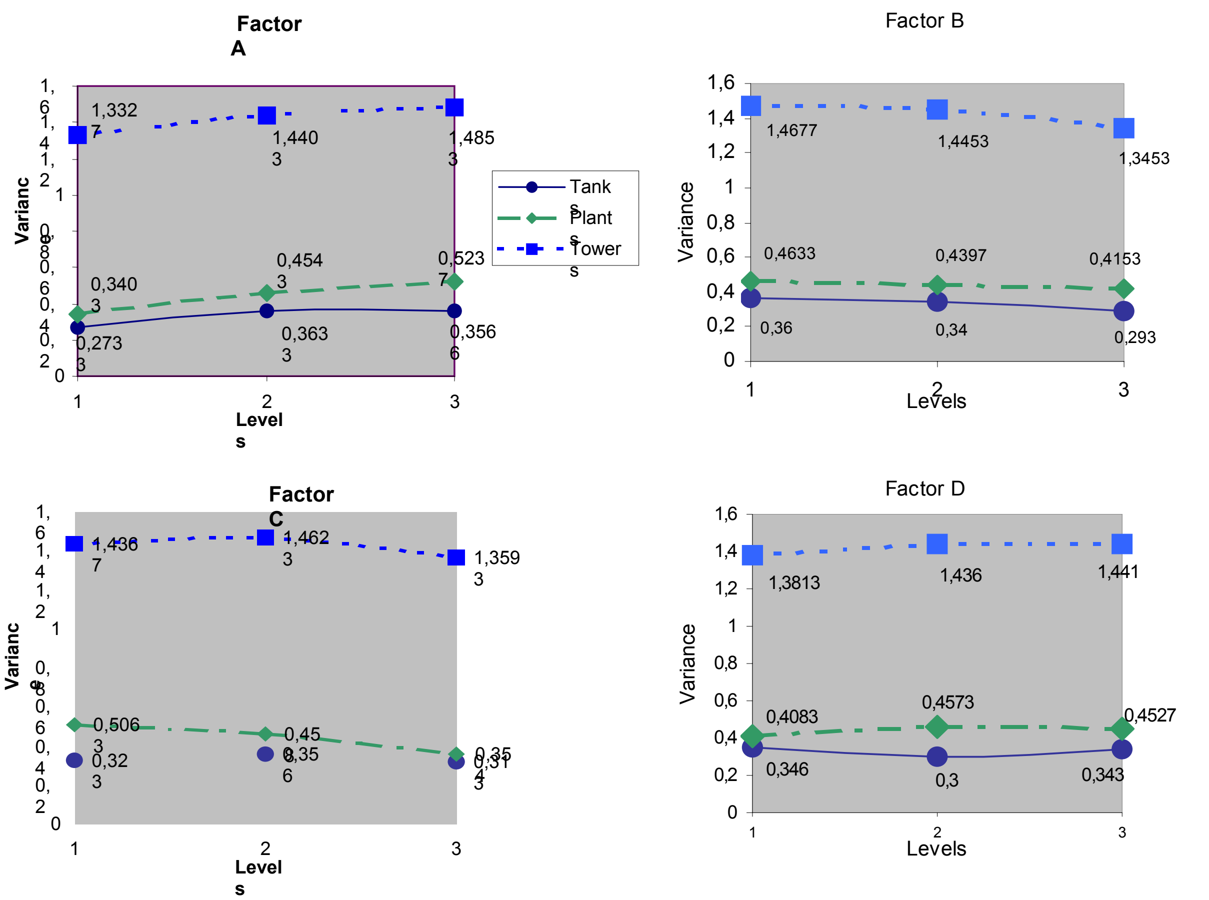


Fig. 5.16: All Projects: Comparison of Level Effects by Factor and Project

A comparison of the effect of the different levels on the variance within one factor and project was presented previously. The same comparison for the effect of the different factors in all the projects is presented in Fig. 5.16 above. The trend curve visualization was calculated according to a plotting method described previously, thus clarifying how the factors are changing the response.

5.3.8 Observations and Conclusions

The curves of all factors follow the same trend in the different projects. This confirms that the factors and levels chosen are relevant and do produce results. It also proves that the resistance of complex, reality-based schedules to uncertainty can be improved. Thus, taking the definition of robustness given by Taguchi, it was proven that the schedules can be made robust. This justified the utilization given to the method in this context.

The factor “uniformity” (factor A) proved to have the strongest effect, with percent weights around 50%. The most visible effects occur for level 1, corresponding to full uniformity of durations. Levels 2 and 3 do not differ significantly from each other.

However, it should be stressed that this does not mean that the optimal solution involves making the durations of all activities uniform. This factor only affects the activities with the highest DUS values, which proved to be the ones that produce results. Other experiments were carried out where up to 33% of the activities, regardless of their DUS, were made uniform. There was no significant change in the improvements obtained. In some cases, excessive utilization of this effect proved to have negative effects, as mentioned later in section 6.3.1.2.

In practical terms, this effect serves as an indicator, showing where the schedule has to be detailed and to what degree.

Parallelism showed the biggest dispersion of percent weights, varying from 4,00% to 29,53%. This indicates that, unlike factor A, the effects of factor B strongly depend on the characteristics of the project being optimized.

Level 1 (full parallelism) consistently produced the worst results. The performance increases for level 2, but the best results are achieved at level 3 (half parallelism).

The percent weight of factor C varied from 10,80% to 38,02%. This factor has the second highest importance overall. The variance consistently decreases when increasing the density of ties (shifting from level 1 to level 2, and then to level 3).

Factor D has the lowest average percent weight of all factors. It averaged 8,13% on a range of +/- 4%. Thus, the effect of this factor is, like factor A, approximately constant for all projects. Level 1 shows the best results and level 3 the worst, but levels 2 and 3 don't differ as much as levels 1 and 2. Thus, schedules where the center of mass of the DUS is located at the beginning consistently produce the best results. Locating the center of mass of the DUS at the end of the schedule proved to provide the worst results.

5.3.9 Practical Application

Up to this point, the results presented have been exclusively descriptive. However, their potential for improving the quality of activity scheduling is clear. They reveal the mechanisms by which robustness to uncertainty can be achieved in scheduling. The author proposes that the results obtained in this chapter should be compiled into a broad range Computer Assisted Procedure for Delivery Date Assurance (DDA) for Activity Scheduling. This new method is presented, described, and validated in the next chapter.

6. Computer Assisted Procedure for Delivery Date Assurance

6.1 INTRODUCTION

The results obtained in the previous chapter showed that the factors chosen affect the schedules robustness in a constant way. They showed that certain schedule topologies consistently produce better results, allowing a group of scheduling principles and procedures to be created. These can be arranged into a 2 step schedule optimization method:

Step 1 – Improvement phase

No extra simulation is needed. The schedule is improved using the principles obtained. The end date is not changed (Fig. 9.2 and Fig. 9.4).

Step 2 – Optimization phase

The method provides a specific, small set of schedule topologies that need to be simulated in order to obtain further improvements. The end date is generally extended, so a trade-off has to be made between total project duration and its certainty (Fig. 9.3 and Fig. 9.5).

This allows for simple implementation on site. The scheduler is provided with a group of simple principles that assist him during schedule optimization. There is no need for designing experiments or for conducting long and complex simulations. The user, therefore, does not need powerful hardware or a background in statistics and the Taguchi method. The single requirement for its implementation is a working knowledge of how to use and read the data of MS-Project, together with knowledge of how to enter the input data for Simunet.

6.2 METHOD DESCRIPTION

DDA requires that the schedule topology first be observed and analysed. It guides the user through this process, emphasizing the important aspects and enabling a deep insight into the project. This preliminary work consists of the following 5 points:

1 - Identifying the target activities

The 4 to 6 activities with the highest DUS per parallel body of activities should be identified, as shown in Fig. 9.6. For this purpose, a stochastic information table should be prepared. An example is given in Tab. 9.1. This table should include the average duration of all activities with K > 0,6. This is easily achieved by importing the simulation data obtained from the columns of MS-Project to a spreadsheet, such as Excel. The number of activities that are taken into consideration depends on the their DUS values. Generally, a few activities have a significantly higher DUS, such that, only 4 activities are needed usually. However, if this is not the case, 5 or even 6 should be considered.

It should be kept in mind that increasing the number of activities considered does not necessarily increase the accuracy. It does, however, always increases the complexity and amount of work needed. Thus, utilizing more than 4 activities should be restricted to schedules with high uniformity of DUS values.

Once this is done, the location of the center of mass of the DUS should be obtained according to the method described in section 5.3.5.1.

2 - Uniformity of durations

Onc the target activities and the average duration of the activities with the highest K (AD) have been identified, the target activities with durations larger than 1,5 times the AD should be examined. They should be detailed and broken down into 2 or more activities having approximately the AD size. The effect of this detailing on the location of the center of mass of the DUS has to be evaluated, as described later, in section 6.3.1.2. This effect is visible in all schedules and was therefore classified as being global.

3 - Parallelism

Parallelism between target activities should be avoided. A delay in one of these parallel activities an generally be seen in the total project duration, since there is no room to absorb it. Full parallelism is always the worse situation, but the choice between half and zero parallelism has to be evaluated for each schedule individually. Thus, this factor is considered a local parameter.

4 - Density of ties

Increasing the number of connections between activities allows, for instance, resource to be levelled and the better coordination of activities. An example of this type of increase in interconnectedness would be the creation of a precedence tie between the processes of casting foundation slabs in different towers of the same project. This increases the density of ties while requiring a lower level of resources. Moreover, the level of parallelism is also decreased to zero. This has two positive effects: higher robustness and better resource management. However, it should be weighed against a possible increase in the total project duration. Its impact on the level of parallelism should also be examined, since in many situations, half parallelism provides better results than zero parallelism.

Configuring these factors demands a lot of attention, since this can affect other factors, the total project duration or create unrealistic plans. Moreover, the effect of this configuration strongly depends on the fundamental topology of the schedule, thus being project specific. It was classified local parameter.

5 - Location of the center of mass of the DUS

Although having been found to shown little percent weight, the effect of this factor is noticeable in all schedules. Locating the center of mass of the DUS involves identifying the location of the uncertainty in the schedule. If it is towards the end of the schedule, there is no room left for absorbing or recovering a delay. It will, therefore, necessarily impact upon the total project duration. Thus, when it does fall towards the end of the schedule, the reasons for this should be analyzed and corrected. This can be achieved in two ways:

- Detailing: looking at the activities in further depth and breaking them down into more detailed activities. This simultaneously increases the level of uniformity of the schedule, giving detailing two positive contributions.

- Removal of uncertainty factors: identifying the causes of the uncertainty in the activities in question and removing them. These can come in the form of an unreliable subcontractor or equipment, or the utilization of untested techniques or weather conditioned works. The solution, therefore, would involve changing the plan by replacing the subcontractor or planned equipment, or utilizing tested techniques or planning weather protection for the works in question, respectively. It should be noted that these measures should not be applied to the entire schedule indiscriminately, creating unrealistic or cost unsustainable plans. They are applied in a surgical manner, to a specific location were they are needed and produce the best results.

The algorithm for DDA is shown in the annex. It includes procedures for coping with the most common difficulties encountered when applying the method to real case studies. Thus, it is adjusted and ready for practical application.

6.3 DDA APPLIED TO REAL CASE STUDIES

DDA was validated using 4 real-life construction projects, based on the data stored at the time of their conclusion. Special care was taken to chose projects with different characteristics, such that, the flexibility of the methodology could be tested clearly.

The fundamental structure of the schedule determines the optimization that can be done. The nearer the schedule structure is to the optimal structure, the less its can be improved. Some of the validation schedules were already near the optimum topology for one or more factors. Thus, in these cases, the validation was done in reverse, that is, by "unoptimizing" the schedule. This meant applying the inverse of the methodology and observing the decrease in performance, measured by the increase of the variance. In these cases, the improvement values in the tables were given with a minus sign. Accordingly, a percent value of the real improvement and another for potential improvement are listed. The first corresponds to the percent improvement that the method can achieve for the fundamental structure given. The second respresents the percent improvement that could be acheived for a structure where all the levels of the different factors are at their worst. In order to make the process easier to follow, the method sequence shown in the *DDA* flowcharts (see the annex), was followed exactly. Thus, the improvement values indicated for step 2 correspond to the improvement achieved starting from the optimized structure at the conclusion of step 1, but taking, as reference for percent calculation, the variance value of the original structure.

Hence, if

$$\mathrm{var}_{Step1} = \mathrm{var}_{original} - \mathrm{Im}_{Step1} \tag{6.1}$$

then

$$\mathrm{Im}[\%]_{Step1} = \frac{\mathrm{Im}_{Step1}}{\mathrm{var}_{original}} \times 100 \tag{6.2}$$

where

Im = improvement in the variance value and

var = total duration variance of the project simulated

Accordingly,

$$\mathrm{var}_{Step2} = \mathrm{var}_{Step1} - \mathrm{Im}_{Step2} \tag{6.3}$$

$$\mathrm{Im}[\%]_{Step2} = \frac{\mathrm{Im}_{Step2}}{\mathrm{var}_{original}} \times 100 \tag{6.4}$$

6.3.1 Validation project 1: Bridge over the Lister Dam

6.3.1.1 Project Description

This project consists of the construction of a 186,70m long concrete bridge and its accesses. The pilars are erected to a total height of approximately 12,00m above foundation, and to a maximum of 2,30m above maximum water level. The contracted maximum total project duration was 380 work days.

The fundamental schedule structure is shown in Fig. 9.11. It consists of 84 activities, divided into 2 main, parallel groups. There are 2 major activities and 3 groups of smaller, but nonetheless important activities. These make up the top 5 ranking of the DUS. The AD value is approximately 22 work days. Given that 0% represents the begin and 100% the end of the schedule, the 2 major activities place the location of CM of DUS at a relative location of 56,2%, thus corresponding to a factor D level 2 topology. The two major activities are around twice as big as the other target activities, thus profiling a topology of factor A at level 3. There is parallelism between target activity 1 and the group of activities that correspond the target activities 5, thus the factor parallelism exists but is not expressive.

Since the K degree of the activities in this schedule is either 0 or 1, that is, consistent with the classical model of constant critical path, increasing the density of ties would mean connecting non-critical activities to the critical path and is therefore irrelevant. Hence, factor C does not have the ability to optimize this schedule.

An interesting feature of this schedule is the fact that, due to the linearity of its schedule bodies, it consists almost exclusively of rows of activities (sequence of activities with finish-to-start ties) without cross ties to other groups. In such a topology, any change in the level of uniformity will have a direct and visible impact in the CM of DUS location. This represents an ideal case study for the combined effect of uniformity and CM of DUS's shifting. This study was carried out and the ideal balance for this schedule found.

6.3.1.2 Combined Effect of Uniformity and CM of DUS Shifting

Method Statement

The study is carried out based on *DDA*. The fundamental structure was entered, simulated, and the simulation data imported to a spreadsheet, where the stochastic information table was prepared and AD calculated. The top 5 DUS activities (target activities) were then identified. In this case, activities ranked 1st and 2nd are individual, whereas those ranked 3rd, 4th and 5th consist of clusters of activities sharing approximately the same DUS. The CM of DUS location was determined.

For this specific study, the location of the CM of each target activity or activities cluster was also determined. This was done by obtaining the average between average start and end date (for the clusters start and end dates), as indicated in the schedule output of *Simunet*.

The simulation strategy consisted of splitting the target activities from the end to the beginning of the schedule. Since target activity 2 is the last in the schedule, it was the first to be split. Note that this does not correspond to the DDA, which indicates that the first activity to be split should be target activity 1. The schedule obtained was named "Uniformity Step 1" and its variance obtained through simulation.

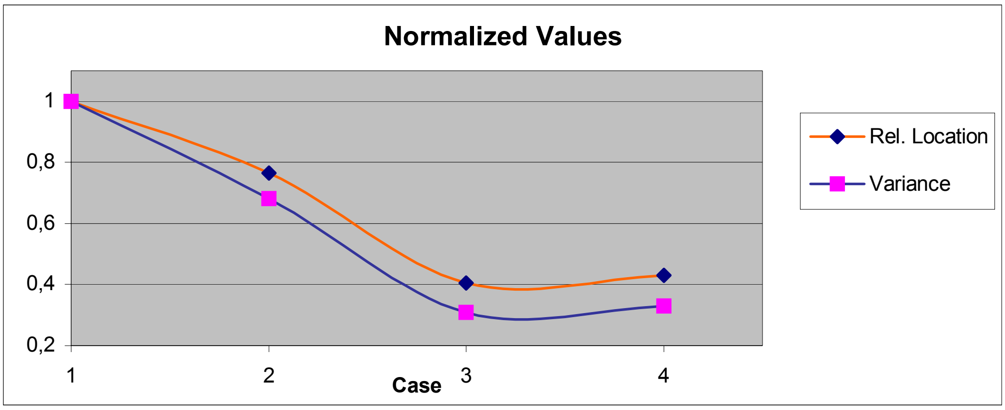
The second step consisted of splitting the second last target activity. Again the variance of the schedule obtained was recorded and the schedule named "Uniformity step 2".

This procedure was repeated again for target activities 3.

In each case, the CM of DUS relative location was calculated. Taking the original variance and CM of DUS relative location as unitary reference, the values obtained for the 3 cases simulated were normalized. This makes the comparison of values with different units possible. Thus, a comparative trend diagram was created and the trend of its curves examined and compared. The gap between the curves was calculated. All values mentioned were arranged in the table given below.

Results

Activitiy's DUS Ranking	1	2	3	4	5	CM of DUS	Rel. Location	Variance	Gap
Activitiy's DUS Value	307,8	252	126	112,73	100,25				
Case									
Original	14,3	20	4,5	10	15,5	12,308	0,562	0,933	0,0%
Unif. 1	14,3	0	4,5	10	15,5	9,425	0,430	0,636	8,4%
Unif. 2	0	0	4,5	10	15,5	4,998	0,228	0,289	9,6%
Unif. 3	0	0	0	10	15,5	5,293	0,242	0,307	10,1%



Note: The values in the 2nd to 6th columns indicate the CM location of the respective target activities. A zero means that the activity has been split. Split activities cease to be a target activity and are therefore not considered in the calculation of the CM of DUS.

Fig. 6.1: Combined Effect of Uniformity and CM of DUS Shifting – Comparison of Trends

Observations and Conclusions

The two lines in the graph follow the same trend. This proves that:

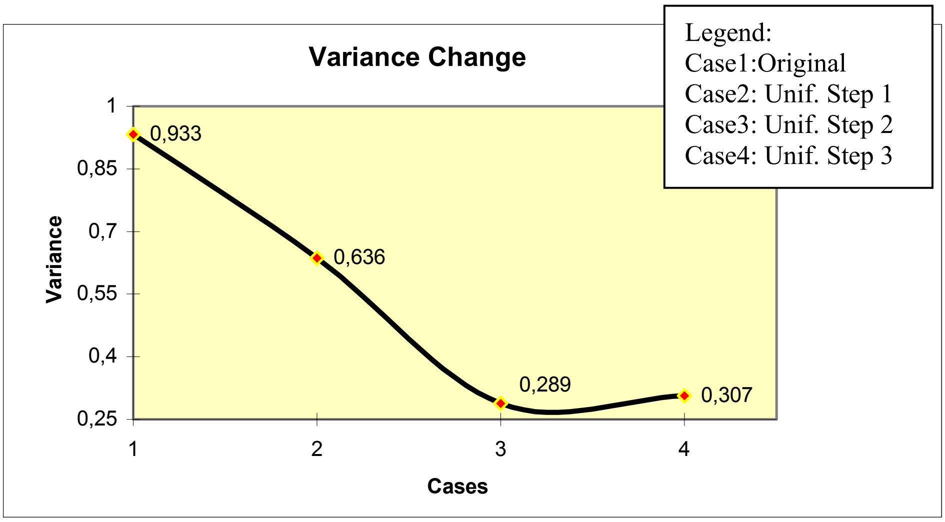
1. Shifting the DUS's CM to the beginning (lower values) does decrease the variance.
2. Increasing the level of uniformity by splitting activities with high DUS is effective in reducing the variance, but the impact of doing so on the CM of DUS location has to be taken into consideration. Otherwise, the results might be counterproductive (see Case 4).

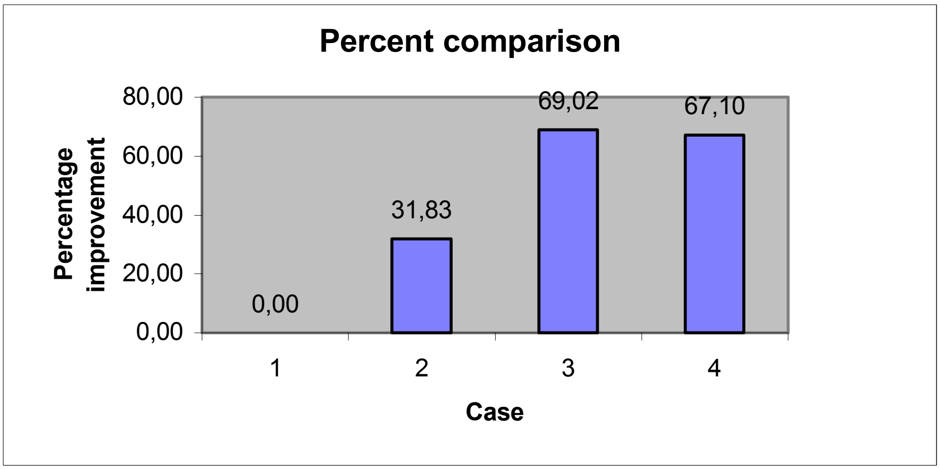
However, the gap between them increases (see last column in the table). This is due to the fact that not only the CM of DUS is being shifted, but the uniformity is also being increased. Hence, when comparing case 3 and 4, the variance follows the increase of the relative location, but since uniformity increased as well, the gap between the two lines also increases.

6.3.1.3 Results

Description	Variance	% Improvement
Original	0,933	
Global Parameters		
Unif. Step 1	0,636	31,83
Unif. Step 2	0,289	69,02
Unif. Step 3	0,307	67,10
Project specific parameters		
Ties		
Level 2	N.N	
Level 3	N.N	
Parallelism		
Full	1,017	-9,00
Half	0,977	-4,72
None	0,885	5,14

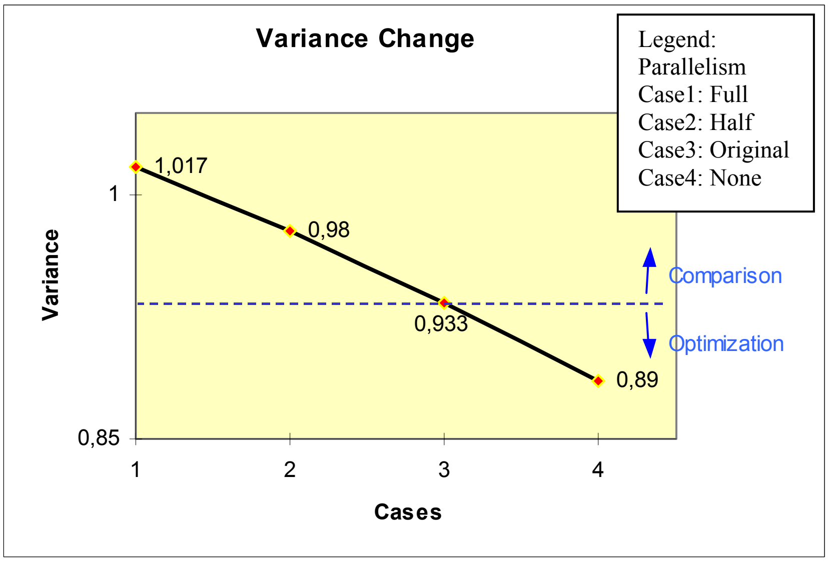
Step 1: Global Parameters – Uniformity and CM of DUS location

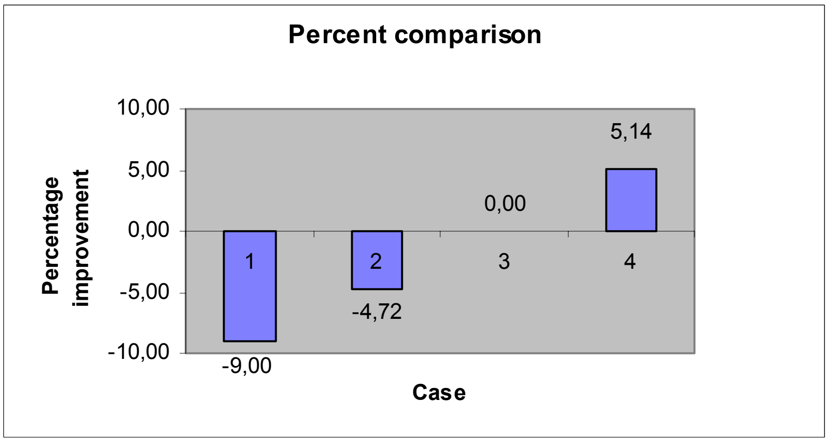




Real improvement: 69,02%
Potential improvement: 69,02%

Step 2: Local Parameters – Parallelism





Real improvement: 5,14%
Potential improvement: 14,14%

6.3.2 Validation Project 2: Federal Ministry of Telecommunications

6.3.2.1 Project Description

At the beginning of the 90's the German government called for bids for the construction of a new building for the federal ministry of telecommunications in the old capital Bonn. The main building has a total construction volume of 235 000 m3 on an plan area of 67 000m2. There are 3 parking levels with 450 places. The biggest dimensions of the building are: length – 230m, width – 190m. The main body of the building is 6 stories high and splits into two administrative wings, northwest and northeast. The height of the wings range between 4 and 6 stories. A yard with one underground level connects both wings.

The fundamental schedule structure is shown in Fig. 9.6. It consists of 85 activities, divided into 3 parallel schedule groups of 31, 27 and 27 activities, respectively. More than 50% of the DUS is concentrated in 4 activities, namely activity numbers 54, 39, 37 and 86. These make up the set of target activities in ascending order, as mentioned. The CM of DUS is located towards the early end of the schedule due to the location and high relative value of DUS of target activity 1. Thus, this schedule serves as a case where a well chosen uniformity increase will shift the CM of DUS location further towards the beginning. However, to stress and separate the effect of these 2 factors, a first experiment was done where the CM of DUS location was shifted towards the early middle by exchanging the stochastic data of target activities 1 and 2 (experiment "DUS middle"). A second experiment was also carried out with the original schedule structure where all target durations were split (experiment "Uniformity"). Both values were compared.

The optimization phase was conducted based on the best solution obtained in step 1 of the method (experiment "DUS middle + Uniformity"). This is represented in Fig. 9.7. The increase in the density of ties was achieved in two steps:

1. by connecting slabs ("Bodenplatte" and "Decke U2") in one schedule body to walls and columns (Wände/Stützen) in the following body, for a total of 2 pairs of ties (Fig. 9.8)
2. by connecting slabs and columns back to slabs ("Decke U3") in the previous schedule body, also for a total of 2 pairs of ties (Fig. 9.9)

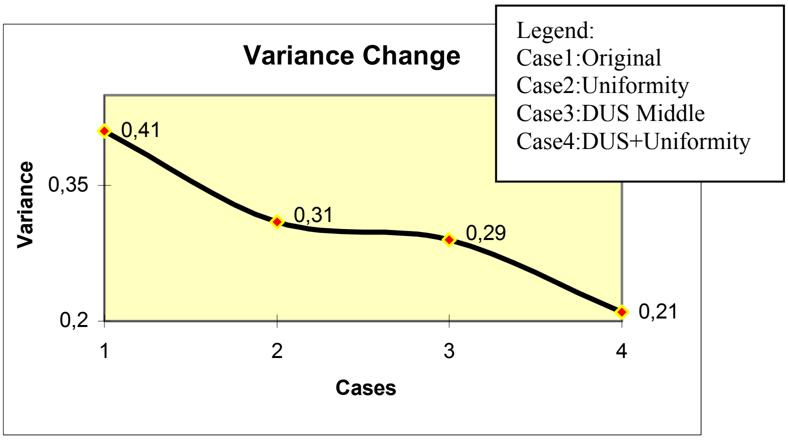
In this way, the second step has not only a higher density of ties, but also a crossed mesh of ties. The ties added would correspond to a resource management policy in practice, such as sharing concrete pumping equipment.

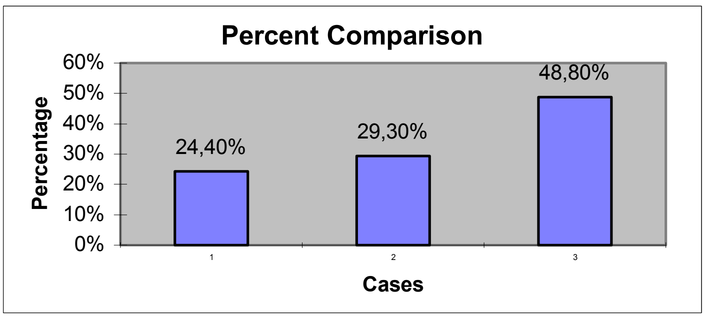
There was no scope for increasing the parallelism with real meaning, so target activities 2, 3 and 4 were simply made full and half parallel, regardless of their real-life meaning. This is shown in Fig. 9.10.

6.3.2.2 Results

Description	Variance	% Improvement
Original	0,41	
Global Parameters		
DUS Middle	0,29	29,3
DUS Beginning	N:N	
Uniformity	0,31	24,4
DUS Middle+Uniformity	0,21	48,8
Project specific parameters		
Ties		
Level 2	0,275	-15,8
Level 3	0,254	-10,7
Parallelism		
Half	0,317	-26,1
Full	0,323	-27,6

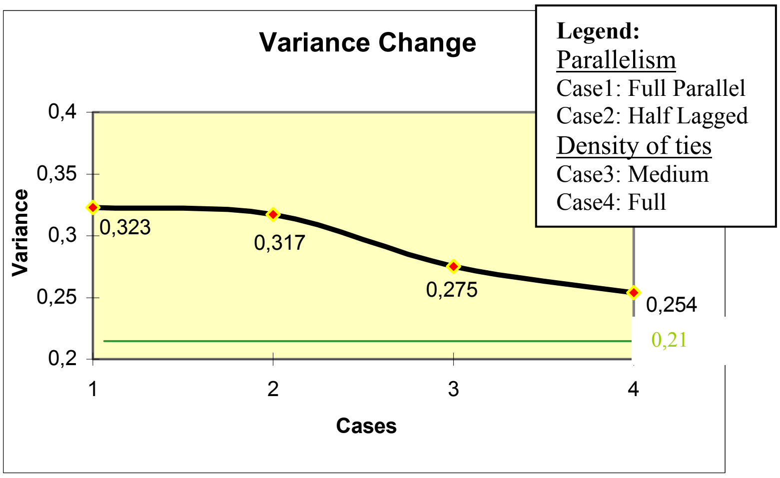
Step 1: Global Parameters – Uniformity and CM of DUS location

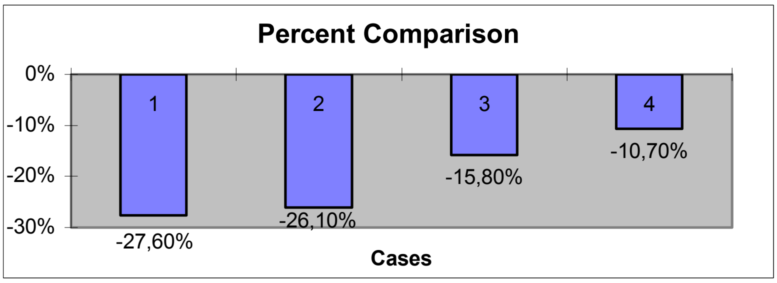




Real improvement: 48,80%
Potential improvement: 48,80%

Step 2: Local Parameters – Parallelism and Density of Ties





Real improvement: 0,00%

Potential improvement: 27,60%

6.3.2.3 Comments

The improved structure obtained at the conclusion of step 1 has an CM of DUS location at 35,82% along the time-line, that is, it is almost at the beginning (first third). This represents a very favorable topology. When increasing the density of ties according to the improved structure obtained from step 1, the CM of DUS gets shifted to a 42,97% location, thus further towards the end of the project. The positive effect of the local parameter (Increase in the density of ties) is overshadowed by the negative effect of the global parameter (CM of DUS location) and the variance increases. However, increasing the density of ties in this new structure again, to obtain experiment “Ties 3” (case 4), significantly increases the density of ties, causing the variance to decrease compares with case 3, even though the CM of DUS location is also shifted further towards the end of the project, that is, to a location of 57,19%. This confirms the expected trend for the effect of increasing the density of ties.

Since the factor parallelism is at its optimum level for the fundamental structure of the schedule, the validation of this effect was carried out on reverse, that is, by "unoptimizing" the structure, as described in section 6.3.3 below. The results confirm the expected trend.

6.3.3 Validation Project 3: New Convention Center of Munich

6.3.3.1 Project Description

This project involves of the construction of a new city convention center in Munich in Bavaria, Germany, on a total area of approximately 90ha.

The schedule studied only deals with the first part of the construction, which includes the following works:

1. Two aligned wings with a total area of 292 500m2

2. One administration and meetings building west of the main wings, with a total area of 54 000m2

3. Support service building and small wing, east of the wings, with a total area of 36 000m2

The fundamental structure consists of 48 activities divided into 8 groups of 6 activities. These groups run parallel and have an intricate and very dense mesh of ties between them, as can be seen in Fig. 9.12. The activities show K degrees of either 0 or 1, making the fundamental structure a case of classic constant critical path. This was changed by the interventions in this study. The K values of several activities became intermediate.

The target activities (activities # 13, 19, 25, and 31) are all parallel and concentrated at the beginning of the schedule. Thus, this schedule shows the following characteristics:

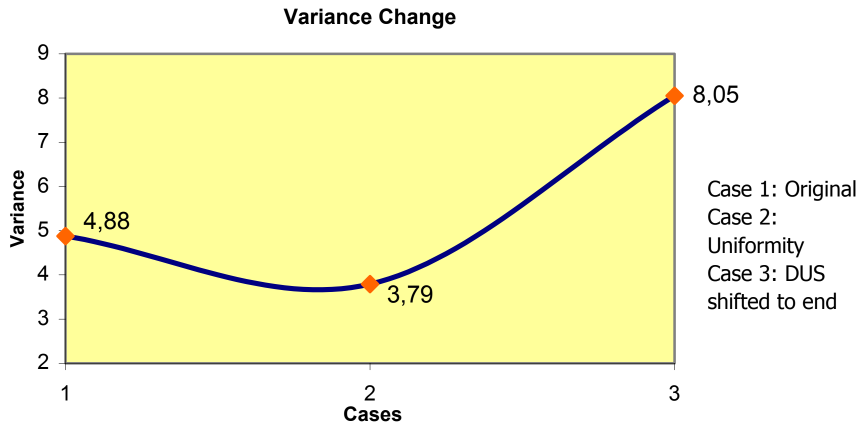
1. High, although not full, uniformity of durations
2. CM of DUS located at the beginning
3. Full parallelism
4. High density of ties

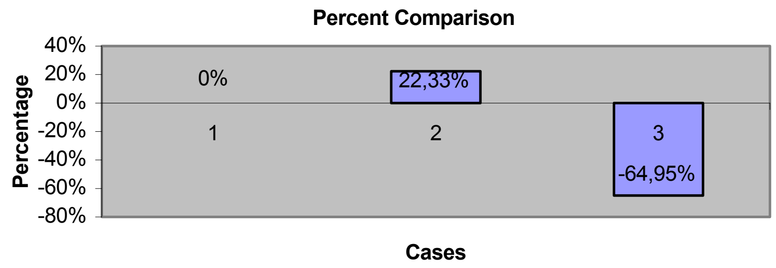
Although factor parallelism provides a high potential for optimization in this schedule, the dense mesh of ties makes it impossible to decrease the level of parallelism without decreasing the density of ties. Since these two actions have opposite effects and this schedule has a pragmatically high density of ties, the decision was made to manipulate this last factor only. Since the density of ties is very high, the validation will be done in reverse, that is, by "unoptimizing" the structure, decreasing its density of ties stepwise.
The location of the CM of DUS at the absolute beginning of the schedule also makes it possible to shift the CM of DUS to the end of the schedule, that is, again "unoptimizing" the schedule, for the sake of illustration.

6.3.3.2 Results

Description	*Variance*	*% Improvement*
Original	4,88	
Global Parameters		
Uniformity	3,79	22,33%
DUS at End	8,05	-64,95%
Local Parameters		
Uniformity+Ties 2	4,132	-7,01%
Uniformity+Ties 1	4,01	-4,15%

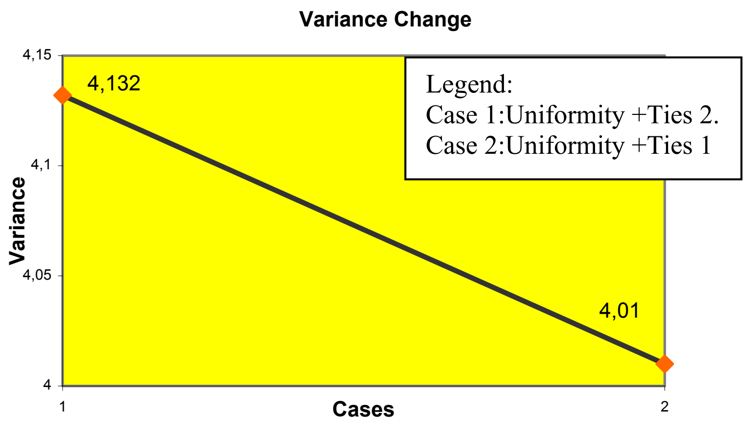
Step 1: Global Parameters – Uniformity and CM of DUS location

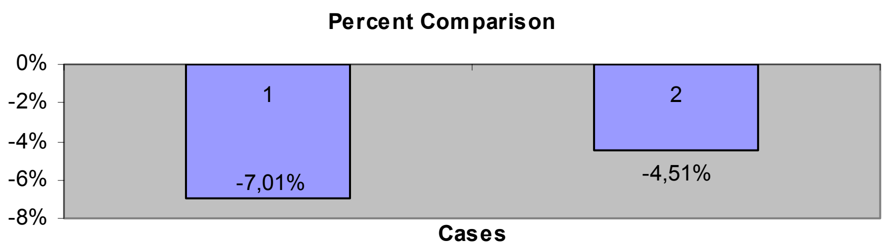




Real improvement: 22,33%
Potential improvement: 87,28%

Step 2: Local Parameters – Parallelism and Density of Ties





Real improvement: 0,00%
Potential improvement: 7,01%

6.3.4 Validation Project 4: Workshop for handicapped in Rastenberg

6.3.4.1 Project Description

This project involves the construction of a one-story workshop for the handicapped with an approximate total construction area of 60 X 66 m2. It includes excavation, the construction of the building, and outfitting the facility with all the necessary installations and equipment.

Unlike the previous validation projects, validation project 4 is a typical small construction project, covering all the trades and installations of a building. Its construction segments are not clearly separated, but are rather sequential and linear along the construction process.

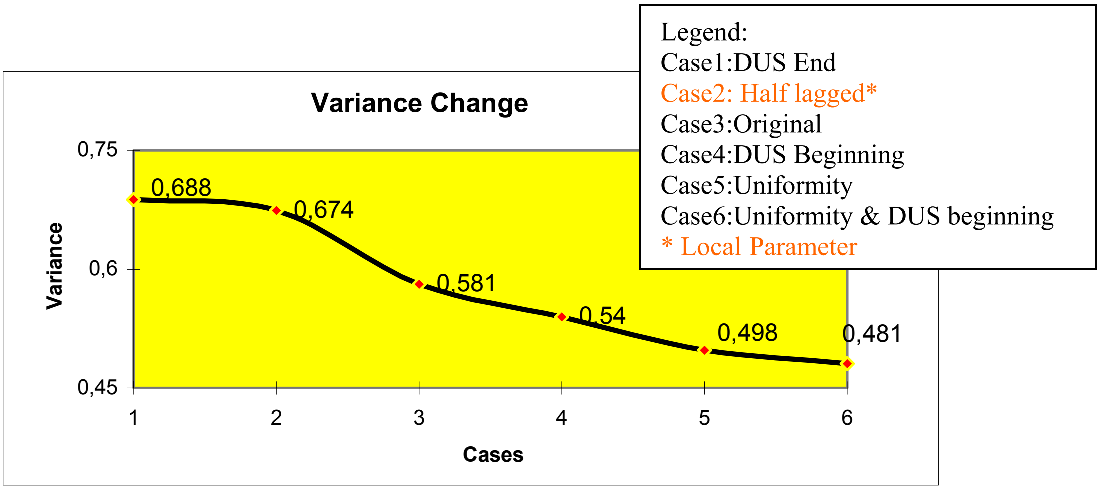
The schedule consists of 90 activities with a large number of small activities at the beginning of the project. The ties mesh is intricate, and the larger activities are concentrated at the late-middle of the project.

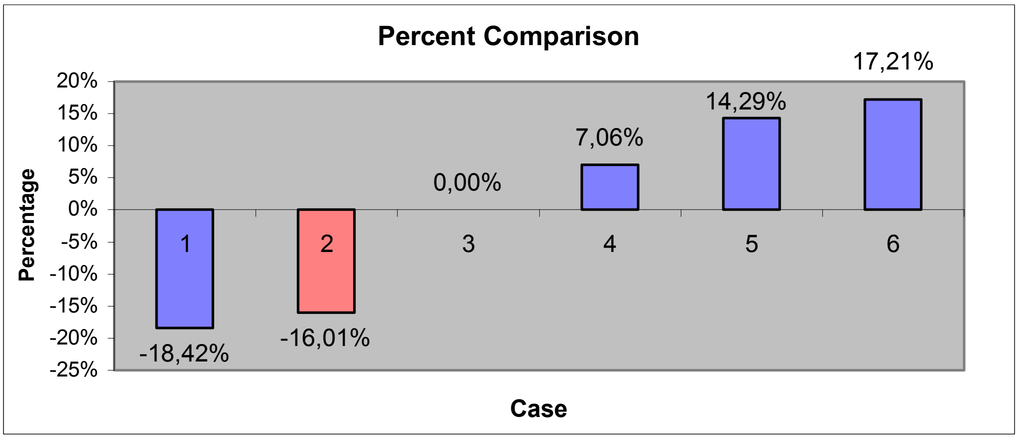
This project is intended to mark the boundaries for the application of DDA, since it does not fit into the typical cases for which DDA was developed.

6.3.4.2 Results

Description	Variance	% Improvement
Original	0,581	
Global Parameters		
DUS Beginning	0,54	7,06
DUS End	0,688	-18,42
Uniformity	0,498	14,29
DUS Beginning+Uniformity	0,481	17,21
Project specific parameters		
Parallelism		
Half*	0,674	-16,01
Full	N.N	

Steps 1 and 2: Global and Local Parameters





Real improvement: 17,21%
Potential improvement: 35,63%

6.4 POSSIBILITIES AND LIMITATIONS

The validation process showed that the method developed is effective in reducing the uncertainty of the total project duration for a set of projects with a wide range of characteristics and fundamental structures. It stressed the importance of the structure in determining the impact of the duration uncertainty of its activities on the total project duration. The validation strategy, which involved optimizing schedule structures with inconvenient topologies and “unoptimizing” fundamental structures that were nearer to the optimized solution, showed the potential and limitations of the method proposed; there is, in fact, one improved structure for each schedule, and the optimization potential corresponds to the difference/distance between the fundamental structure and the improved structure. The real improvements due to optimization ranged from the 17,21% found for validation project 4 to the 74,16% found for validation project 1. All schedules tested, including the 3 work schedules, could still be improved.

The weight of the different factors in the optimization potential obtained in chapter 5 was confirmed by the validation results. Support was also found for the two step optimization approach using global and local parameters.

The procedure based on global parameters, that is, step 1, which took the interaction between factors into consideration, always produced improved schedules. Step 2 optimization, on the other hand, which was based on local parameters, required more attention and experimenting different possibilities. These are nevertheless limited to a small number, always less to 5, which is, therefore, significantly lower than the 9 trial tests required by the Taguchi method. Moreover, the Taguchi method requires trials with schedule structures that are sometimes unfeasible in practice, whereas the method developed centers simulation on a few specific, feasible schedule structures. The best solution obtained can be applied directly, without needing to check its practical applicability in advance.

The method does require basic qualification in scheduling, but is independent from the scheduler's amount of previous experience and empirical knowledge. It provides a structured, systematic procedure to obtaining optimized solutions for any schedule at hand.

Although it can be applied to any schedule, there is a range of projects where the method produces best results. It is ideally applied to schedules with a wide variety of activities durations, a high degree of activity parallelism, and a large number of activities with intermediate K degrees (lower than 1 and higher than 0), that is, schedules with a floating critical path, low interconnection between different schedule bodies or activities, and with schedule uncertainty concentrated towards the end of the project. These conditions are typically found in large scale projects with large construction areas. In these cases, the site is generally divided into sub-areas, operating with similar, parallel schedule bodies with low physical interconnection. The ties between them depend on the scheduling strategy adopted. These scheduling strategies can be either resource driven or time driven, or, as proposed in this work, modelled according to delivery date assurance driven optimization. Due to the complexity of the interactions between stakeholders and the high level of uncertainty involved, the activities in these schedules tend to have intermediate K degrees. Since many and different tasks are required, large scale projects typically have a wide range of activities durations, thus presenting all the necessary conditions for the effective application of *DDA*.

7. Revelations and Open Fields of Research

The methodology developed has proven to be applicable to real cases. This is an important condition, but it is not the only one. Other conditions exist that limit the applicability of this new procedure. At this stage, a cost-benefit analysis is particularly pertinent.

The advantages of DDA and the need for such a methodology have already been addressed. However, the appliance of DDA to construction projects in progress is necessarily associated with some effort and obstacles.

As all new methods, DDA implies getting acquainted with new a set of concepts, procedures and operations. Its touchstone, the principle of process optimization as it applies to the schedule structure, is new and needs to be accepted by the user. Many high class, experienced schedulers maintain that the frequent progress update and rescheduling strategy is truer to the unpredictability of reality. This point of view is understandable. However, following this line of reasoning to the extreme, one could equally question whether or not it makes sense to make a schedule at all. Uncertainty brings about change, and one of the objectives of planning is to minimize the negative consequences of this change.

This work is predominately engineering in nature. Thus, it uses science and mathematics to achieve practical results. It should be applied with the least possible difficulties and costs to produce the best results and the highest profit. The methodology developed is based on the broad concept of simulation and optimization principles accepte by the scientific community worldwide, namely, stochastic simulation and the robust design process. The final computer assisted procedure was validated and produces results which can be applied and used with a minimum degree of complexity.

Nevertheless, the application of DDA requires training and familiarisation. It also requires extra time and effort in gathering the information necessary to construct duration uncertainty data and entering it into the software application.

Other limitations to the application of DDA include the costs of hardware and software. The first are negligible; computers are ubiquitous tools for any medium and large scale construction site and the requirements of MS-Project and the Simulation software are modest in comparison to other software programs commonly used today. Simunet and DDA are still prototypes for academic research. Neither author has estimated how much the product licenses for these tools might be. At present, therefore, the only quantifiable cost is that for the license for MS-Project.

Another major limitation is the investment in time necessary to train an operator, specialized in the effective use of the methodology proposed. It has been estimated that a user takes on average 2 to 3 weeks to become productive with a new software tool.

On the other hand, DDA and its associated software offer several benefits. Increasing the certainty of the delivery date is synonymous with less delays, thus it:

- decreases time dependent costs
- decreases the risk of penalties for non-conformity with the contract and capital costs by the investors
- increases the credibility of a schedule, since it gives the project manager or contractor strong support when defining its activities durations, sequencing and, above all, its total project duration.

As a whole, the benefits and limitations of using DDA should be consider with the context of each concrete case. Nevertheless, even in cases where the application of DDA proves to be non-beneficial, the theoretical principles that underlie it always allow for a deeper insight into a schedule, highlighting its uncertainty weak points.

Returning to the final recommendations in Han (1997), the author would like to point out that, just like in the original Simunet/MS-Project package, the optimistic and pessimistic durations, as well as the tendency for the activities in this work are estimated. The tendency concept, proposed by Han (1997), does mend some of the accuracy shortcomings of the original PERT methodology, but there is still much room for further improvement. Following similar lines to the author’s work, a structured, systematic, and objective method for the assignment of the uncertainty data would greatly improve the effectiveness of Simunet and DDA.

In terms of the assignment of durations, however, a lot of work has been done. There are criteria and methods commonly accepted, generally based on quantities, productivity and resources available. This provides a good starting ground but it is still essentially deterministic. The durations obtained in this way reflect an ideal, that is, continuous and undisturbed work, which seldom corresponds to reality. This is particularly true in cases where the objective right at inception is to create an application for dealing with uncertainty.

The tendency is part of the uncertainty data of the activities. It limits the generation of the pseudo-random durations for simulation, thus playing a major role in the accuracy and relevance of the method proposed. It is a recent concept, hence its assignment has been studied much less than the one of the durations. Its systematic definition would certainly increase the accuracy of the durations obtained in the simulation, thus being an interesting field for further research and improvement.

The whole area of soft-data computing and prognosis has shown tremendous development in recent times. This has opened up many interesting possibilities and new theories and tools are being presented to the scientific community and to the market everyday. It is to be expected that powerful prognosis systems, capable of completing and enhancing the work presented in this thesis, will come to light very soon. Thus, the author recommends that developments in this area be observed with great interest.

8. Bibliography

1. Abdel-Razek,R.H (1998) "*Quality improvement in Egypt: Methodology and Implementation*" Journal of Construction Engineering and Management, vol.124, no.5 1998

2. Bubshait, A(1994) "*Owner involvement in project quality*" International Journal of Project Managemen*t*, vol.12, no.2 1994

3. Cachadinha, N. (1998) "*Estudo da Influencia da Estrutura do Planeamento no Impacto de Alteracoes à Duracao de Actividades Individuais na Duracao Total do Projecto"* Gestao de Projectos 1999 (Conference Proceedings), APDIO & FUNDEC, Lisbon.

4. Cachadinha, N. and Kulkarni, R. (2000) "*Quality in construction scheduling and delivery date assurance"*, Conference Proceedings, University of Salford, UK.

5. Chadwick, W.L. (1986) "*Impact of Design, Construction and Cost on Project Quality*" Journal of Professional Issues in Engineering, vol.112,no.2 1986

6. Coleman, G. B., Kline, D. H. (1992) "Four propositions for quality management in design organizations", Journal of Management in Engineering, vol. 8, no.1 1992

7. Bauknecht, K., Kohlas, J., Zehnder, C. (1976) "*Simulationstechnik*", Springer Verlag 1976

8. DIN 69 900 (1987) "*Netzplantechnik*", Beuth Verlag GmbH, Berlin 1987

9. ENCARTA Bookshelf 99 (1999), Chamber's Dictionary, Microsoft Corporation

10. Fisz, M. (1989) "*Wahrscheinlichkeitsrechnung und mathematische Statistik*" VEB Deutscher Verlag der Wissenschaften, Berlin 1989

11. Graves, R. (1993) "*Total Quality –Does it work in Engineering Management"* Journal of Management in Engineering, Vol. 9, no.4 1993

12. Gunaydin, H.M., Arditi, D.(1998) "*Factors that affect process quality in life cycle of building projects*", Journal of Construction Engineering and Management ,vol. 124, no.3 1998

13. Han, G. (1997) "*Computergestützte Ablaufplannung zur optimalen Baustellensteuerung mit Hilfe stochastischer Simulation*", Lehrstuhlbericht Baubetrieb und Bauwirtschaft, TU Cottbus

14. Hellard.R.B (1993), "Total quality in construction projects, achieving profitability *with customer satisfaction"* , Thomas Telford , London (1993)

15. ISO/TC 176/SC2 (1997) "*Quality Management Principles and Guidelines on their Application*", http://www.iso.ch

16. Juran, J.M. (1993) "*Made in U.S.A: A renaissance in Quality*", Harvard Business Review, Jul-Aug . 1993

17. Kacker, R. N., Shoemaker, A.C. (1988) "*A Methodology for Planning Experiments in Robust product and Process Design*" Quality and Reliability Engineering International,vol.4,no.2, 1988, pp.95-103

18. Keller, G. et al (1994), "*Statistics for Management and Economics*" Wadsworth Publishing, Belmont, California, USA

19. King, H. (1965) "*PERT as related to quality management*", Industrial Quality Control, Oct. 1965

20. Laufer, A. and Howell, G. A. (1993) "*Construction planning: revising the paradigm*" PM J. XXIV(3), 23-33

21. Lessmann, H., Mühlögger, J. and Oberguggenberger, M. (1994) „*Netzplantechnik mit unscharfen Methoden*", Bauingenieur 69 (1994) 469-478, Springer Verlag

22. Mallon, J.C. (1993) *"Quality function deployment – system for meeting costumer's needs"*, Journal of Construction Engineering and Management, vol. 119, No.3 1993

23. Mikkelsen, H. (1990) "*Quality of Project work and Project Management*" , Project Management, vol.8, no.3 1990

24. Mitrani, I. (1982) "*Simulation techniques for discrete event syst*ems" Cambridge Computer Science Texts 14, 1982

25. Mon, D.-L., Cheng, C.-H., Lu, H.-C. (1995) « *Application of fuzzy distributions on project management* », Fuzzy Sets and Systems 73 (1995) 227-234

26. Mulholland, B. and Christian, J. (1999) "*Risk Assessment in Construction Schedules*", Journal of Construction Engineering and Management, Jan./Feb. 99, ASCE

27. Neumann, K. (1975) "*Operations Research*" Verfahren B2 and B3, Carl Hanser Verlag 1975

28. Petzschmann, E. (1992/93) "*Baubetrieb und Planungsverfahren*", Lecture Material, Lehrstuhl Baubetrieb und Bauwirtschaft, WS1992/1993

29. Rabetge, C. (1990) "*Fuzzy Sets in der Netzplantechnik*", DUV 1990

30. Ross, P. J. (1996) "*Taguchi Techniques for Quality Engineering*", Mc-Graw Hill, New York

31. Roy, R. K. (1990) "*A Primer on Taguchi Method*", Von-Nostrand Reinhold, New York

32. Schubert, J. (1999) "*Die Auswirkung von ungenauer Vorgangsdauern auf die Projektdauer*", Inst. Für Planungsverfahren im Baubetrieb der RWTH Aachen

33. Seeling, R. (1990) "*Steuerung von Bauabläufen mit moderner Technologie*", in Baumarkt 12/90

34. Seeling, R. (1996) "*Vorlesungen über Theorie und Praxis der Projektsteuerung*", Schriftenreihe Baubetrieb, RWTH Aachen, vol.3 new edition 1996

35. Seeling, R. (1992) "*Vorlesung über Unternehmensplanung im Baubetrieb*", Schriftenreihe Baubetrieb, RWTH Aachen, self-edition, 1992

36. Seeling, R. (1969) "*Die Optimierung von Netzwerken durch Bildung bewerteter Trennungsmengen*", VDI-Z, Fortschritt Berichte vol. 16 nr. 3, 1969

37. Taguchi, G., Clausing, D.(1990) "*Robust Quality*" Harvard Business Review, Jan-Feb1990

38. Taguchi, G., Wu, Y.-I. (1979) "*Off-line Quality Control*" Central Japan Quality Control Association, Nagaya 1979

39. Zimmermann, H.-J.(1971) "*Netzplantechnik*", Berlin – New York, 1971

40. Zimmermann, H.-J. (2000) "*An Application-oriented View of Modelling Uncertainty*", European Journal of Operational Research 122, 2000

41. Zimmermann, H.-J. and Gutsche, L. "*Multi-Criteria Analyse*", Heidelberger Lehrtexte Wirtschafswissenschaften, Springer Verlag Berlin, Heidelberg, New York, Tokyo

42. Chapman and Ward (1997) "*Project Risk Management*", John Wiley&Sons, 1997

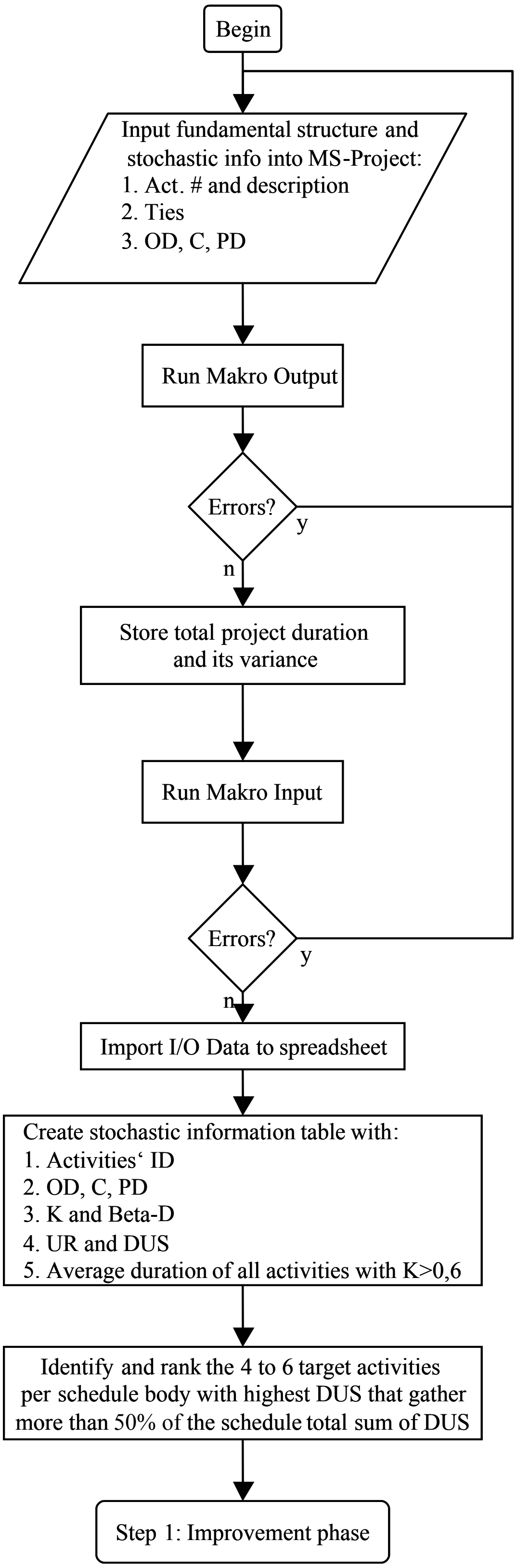


Fig. 9.1: Preliminary Work

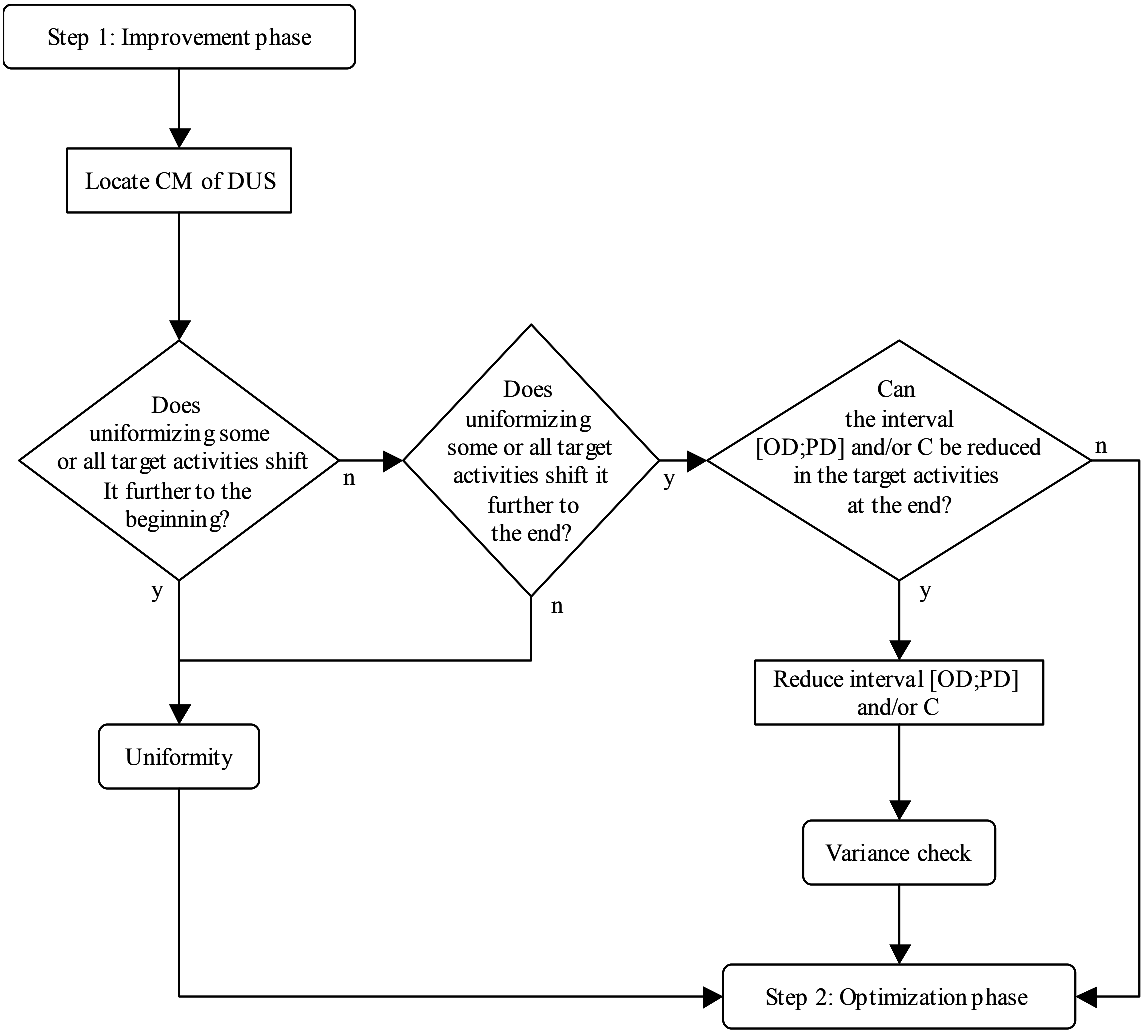


Fig. 9.2: Improvement Phase and its Connections to the Optimization Phase

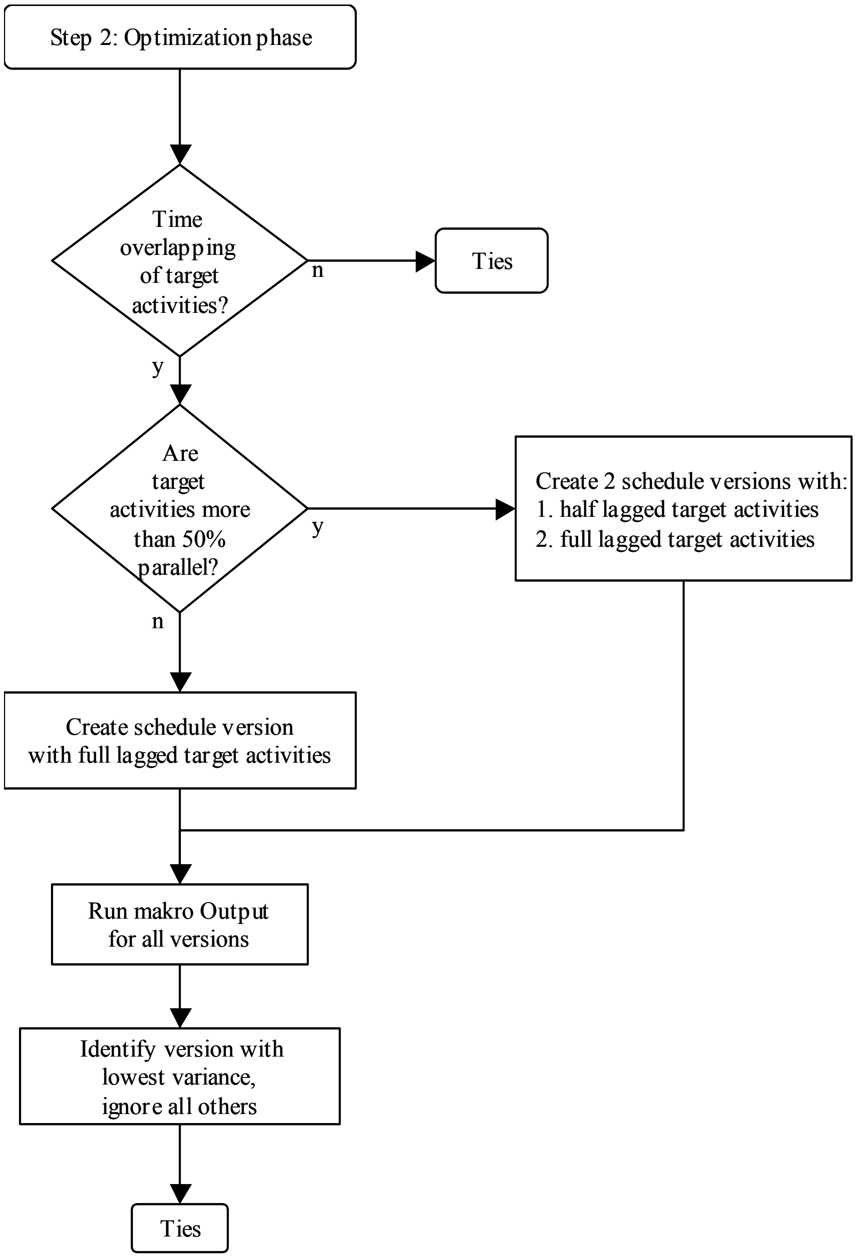


Fig. 9.3: Optimization Phase

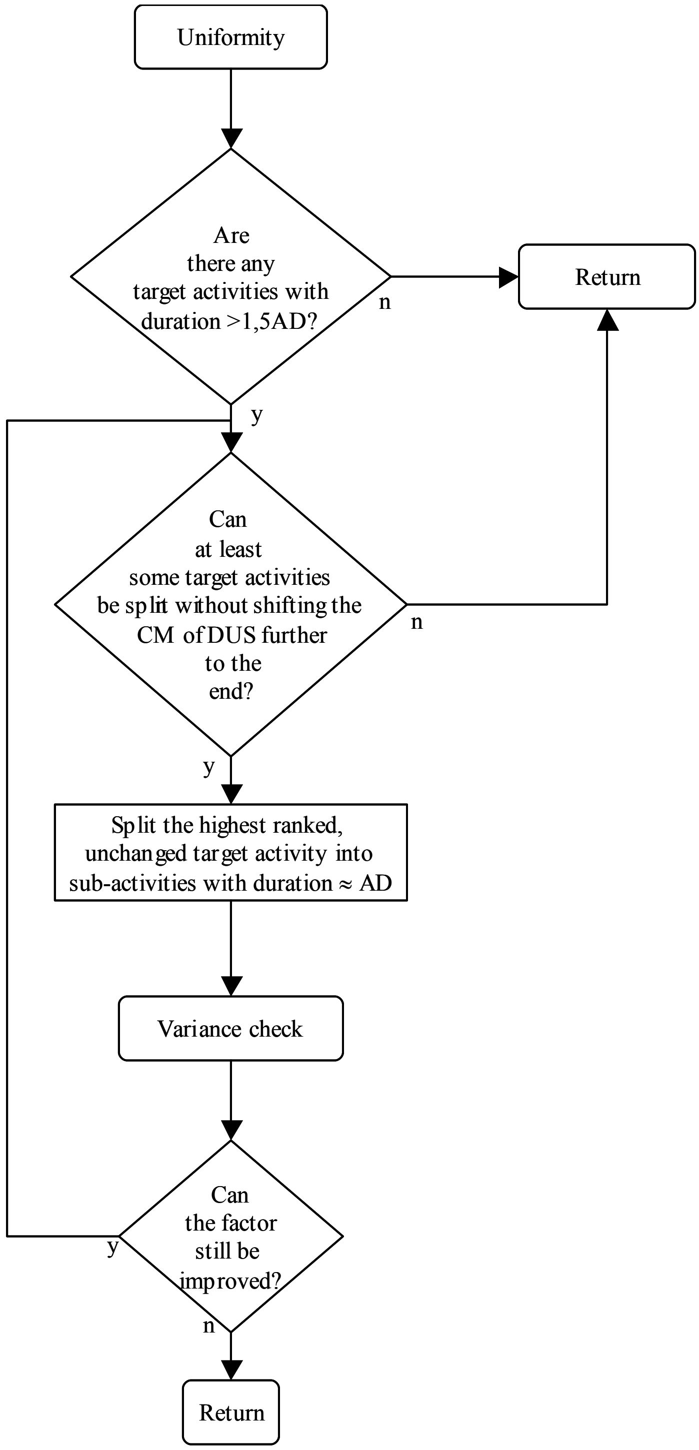
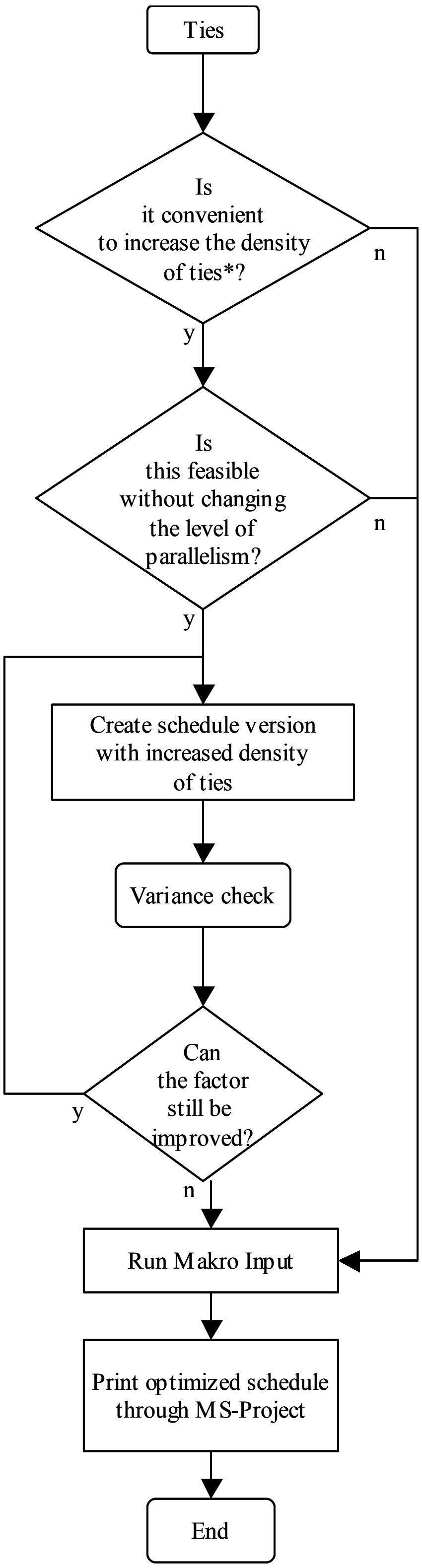


Fig. 9.4: Uniformity Procedure



*Due to resources management, no change in the total project duration, necessity to increase the certainty of the total poroject duration or others

Fig. 9.5: Ties Procedure

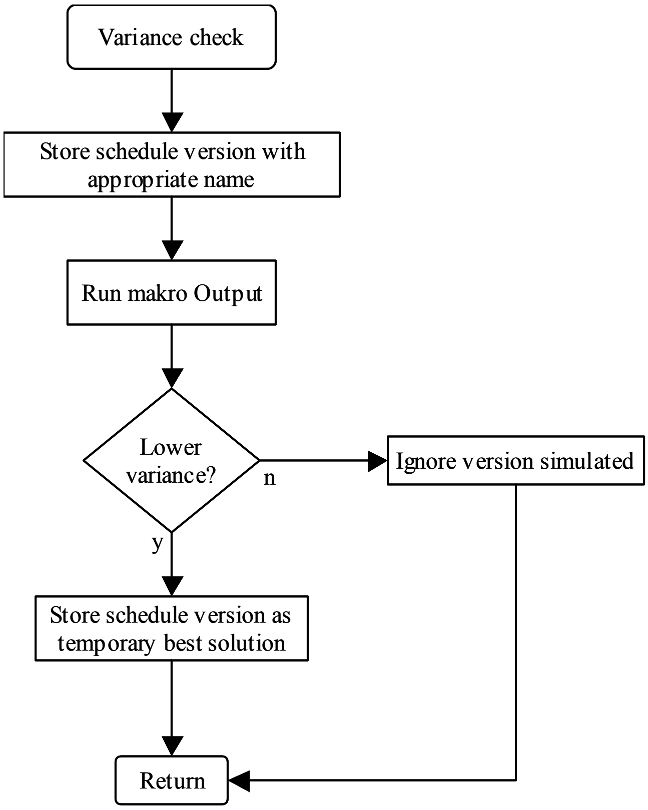


Fig. 9.6: Variance Check Procedure

Project: Federal Ministry
of Telecommunications

Stochastic Information Table

Original Topology

Act#	Act. Desc.	OD	C	PD	UR	Beta-D	K-Deg.	DUS
1	Vergabe	0	1	0		0	1	0
2	AVO	6	3	14	7,00	10,05	0,51	9,33
3	Baust. Einr.	6	3	14	7,00	9,95	0,49	8,19
4	Baustr. herst	3	3	5	5,00	4	0	0,00
5	Stellplatz herst	1	2	3	6,00	1,75	1	10,50
6	TDK aufbauen	5	4	9	7,20	7,55	0	0,00
7	Gleise verlegen	4	3	8	6,00	6	0	0,00
8	Aushub	8	3	11	4,13	9,5	0,08	0,02
9	Aushub Fund.	2	2	4	4,00	2,75	0,08	0,01
10	Fundamente	5	4	9	7,20	7,55	0,08	0,03
11	Sauberkeitsschicht	1	2	3	6,00	1,8	0,08	0,01
12	Bodenplatte	6	3	14	7,00	9,95	0,08	0,04
13	Bodenplatte Rampe	1	2	3	6,00	1,75	0,08	0,01
14	Mon Schalung	1	2	3	6,00	1,75	0,08	0,01
15	Wände/Stützen	20	3	30	4,50	25	0,08	0,06
16	Treppen	2	3	6	9,00	4	0	0,00
17	Mon Schalung	5	4	9	7,20	7,55	0	0,00
18	Wandvorlauf	8	3	12	4,50	10	0,03	0,00
19	Decke U3/Spindel	20	4	29	5,80	25,55	0,03	0,00
20	Wände/Stützen	18	4	24	5,33	21,75	0,05	0,01
21	Treppen	2	3	6	9,00	4,1	0	0,00
22	Wandvorlauf	8	3	12	4,50	10	0,02	0,00
23	Decke U2/Spindel	16	4	24	6,00	21	0,05	0,02
24	Wände/Stützen	18	4	22	4,89	20,5	0,03	0,00
25	Demon . Schalung	1	1	2	2,00	1,25	0	0,00
26	Treppen	2	3	4	6,00	3	0	0,00
27	Wandvorlauf	8	3	12	4,50	10	0,03	0,00
28	Decke U1/Spindel	23	4	31	5,39	28	0,08	0,08
29	Demon . Schalung	2	3	4	6,00	3	0,02	0,00
30	Wandabdichtung	3	3	7	7,00	5	0,06	0,01
31	Deckenabdichtung	5	3	7	4,20	6	0	0,00
32	Verfüllung Baugr.	3	2	6	4,00	4,15	0,06	0,00
33	Aushub	1	1	2	2,00	1,25	0,92	1,95
34	Aushub Fund.	2	2	4	4,00	2,7	0,92	8,41
35	Fundamente	5	4	9	7,20	7,45	0,92	41,77
36	Sauberkeitsschicht	1	2	3	6,00	1,75	0,92	8,18
37	Bodenplatte	12	3	20	5,00	15,85	0,92	61,71
38	Mon Schalung	1	2	5	10,00	2,55	0,91	19,22
39	Wände/Stützen	20	4	26	5,20	23,75	0,91	93,07
40	Treppen	2	3	7	10,50	4,5	0	0,00
41	Mon Schalung	10	2	13	2,60	11,15	0,02	0,00
42	Wandvorlauf	8	3	12	4,50	9,95	0,35	1,92
43	Decke U3	21	4	26	4,95	24	0,37	6,02
44	Mauerwerk	5	2	10	4,00	6,9	0	0,00
45	Wände/Stützen	17	4	21	4,94	19,55	0,56	16,96
46	Treppen	2	3	6	9,00	4,05	0	0,00
47	Wandvorlauf	8	3	12	4,50	10	0,23	0,55
48	Decke U2	15	4	22	5,87	19,3	0,59	23,25
49	Mauerwerk	5	2	10	4,00	6,8	0	0,00
50	Wände/Stützen	17	4	21	4,94	19,5	0,33	3,46
51	Demon . Schalung	1	2	3	6,00	1,75	0	0,00
52	Treppe	2	3	4	6,00	3	0	0,00
53	Wandvorlauf	8	3	12	4,50	10	0,33	1,62
54	Decke U1	29	4	38	5,24	34,55	0,92	141,01
55	Demon . Schalung	7	3	13	5,57	9,95	0,92	43,17
56	Mauerwerk	5	2	10	4,00	6,9	0	0,00
57	Wandabdichtung	2	3	4	6,00	3	0	0,00
58	Deckenabdichtung	2	3	4	6,00	3,05	0	0,00
59	Verfüllen Baugr.	4	2	7	3,50	5,15	0	0,00
60	Aushub	1	1	2	2,00	1,25	0	0,00
61	Aushub Fund.	2	2	4	4,00	2,75	0	0,00
62	Fundamente	5	4	9	7,20	7,45	0	0,00
63	Sauberkeitsschicht	1	2	3	6,00	1,75	0	0,00
64	Bodenplatte	6	3	14	7,00	10	0	0,00
65	Mon Schalung	2	2	5	5,00	3,1	0	0,00
66	Wände/Stützen	18	4	24	5,33	21,75	0	0,00
67	Treppen	2	3	6	9,00	4	0	0,00
68	Mon Schalung	8	2	11	2,75	9,1	0	0,00
69	Wandvorlauf	8	3	12	4,50	10	0	0,00
70	Decke U3	18	4	22	4,89	20,45	0	0,00
71	Wände/Stützen	17	4	20	4,71	18,85	0	0,00
72	Treppen	2	3	4	6,00	3,05	0	0,00
73	Wandvorlauf	8	3	12	4,50	9,95	0	0,00
74	Decke U2	13	4	19	5,85	16,65	0	0,00
75	Wände/Stützen	15	4	21	5,60	18,7	0	0,00
76	Demon . Schalung	1	3	3	9,00	2	0	0,00
77	Treppen	2	3	4	6,00	3	0	0,00
78	Wandvorlauf	8	3	12	4,50	9,9	0	0,00
79	Decke U1	18	4	26	5,78	23	0	0,00
80	Demon . Schalung	4	3	8	6,00	6	0	0,00
81	Wandabdichtung	3	3	5	5,00	4	0	0,00
82	Deckenabdichtung	3	3	5	5,00	4	0	0,00
83	Verfüllen Baugr.	3	2	6	4,00	4,1	0	0,00
84	TDK abbauen	1	4	4	16,00	2,85	0	0,00
85	Gleise abbauen	3	3	9	9,00	6	0,94	44,85
86	Baustellenräumung	2	3	8	12,00	5,1	1	61,20
87	Ende	0	1	0		1	0	0

Average duration for all activities with K>0,6
AD = 12,73

Total Amount of Duration Uncertainty Seriousness
606,63

Total Duration Uncertainty value for the target activities
TDU= 356,99 corresponding to 58,8 % of the total

Tab. 9. 1: Stochastic Information Table - Federal Ministry of Telecommunications

Fig. 9.6: Federal Ministry of Telecommunications - Original Topology

Ministry | Original Topology | Variance: 0,41

Nr.	Vorgangsname	OD	c	PD	Beta-D	K. Grad
1	Vergabe	0 Tage	1	0 Tage	0 Tage	1
2	AVO	6 Tage	3	14 Tage	10,05 Tage	0,51
3	Baust. Einr.	6 Tage	3	14 Tage	9,95 Tage	0,49
4	Baustr. herst	3 Tage	3	5 Tage	4 Tage	0
5	Stellplatz herst	1 Tag	2	3 Tage	1,75 Tage	1
6	TDK aufbauen	5 Tage	4	9 Tage	7,55 Tage	0
7	Gleise verlegen	4 Tage	3	8 Tage	6 Tage	0
8	Aushub	8 Tage	3	11 Tage	9,5 Tage	0,08
9	Aushub Fund.	2 Tage	2	4 Tage	2,75 Tage	0,08
10	Fundamente	5 Tage	4	9 Tage	7,55 Tage	0,08
11	Sauberkeitsschicht	1 Tag	2	3 Tage	1,8 Tage	0,08
12	Bodenplatte	6 Tage	3	14 Tage	9,95 Tage	0,08
13	Bodenplatte Rampe	1 Tag	2	3 Tage	1,75 Tage	0,08
14	Montage Schalung	1 Tag	2	3 Tage	1,75 Tage	0,08
15	Wände/Stützen	20 Tage	3	30 Tage	25 Tage	0,08
16	Treppen	2 Tage	3	6 Tage	4 Tage	0
17	Montage Schalung	5 Tage	4	9 Tage	7,55 Tage	0
18	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0,03
19	Decke U3/Spindel	20 Tage	4	29 Tage	25,55 Tage	0,03
20	Wände/Stützen	18 Tage	4	24 Tage	21,75 Tage	0,05
21	Treppen	2 Tage	3	6 Tage	4,1 Tage	0
22	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0,02
23	Decke U2/Spindel	16 Tage	4	24 Tage	21 Tage	0,05
24	Wände/Stützen	18 Tage	4	22 Tage	20,5 Tage	0,03
25	Demontag. Schalung	1 Tag	1	2 Tage	1,25 Tage	0
26	Treppen	2 Tage	3	4 Tage	3 Tage	0
27	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0,03
28	Decke U1/Spindel	23 Tage	4	31 Tage	28 Tage	0,08
29	Demontag. Schalung	2 Tage	3	4 Tage	3 Tage	0,02
30	Wandabdichtung	3 Tage	3	7 Tage	5 Tage	0,06
31	Deckenabdichtung	5 Tage	3	7 Tage	6 Tage	0
32	Verfüllung Baugr.	3 Tage	2	6 Tage	4,15 Tage	0,06
33	Aushub	1 Tag	1	2 Tage	1,25 Tage	0,92
34	Aushub Fund.	2 Tage	2	4 Tage	2,7 Tage	0,92
35	Fundamente	5 Tage	4	9 Tage	7,45 Tage	0,92
36	Sauberkeitsschicht	1 Tag	2	3 Tage	1,75 Tage	0,92
37	Bodenplatte	12 Tage	3	20 Tage	15,85 Tage	0,92
38	Montage Schalung	1 Tag	2	5 Tage	2,55 Tage	0,91
39	Wände/Stützen	20 Tage	4	26 Tage	23,75 Tage	0,91
40	Treppen	2 Tage	3	7 Tage	4,5 Tage	0
41	Montage Schalung	10 Tage	2	13 Tage	11,15 Tage	0,02
42	Wandvorlauf	8 Tage	3	12 Tage	9,95 Tage	0,35
43	Decke U3	21 Tage	4	26 Tage	24 Tage	0,37
44	Mauerwerk	5 Tage	2	10 Tage	6,9 Tage	0
45	Wände/Stützen	17 Tage	4	21 Tage	19,55 Tage	0,56
46	Treppen	2 Tage	3	6 Tage	4,05 Tage	0
47	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0,23
48	Decke U2	15 Tage	4	22 Tage	19,3 Tage	0,59
49	Mauerwerk	5 Tage	2	10 Tage	6,8 Tage	0
50	Wände/Stützen	17 Tage	4	21 Tage	19,5 Tage	0,33
51	Demontag. Schalung	1 Tag	2	3 Tage	1,75 Tage	0
52	Treppe	2 Tage	3	4 Tage	3 Tage	0
53	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0,33
54	Decke U1	29 Tage	4	38 Tage	34,55 Tage	0,92
55	Demontag. Schalung	7 Tage	3	13 Tage	9,95 Tage	0,92
56	Mauerwerk	5 Tage	2	10 Tage	6,9 Tage	0
57	Wandabdichtung	2 Tage	3	4 Tage	3 Tage	0
58	Deckenabdichtung	2 Tage	3	4 Tage	3,05 Tage	0
59	Verfüllen Baugr.	4 Tage	2	7 Tage	5,15 Tage	0
60	Aushub	1 Tag	1	2 Tage	1,25 Tage	0
61	Aushub Fund.	2 Tage	2	4 Tage	2,75 Tage	0
62	Fundamente	5 Tage	4	9 Tage	7,45 Tage	0
63	Sauberkeitsschicht	1 Tag	2	3 Tage	1,75 Tage	0
64	Bodenplatte	6 Tage	3	14 Tage	10 Tage	0
65	Montage Schalung	2 Tage	2	5 Tage	3,1 Tage	0
66	Wände/Stützen	18 Tage	4	24 Tage	21,75 Tage	0
67	Treppen	2 Tage	3	6 Tage	4 Tage	0
68	Montage Schalung	8 Tage	2	11 Tage	9,1 Tage	0
69	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0
70	Decke U3	18 Tage	4	22 Tage	20,45 Tage	0
71	Wände/Stützen	17 Tage	4	20 Tage	18,85 Tage	0
72	Treppen	2 Tage	3	4 Tage	3,05 Tage	0
73	Wandvorlauf	8 Tage	3	12 Tage	9,95 Tage	0
74	Decke U2	13 Tage	4	19 Tage	16,65 Tage	0
75	Wände/Stützen	15 Tage	4	21 Tage	18,7 Tage	0
76	Demontag. Schalung	1 Tag	3	3 Tage	2 Tage	0
77	Treppen	2 Tage	3	4 Tage	3 Tage	0
78	Wandvorlauf	8 Tage	3	12 Tage	9,9 Tage	0
79	Decke U1	18 Tage	4	26 Tage	23 Tage	0
80	Demontag. Schalung	4 Tage	3	8 Tage	6 Tage	0
81	Wandabdichtung	3 Tage	3	5 Tage	4 Tage	0
82	Deckenabdichtung	3 Tage	3	5 Tage	4 Tage	0
83	Verfüllen Baugr.	3 Tage	2	6 Tage	4,1 Tage	0
84	TDK abbauen	1 Tag	4	4 Tage	2,85 Tage	0
85	Gleise abbauen	3 Tage	3	9 Tage	6 Tage	0,94
86	Baustellenräumung	2 Tage	3	8 Tage	5,1 Tage	1
87	Ende	0 Tage	1	0 Tage	1 Tag	0

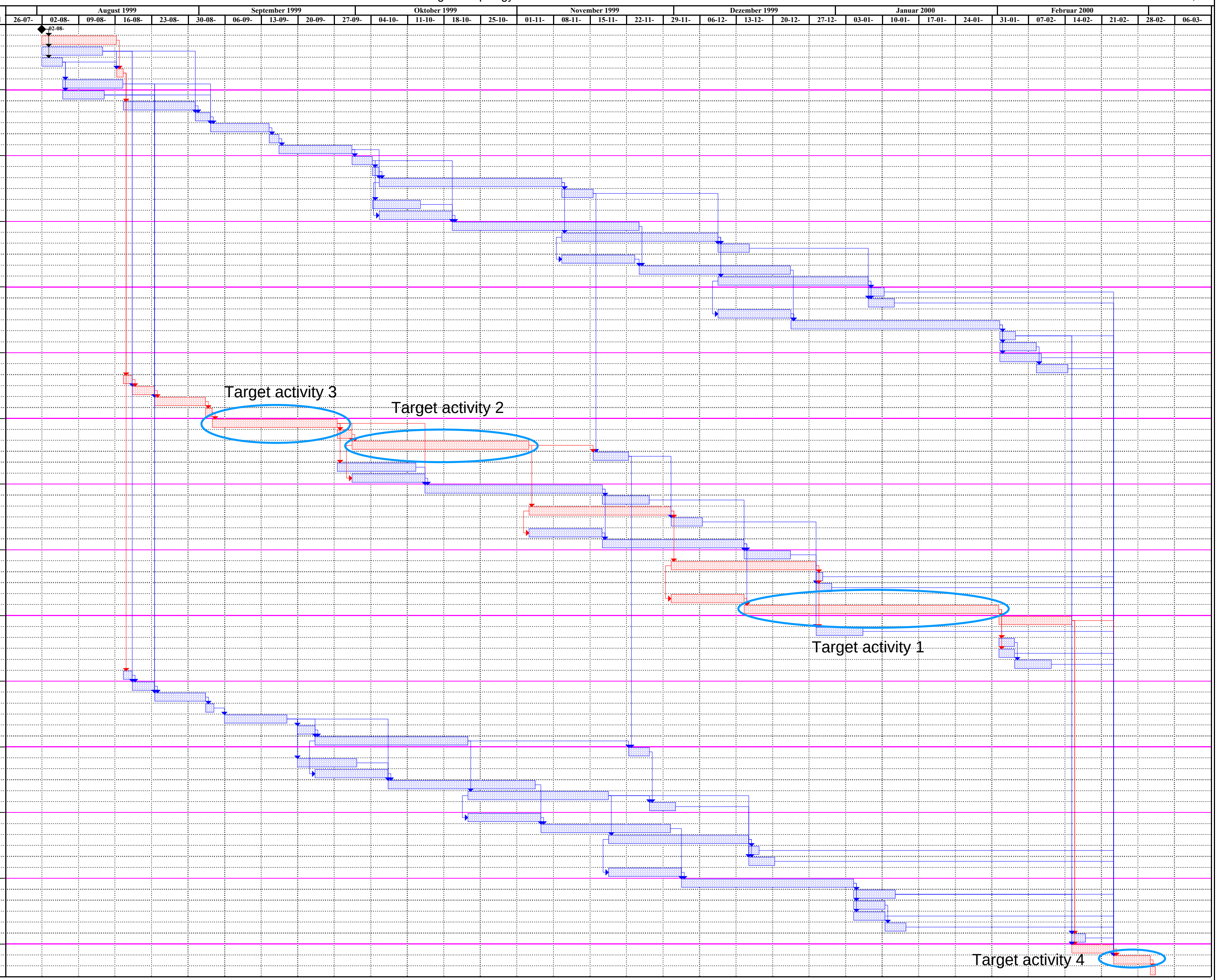


Fig. 9.7: End of Step 1 - DUS C.M. in the middle and Uniformity of Durations

Ministry | DUS Middle + Uniformity | Variance: 0,21

Nr.	Vorgangsname	OD	c	PD	Beta-D	K. Grad
1	Vergabe	0 Tage	1	0 Tage	0 Tage	1
2	AVO	6 Tage	3	14 Tage	10 Tage	0,54
3	Baust. Einr.	6 Tage	3	14 Tage	10 Tage	0,46
4	Baustr. herst	3 Tage	3	5 Tage	4 Tage	0
5	Stellplatz herst	1 Tag	2	3 Tage	1,75 Tage	1
6	TDK aufbauen	5 Tage	4	8 Tage	6,85 Tage	0
7	Gleise verlegen	4 Tage	3	8 Tage	6,05 Tage	0
8	Aushub	8 Tage	3	12 Tage	9,95 Tage	0,01
9	Aushub Fund.	2 Tage	2	4 Tage	2,7 Tage	0,01
10	Fundamente	5 Tage	4	8 Tage	6,85 Tage	0,01
11	Sauberkeitsschicht	1 Tag	2	3 Tage	1,8 Tage	0,01
12	Bodenplatte	6 Tage	3	14 Tage	10,1 Tage	0,01
13	Bodenplatte Rampe	1 Tag	2	3 Tage	1,75 Tage	0,01
14	Montage Schalung	1 Tag	2	3 Tage	1,75 Tage	0,01
15	Wände/Stützen	20 Tage	3	30 Tage	25 Tage	0,01
16	Treppen	2 Tage	3	6 Tage	4 Tage	0
17	Montage Schalung	5 Tage	4	8 Tage	6,9 Tage	0
18	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0
19	Decke U3/Spindel	20 Tage	4	28 Tage	25 Tage	0
20	Wände/Stützen	18 Tage	4	23 Tage	21,1 Tage	0,01
21	Treppen	2 Tage	3	6 Tage	4 Tage	0
22	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0
23	Decke U2/Spindel	16 Tage	4	24 Tage	20,85 Tage	0
24	Wände/Stützen	18 Tage	4	23 Tage	21,1 Tage	0
25	Demontag. Schalung	1 Tag	1	2 Tage	1,25 Tage	0
26	Treppen	2 Tage	3	4 Tage	3 Tage	0
27	Wandvorlauf	8 Tage	3	12 Tage	10,05 Tage	0
28	Decke U1/Spindel	23 Tage	4	29 Tage	26,7 Tage	0,01
29	Demontag. Schalung	2 Tage	3	4 Tage	3 Tage	0
30	Wandabdichtung	3 Tage	3	7 Tage	4,95 Tage	0
31	Deckenabdichtung	5 Tage	3	7 Tage	6 Tage	0
32	Verfüllung Baugr.	3 Tage	2	6 Tage	4,2 Tage	0
33	Aushub	1 Tag	1	2 Tage	1,25 Tage	0,99
34	Aushub Fund.	2 Tage	2	4 Tage	2,75 Tage	0,99
35	Fundamente	5 Tage	4	8 Tage	6,9 Tage	0,99
36	Sauberkeitsschicht	1 Tag	2	3 Tage	1,75 Tage	0,99
37	Bodenplatte	6 Tage	3	10 Tage	8 Tage	0,99
38	split Bodenplatte	6 Tage	3	10 Tage	8,1 Tage	0,99
39	Montage Schalung	1 Tag	2	6 Tage	2,9 Tage	0,99
40	Wände/Stützen	14,5 Tage	4	19 Tage	17,35 Tage	0,99
41	split Wände/Stützen	14,5 Tage	4	19 Tage	17,25 Tage	0,99
42	Treppen	2 Tage	3	8 Tage	5 Tage	0
43	Montage Schalung	10 Tage	2	13 Tage	11,15 Tage	0
44	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0
45	Decke U3	10,5 Tage	4	13 Tage	12,05 Tage	0
46	split Decke U3	10,5 Tage	4	13 Tage	12,05 Tage	0
47	Mauerwerk	5 Tage	2	10 Tage	6,95 Tage	0
48	Wände/Stützen	9 Tage	4	10,5 Tage	9,95 Tage	0,99
49	split Wände/Stützen	9 Tage	4	10,5 Tage	9,95 Tage	0,53
50	Treppen	2 Tage	3	6 Tage	4 Tage	0
51	Wandvorlauf	8 Tage	3	12 Tage	9,95 Tage	0,46
52	Decke U2	8 Tage	4	11 Tage	9,9 Tage	0,46
53	Split Decke U2	8 Tage	4	11 Tage	9,9 Tage	0,46
54	Mauerwerk	5 Tage	2	10 Tage	6,85 Tage	0
55	Wände/Stützen	17 Tage	4	21 Tage	19,5 Tage	0,53
56	Demontag. Schalung	1 Tag	2	3 Tage	1,75 Tage	0
57	Treppe	2 Tage	3	4 Tage	3 Tage	0
58	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0,53
59	Decke U1	5,75 Tage	3	6,25 Tage	6 Tage	0,99
60	Split Decke U1	5,75 Tage	3	6,25 Tage	6 Tage	0,99
61	Split Decke U1	5,75 Tage	3	6,25 Tage	6 Tage	0,99
62	Split Decke U1	5,75 Tage	3	6,25 Tage	6 Tage	0,99
63	Demontag. Schalung	9 Tage	3	11 Tage	10 Tage	0,99
64	Mauerwerk	5 Tage	2	10 Tage	6,85 Tage	0
65	Wandabdichtung	2 Tage	3	4 Tage	3 Tage	0
66	Deckenabdichtung	2 Tage	3	4 Tage	3 Tage	0
67	Verfüllen Baugr.	4 Tage	2	7 Tage	5,05 Tage	0
68	Aushub	1 Tag	1	2 Tage	1,25 Tage	0
69	Aushub Fund.	2 Tage	2	4 Tage	2,75 Tage	0
70	Fundamente	5 Tage	4	10 Tage	8,1 Tage	0
71	Sauberkeitsschicht	1 Tag	2	3 Tage	1,75 Tage	0
72	Bodenplatte	6 Tage	3	14 Tage	10 Tage	0
73	Montage Schalung	2 Tage	2	5 Tage	3,1 Tage	0
74	Wände/Stützen	18 Tage	4	24 Tage	21,7 Tage	0
75	Treppen	2 Tage	3	6 Tage	4 Tage	0
76	Montage Schalung	8 Tage	2	11 Tage	9,1 Tage	0
77	Wandvorlauf	8 Tage	3	12 Tage	10,05 Tage	0
78	Decke U3	18 Tage	4	23 Tage	21,15 Tage	0
79	Wände/Stützen	17 Tage	4	20 Tage	18,95 Tage	0
80	Treppen	2 Tage	3	4 Tage	3 Tage	0
81	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0
82	Decke U2	13 Tage	4	19 Tage	16,75 Tage	0
83	Wände/Stützen	15 Tage	4	21 Tage	18,7 Tage	0
84	Demontag. Schalung	1 Tag	3	3 Tage	2 Tage	0
85	Treppen	2 Tage	3	4 Tage	3 Tage	0
86	Wandvorlauf	8 Tage	3	12 Tage	10,05 Tage	0
87	Decke U1	18 Tage	4	26 Tage	22,95 Tage	0
88	Demontag. Schalung	4 Tage	3	8 Tage	6 Tage	0
89	Wandabdichtung	3 Tage	3	5 Tage	4 Tage	0
90	Deckenabdichtung	3 Tage	3	5 Tage	4 Tage	0
91	Verfüllen Baugr.	3 Tage	2	6 Tage	4,2 Tage	0
92	TDK abbauen	1 Tag	4	4 Tage	2,85 Tage	0
93	Gleise abbauen	5 Tage	3	7 Tage	5,95 Tage	1
94	Baustellenräumung	4 Tage	3	6 Tage	5 Tage	1
95	Ende	0 Tage	1	0 Tage	0 Tage	0

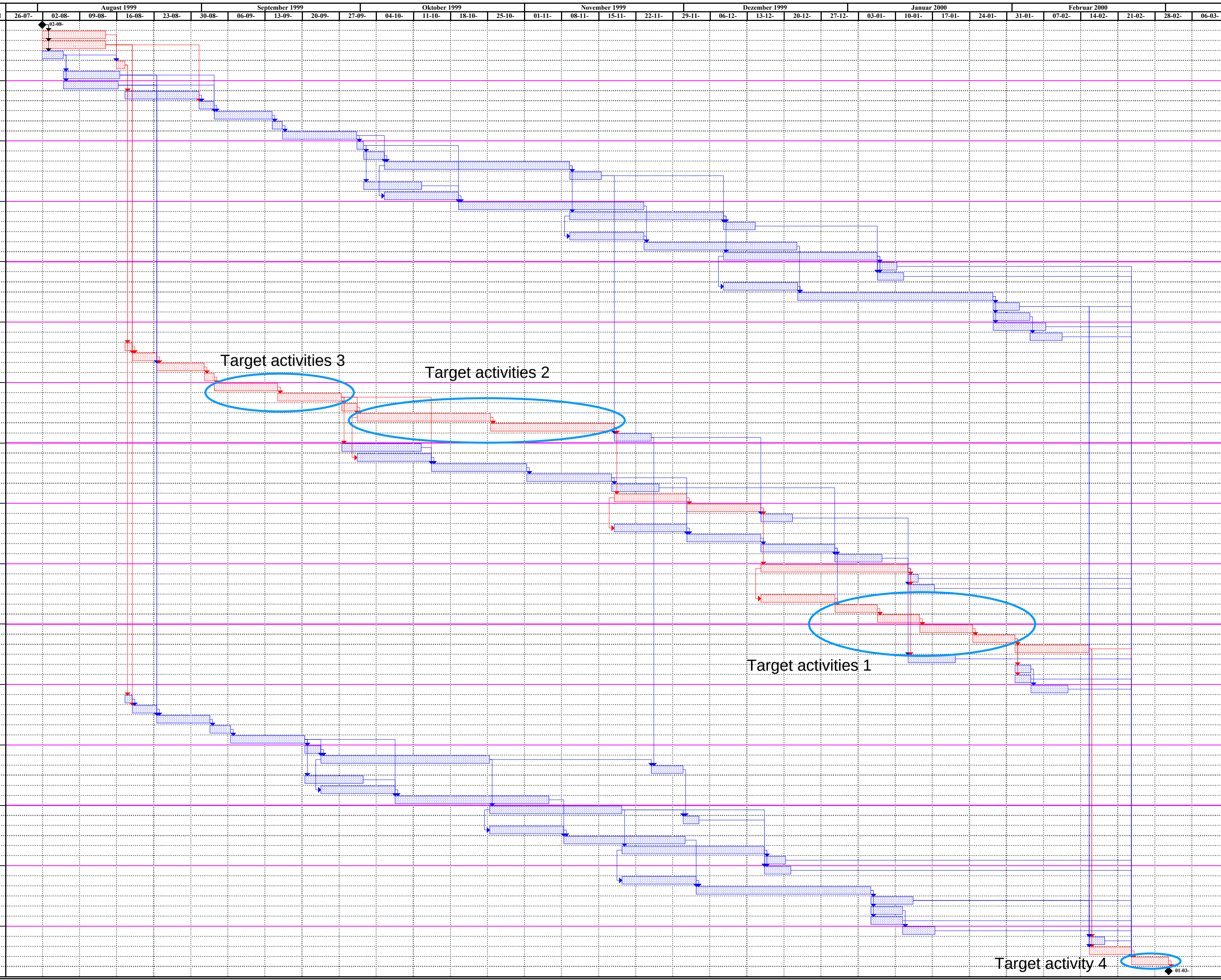


Fig. 9.8: Step 2 - Increased Ties Density - Level 2

Ministry — Ties Level 2 — Variance: 0,275

Nr.	Vorgangsname	OD	c	PD	Beta-D	K. Grad
1	Vergabe	0 Tage	1	0 Tage	0 Tage	1
2	AVO	6 Tage	3	14 Tage	9,95 Tage	0,49
3	Baust. Einr.	6 Tage	3	14 Tage	10 Tage	0,51
4	Baustr. herst	3 Tage	3	5 Tage	4 Tage	0
5	Stellplatz herst	1 Tag	2	3 Tage	1,75 Tage	1
6	TDK aufbauen	5 Tage	4	8 Tage	6,9 Tage	0
7	Gleise verlegen	4 Tage	3	8 Tage	6,05 Tage	0
8	Aushub	8 Tage	3	12 Tage	10 Tage	0,86
9	Aushub Fund.	2 Tage	2	4 Tage	2,75 Tage	0,86
10	Fundamente	5 Tage	4	8 Tage	6,9 Tage	0,86
11	Sauberkeitsschicht	1 Tag	2	3 Tage	1,75 Tage	0,86
12	Bodenplatte	6 Tage	3	14 Tage	10,1 Tage	0,86
13	Bodenplatte Rampe	1 Tag	2	3 Tage	1,75 Tage	0,86
14	Montage Schalung	1 Tag	2	3 Tage	1,75 Tage	0,39
15	Wände/Stützen	20 Tage	3	30 Tage	25 Tage	0,39
16	Treppen	2 Tage	3	6 Tage	3,95 Tage	0
17	Montage Schalung	5 Tage	4	8 Tage	6,9 Tage	0
18	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0,19
19	Decke U3/Spindel	20 Tage	4	28 Tage	25,1 Tage	0,19
20	Wände/Stützen	18 Tage	4	23 Tage	21,15 Tage	0,2
21	Treppen	2 Tage	3	6 Tage	4 Tage	0
22	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0,2
23	Decke U2/Spindel	16 Tage	4	24 Tage	20,9 Tage	0,39
24	Wände/Stützen	18 Tage	4	23 Tage	21,05 Tage	0
25	Demontag. Schalung	1 Tag	1	2 Tage	1,25 Tage	0
26	Treppen	2 Tage	3	4 Tage	3,05 Tage	0
27	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0
28	Decke U1/Spindel	23 Tage	4	29 Tage	26,65 Tage	0
29	Demontag. Schalung	2 Tage	3	4 Tage	3 Tage	0
30	Wandabdichtung	3 Tage	3	7 Tage	5,05 Tage	0
31	Deckenabdichtung	5 Tage	3	7 Tage	6 Tage	0
32	Verfüllung Baugr.	3 Tage	2	6 Tage	4,1 Tage	0
33	Aushub	1 Tag	1	2 Tage	1,25 Tage	0,14
34	Aushub Fund.	2 Tage	2	4 Tage	2,75 Tage	0,14
35	Fundamente	5 Tage	4	8 Tage	6,85 Tage	0,14
36	Sauberkeitsschicht	1 Tag	2	3 Tage	1,75 Tage	0,14
37	Bodenplatte	6 Tage	3	10 Tage	8 Tage	0,14
38	split Bodenplatte	6 Tage	3	10 Tage	7,95 Tage	0,14
39	Montage Schalung	1 Tag	2	6 Tage	2,9 Tage	0,14
40	Wände/Stützen	14,5 Tage	4	19 Tage	17,3 Tage	0,61
41	split Wände/Stützen	14,5 Tage	4	19 Tage	17,3 Tage	0,61
42	Treppen	2 Tage	3	8 Tage	4,95 Tage	0
43	Montage Schalung	10 Tage	2	13 Tage	11,15 Tage	0
44	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0
45	Decke U3	10,5 Tage	4	13 Tage	12,05 Tage	0
46	split Decke U3	10,5 Tage	4	13 Tage	12,05 Tage	0
47	Mauerwerk	5 Tage	2	10 Tage	6,8 Tage	0
48	Wände/Stützen	9 Tage	4	10,5 Tage	9,95 Tage	0,61
49	split Wände/Stützen	9 Tage	4	10,5 Tage	9,95 Tage	0
50	Treppen	2 Tage	3	6 Tage	4 Tage	0
51	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0,61
52	Decke U2	8 Tage	4	11 Tage	9,85 Tage	0,61
53	Split Decke U2	8 Tage	4	11 Tage	9,85 Tage	0,61
54	Mauerwerk	5 Tage	2	10 Tage	6,9 Tage	0
55	Wände/Stützen	17 Tage	4	21 Tage	19,45 Tage	0,39
56	Demontag. Schalung	1 Tag	2	3 Tage	1,75 Tage	0
57	Treppe	2 Tage	3	4 Tage	3 Tage	0
58	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0,39
59	Decke U1	5,75 Tage	3	6,25 Tage	6 Tage	0,39
60	Split Decke U1	5,75 Tage	3	6,25 Tage	6 Tage	0,39
61	Split Decke U1	5,75 Tage	3	6,25 Tage	6 Tage	0,39
62	Split Decke U1	5,75 Tage	3	6,25 Tage	6 Tage	0,39
63	Demontag. Schalung	9 Tage	3	11 Tage	10 Tage	0,39
64	Mauerwerk	5 Tage	2	10 Tage	6,85 Tage	0
65	Wandabdichtung	2 Tage	3	4 Tage	3 Tage	0
66	Deckenabdichtung	2 Tage	3	4 Tage	3 Tage	0
67	Verfüllen Baugr.	4 Tage	2	7 Tage	5,1 Tage	0
68	Aushub	1 Tag	1	2 Tage	1,3 Tage	0
69	Aushub Fund.	2 Tage	2	4 Tage	2,75 Tage	0
70	Fundamente	5 Tage	4	10 Tage	8,1 Tage	0
71	Sauberkeitsschicht	1 Tag	2	3 Tage	1,75 Tage	0
72	Bodenplatte	6 Tage	3	14 Tage	10 Tage	0
73	Montage Schalung	2 Tage	2	5 Tage	3,1 Tage	0
74	Wände/Stützen	18 Tage	4	24 Tage	21,8 Tage	0
75	Treppen	2 Tage	3	6 Tage	4 Tage	0
76	Montage Schalung	8 Tage	2	11 Tage	9,15 Tage	0
77	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0
78	Decke U3	18 Tage	4	23 Tage	21,05 Tage	0
79	Wände/Stützen	17 Tage	4	20 Tage	18,85 Tage	0
80	Treppen	2 Tage	3	4 Tage	3,05 Tage	0
81	Wandvorlauf	8 Tage	3	12 Tage	10,05 Tage	0
82	Decke U2	13 Tage	4	19 Tage	16,7 Tage	0
83	Wände/Stützen	15 Tage	4	21 Tage	18,8 Tage	0,61
84	Demontag. Schalung	1 Tag	3	3 Tage	2 Tage	0
85	Treppen	2 Tage	3	4 Tage	3 Tage	0
86	Wandvorlauf	8 Tage	3	12 Tage	9,95 Tage	0,61
87	Decke U1	18 Tage	4	26 Tage	23,1 Tage	0,61
88	Demontag. Schalung	4 Tage	3	8 Tage	5,95 Tage	0,61
89	Wandabdichtung	3 Tage	3	5 Tage	4 Tage	0
90	Deckenabdichtung	3 Tage	3	5 Tage	3,95 Tage	0
91	Verfüllen Baugr.	3 Tage	2	6 Tage	4,1 Tage	0
92	TDK abbauen	1 Tag	4	4 Tage	2,9 Tage	0
93	Gleise abbauen	5 Tage	3	7 Tage	5,95 Tage	1
94	Baustellenräumung	4 Tage	3	6 Tage	4,95 Tage	1
95	Ende	0 Tage	1	0 Tage	0 Tage	0

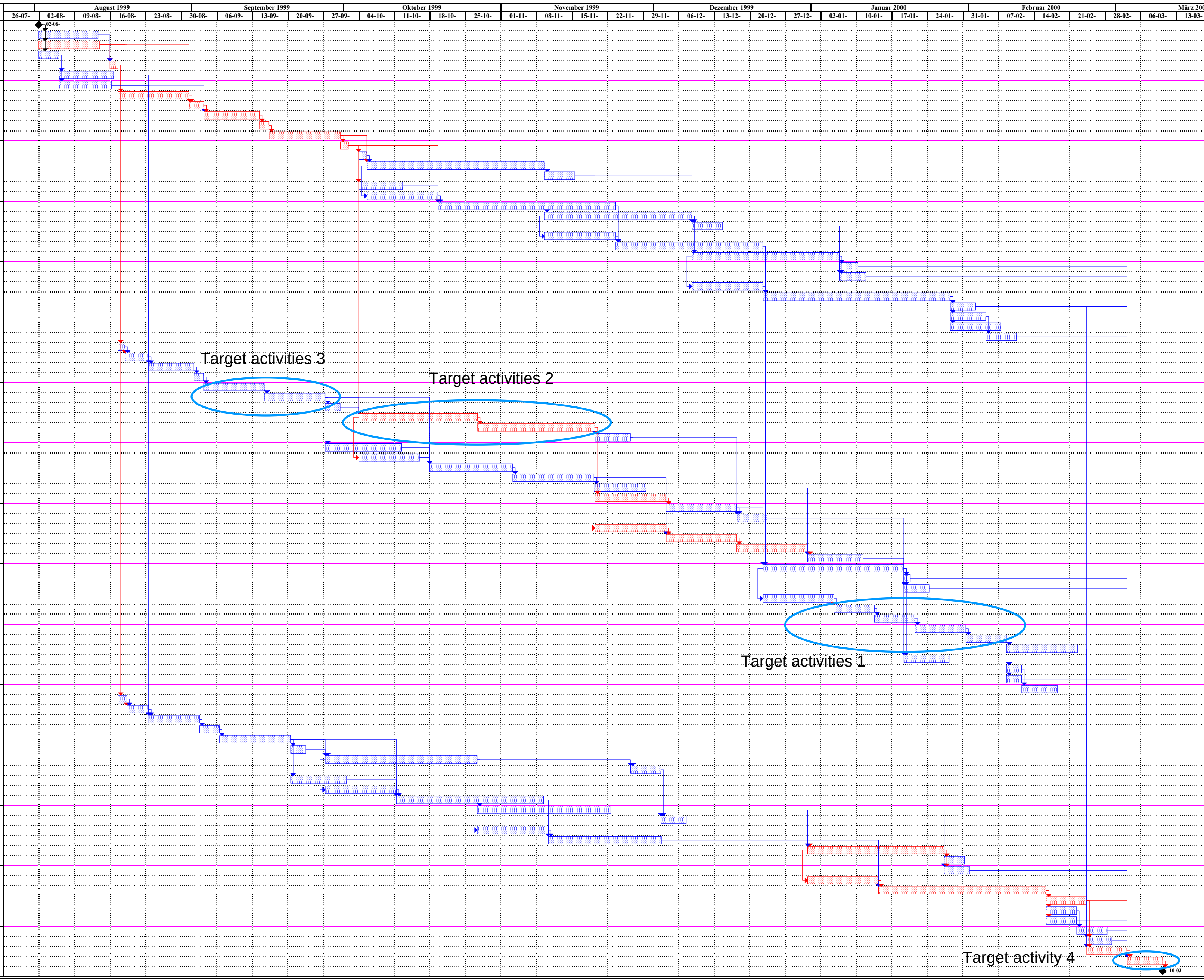


Fig. 9.9: Step 2 - Increased Ties Density - Level 3

Ministry

Nr.	Vorgangsname	OD	c	PD	Beta-D	K. Grad
1	Vergabe	0 Tage	1	0 Tage	0 Tage	1
2	AVO	6 Tage	3	14 Tage	10 Tage	0,51
3	Baust. Einr.	6 Tage	3	14 Tage	10 Tage	0,49
4	Baustr. herst	3 Tage	3	5 Tage	4 Tage	0
5	Stellplatz herst	1 Tag	2	3 Tage	1,75 Tage	1
6	TDK aufbauen	5 Tage	4	8 Tage	6,9 Tage	0
7	Gleise verlegen	4 Tage	3	8 Tage	6 Tage	0
8	Aushub	8 Tage	3	12 Tage	10 Tage	0,83
9	Aushub Fund.	2 Tage	2	4 Tage	2,75 Tage	0,83
10	Fundamente	5 Tage	4	8 Tage	6,9 Tage	0,83
11	Sauberkeitsschicht	1 Tag	2	3 Tage	1,75 Tage	0,83
12	Bodenplatte	6 Tage	3	14 Tage	10,2 Tage	0,83
13	Bodenplatte Rampe	1 Tag	2	3 Tage	1,75 Tage	0,83
14	Montage Schalung	1 Tag	2	3 Tage	1,75 Tage	0,4
15	Wände/Stützen	20 Tage	3	30 Tage	25,05 Tage	0,4
16	Treppen	2 Tage	3	6 Tage	4 Tage	0
17	Montage Schalung	5 Tage	4	8 Tage	6,85 Tage	0
18	Wandvorlauf	8 Tage	3	12 Tage	10,05 Tage	0,18
19	Decke U3/Spindel	20 Tage	4	28 Tage	25 Tage	1
20	Wände/Stützen	18 Tage	4	23 Tage	21,05 Tage	0,21
21	Treppen	2 Tage	3	6 Tage	4 Tage	0
22	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0,21
23	Decke U2/Spindel	16 Tage	4	24 Tage	21,1 Tage	0,4
24	Wände/Stützen	18 Tage	4	23 Tage	21,05 Tage	0
25	Demontag. Schalung	1 Tag	1	2 Tage	1,25 Tage	0
26	Treppen	2 Tage	3	4 Tage	3 Tage	0
27	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0
28	Decke U1/Spindel	23 Tage	4	29 Tage	26,75 Tage	0,95
29	Demontag. Schalung	2 Tage	3	4 Tage	3 Tage	0
30	Wandabdichtung	3 Tage	3	7 Tage	4,95 Tage	0
31	Deckenabdichtung	5 Tage	3	7 Tage	5,95 Tage	0
32	Verfüllung Baugr.	3 Tage	2	6 Tage	4,15 Tage	0
33	Aushub	1 Tag	1	2 Tage	1,3 Tage	0,17
34	Aushub Fund.	2 Tage	2	4 Tage	2,8 Tage	0,17
35	Fundamente	5 Tage	4	8 Tage	6,85 Tage	0,17
36	Sauberkeitsschicht	1 Tag	2	3 Tage	1,75 Tage	0,17
37	Bodenplatte	6 Tage	3	10 Tage	8 Tage	0,17
38	split Bodenplatte	6 Tage	3	10 Tage	8 Tage	0,17
39	Montage Schalung	1 Tag	2	6 Tage	2,85 Tage	0,17
40	Wände/Stützen	14,5 Tage	4	19 Tage	17,3 Tage	0,6
41	split Wände/Stützen	14,5 Tage	4	19 Tage	17,35 Tage	0,6
42	Treppen	2 Tage	3	8 Tage	5,05 Tage	0
43	Montage Schalung	10 Tage	2	13 Tage	11,1 Tage	0
44	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0
45	Decke U3	10,5 Tage	4	13 Tage	12,1 Tage	0,97
46	split Decke U3	10,5 Tage	4	13 Tage	12,05 Tage	0
47	Mauerwerk	5 Tage	2	10 Tage	6,9 Tage	0
48	Wände/Stützen	9 Tage	4	10,5 Tage	9,95 Tage	0,6
49	split Wände/Stützen	9 Tage	4	10,5 Tage	9,9 Tage	0
50	Treppen	2 Tage	3	6 Tage	4 Tage	0
51	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0,6
52	Decke U2	8 Tage	4	11 Tage	9,95 Tage	0,6
53	Split Decke U2	8 Tage	4	11 Tage	9,9 Tage	0,6
54	Mauerwerk	5 Tage	2	10 Tage	6,8 Tage	0
55	Wände/Stützen	17 Tage	4	21 Tage	19,45 Tage	0,4
56	Demontag. Schalung	1 Tag	2	3 Tage	1,75 Tage	0
57	Treppe	2 Tage	3	4 Tage	3 Tage	0
58	Wandvorlauf	8 Tage	3	12 Tage	9,95 Tage	0,4
59	Decke U1	5,75 Tage	3	6,25 Tage	6 Tage	1
60	Split Decke U1	5,75 Tage	3	6,25 Tage	6 Tage	0,4
61	Split Decke U1	5,75 Tage	3	6,25 Tage	6 Tage	0,4
62	Split Decke U1	5,75 Tage	3	6,25 Tage	6 Tage	0,4
63	Demontag. Schalung	9 Tage	3	11 Tage	10,05 Tage	0,4
64	Mauerwerk	5 Tage	2	10 Tage	7 Tage	0
65	Wandabdichtung	2 Tage	3	4 Tage	3,05 Tage	0
66	Deckenabdichtung	2 Tage	3	4 Tage	3 Tage	0
67	Verfüllen Baugr.	4 Tage	2	7 Tage	5,1 Tage	0
68	Aushub	1 Tag	1	2 Tage	1,25 Tage	0
69	Aushub Fund.	2 Tage	2	4 Tage	2,75 Tage	0
70	Fundamente	5 Tage	4	10 Tage	8,1 Tage	0
71	Sauberkeitsschicht	1 Tag	2	3 Tage	1,75 Tage	0
72	Bodenplatte	6 Tage	3	14 Tage	9,95 Tage	0
73	Montage Schalung	2 Tage	2	5 Tage	3,15 Tage	0
74	Wände/Stützen	18 Tage	4	24 Tage	21,8 Tage	0
75	Treppen	2 Tage	3	6 Tage	3,95 Tage	0
76	Montage Schalung	8 Tage	2	11 Tage	9,1 Tage	0
77	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0
78	Decke U3	18 Tage	4	23 Tage	21,2 Tage	0
79	Wände/Stützen	17 Tage	4	20 Tage	18,85 Tage	0
80	Treppen	2 Tage	3	4 Tage	2,95 Tage	0
81	Wandvorlauf	8 Tage	3	12 Tage	9,95 Tage	0
82	Decke U2	13 Tage	4	19 Tage	16,75 Tage	0
83	Wände/Stützen	15 Tage	4	21 Tage	18,6 Tage	0,6
84	Demontag. Schalung	1 Tag	3	3 Tage	1,95 Tage	0
85	Treppen	2 Tage	3	4 Tage	3 Tage	0
86	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0,6
87	Decke U1	18 Tage	4	26 Tage	23,05 Tage	0,6
88	Demontag. Schalung	4 Tage	3	8 Tage	6 Tage	0,6
89	Wandabdichtung	3 Tage	3	5 Tage	4 Tage	0
90	Deckenabdichtung	3 Tage	3	5 Tage	4 Tage	0
91	Verfüllen Baugr.	3 Tage	2	6 Tage	4,15 Tage	0
92	TDK abbauen	1 Tag	4	4 Tage	2,85 Tage	0
93	Gleise abbauen	5 Tage	3	7 Tage	6 Tage	1
94	Baustellenräumung	4 Tage	3	6 Tage	5 Tage	1
95	Ende	0 Tage	1	0 Tage	0 Tage	0

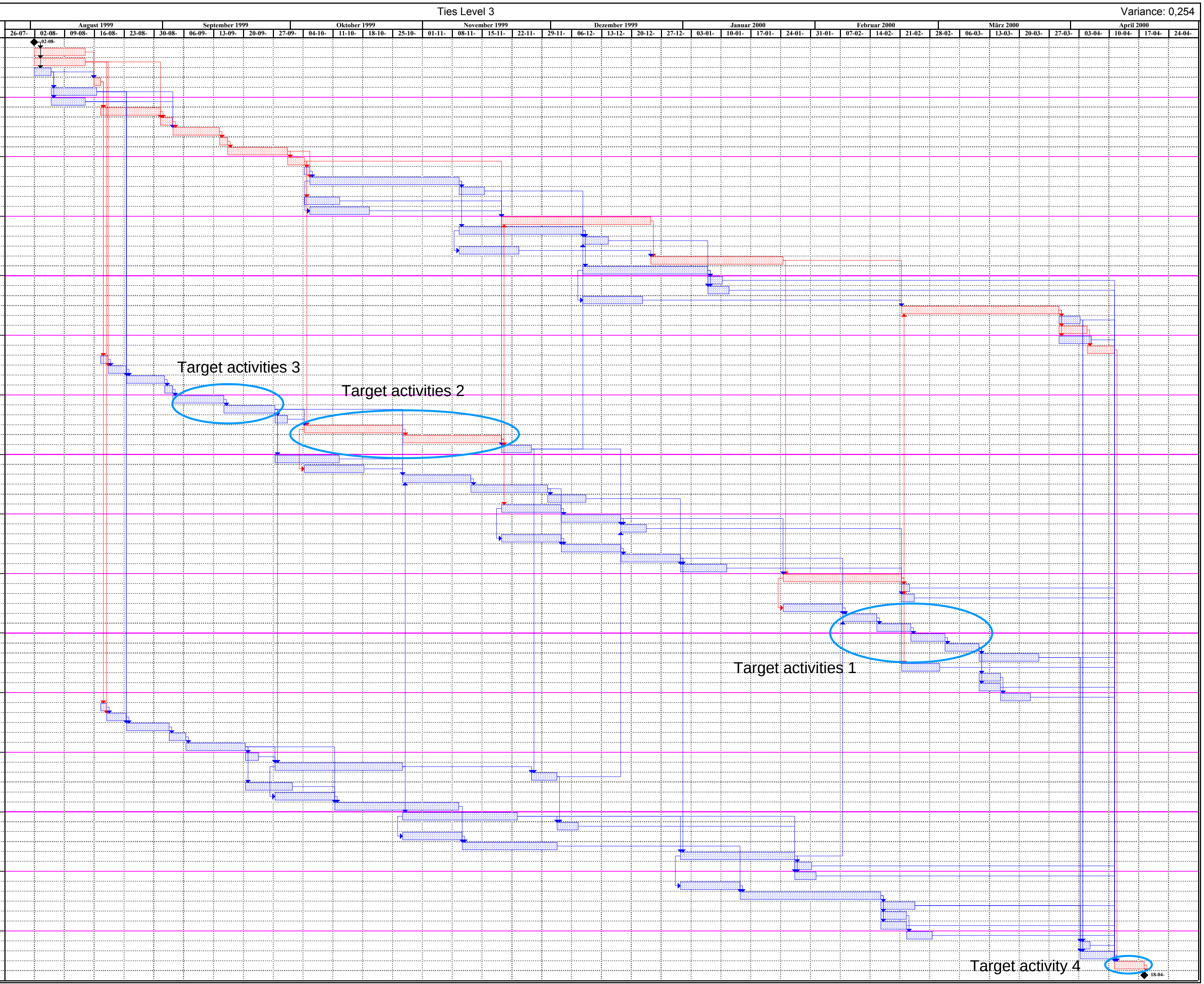
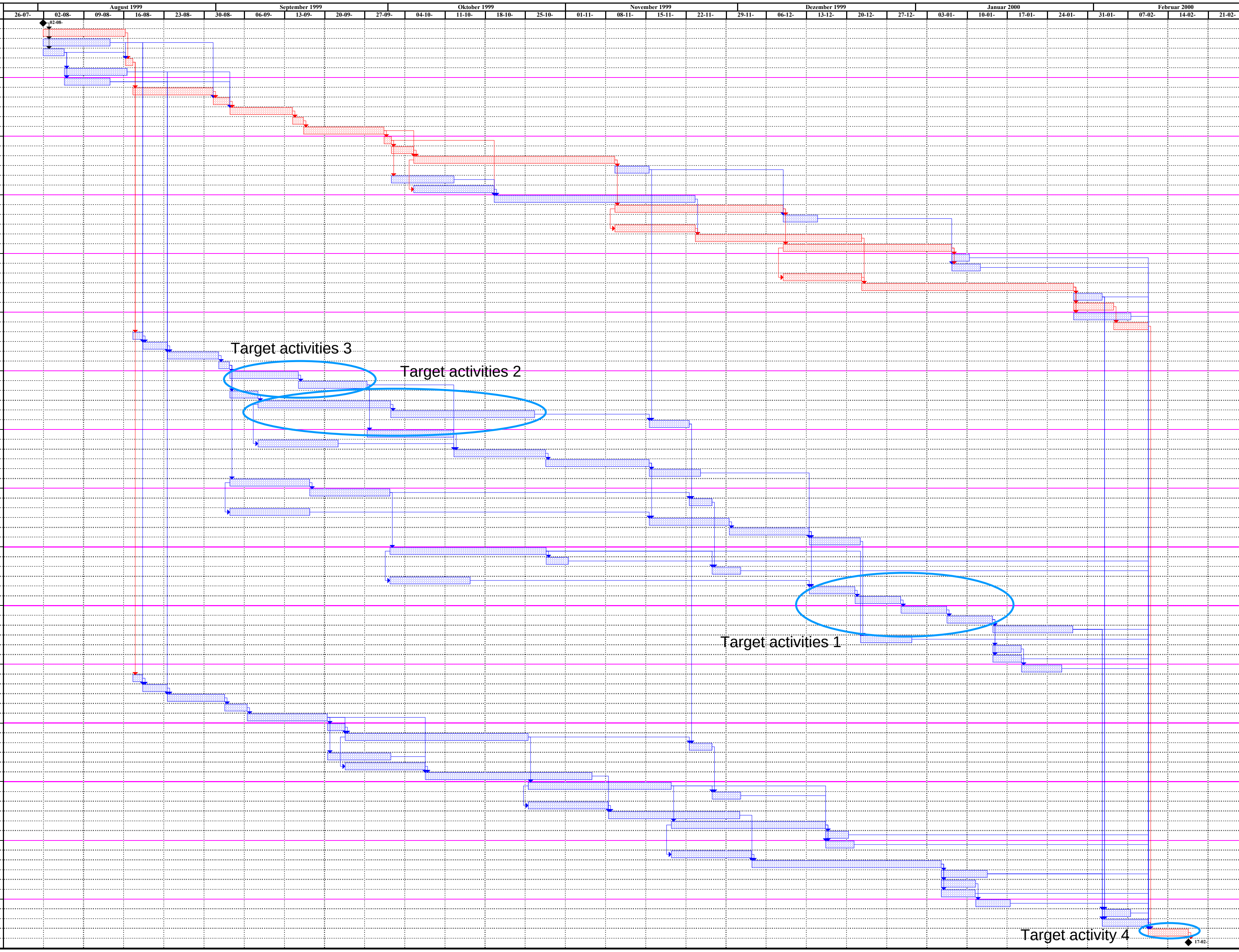


Fig. 9.10: Step 2 - Full Parallelism

Ministry | Full Parallelism | Variance: 0,323

Nr.	Vorgangsname	OD	c	PD	Beta-D	K. Grad
1	Vergabe	0 Tage	1	0 Tage	0 Tage	1
2	AVO	6 Tage	3	14 Tage	10,05 Tage	0,5
3	Baust. Einr.	6 Tage	3	14 Tage	9,95 Tage	0,5
4	Baustr. herst	3 Tage	3	5 Tage	3,95 Tage	0
5	Stellplatz herst	1 Tag	2	3 Tage	1,75 Tage	1
6	TDK aufbauen	5 Tage	4	8 Tage	6,9 Tage	0
7	Gleise verlegen	4 Tage	3	8 Tage	5,95 Tage	0
8	Aushub	8 Tage	3	12 Tage	10 Tage	0,96
9	Aushub Fund.	2 Tage	2	4 Tage	2,75 Tage	0,96
10	Fundamente	5 Tage	4	8 Tage	6,9 Tage	0,96
11	Sauberkeitsschicht	1 Tag	2	3 Tage	1,75 Tage	0,96
12	Bodenplatte	6 Tage	3	14 Tage	10,05 Tage	0,96
13	Bodenplatte Rampe	1 Tag	2	3 Tage	1,7 Tage	0,96
14	Montage Schalung	1 Tag	2	3 Tage	1,75 Tage	0,96
15	Wände/Stützen	20 Tage	3	30 Tage	25,15 Tage	0,96
16	Treppen	2 Tage	3	6 Tage	4 Tage	0
17	Montage Schalung	5 Tage	4	8 Tage	6,85 Tage	0
18	Wandvorlauf	8 Tage	3	12 Tage	10,05 Tage	0,36
19	Decke U3/Spindel	20 Tage	4	28 Tage	25,1 Tage	0,36
20	Wände/Stützen	18 Tage	4	23 Tage	21,15 Tage	0,6
21	Treppen	2 Tage	3	6 Tage	4 Tage	0
22	Wandvorlauf	8 Tage	3	12 Tage	10,05 Tage	0,29
23	Decke U2/Spindel	16 Tage	4	24 Tage	21,05 Tage	0,65
24	Wände/Stützen	18 Tage	4	23 Tage	21,15 Tage	0,31
25	Demontag. Schalung	1 Tag	1	2 Tage	1,3 Tage	0
26	Treppen	2 Tage	3	4 Tage	3 Tage	0
27	Wandvorlauf	8 Tage	3	12 Tage	9,95 Tage	0,31
28	Decke U1/Spindel	23 Tage	4	29 Tage	26,75 Tage	0,96
29	Demontag. Schalung	2 Tage	3	4 Tage	3 Tage	0,45
30	Wandabdichtung	3 Tage	3	7 Tage	5 Tage	0,51
31	Deckenabdichtung	5 Tage	3	7 Tage	6 Tage	0
32	Verfüllung Baugr.	3 Tage	2	6 Tage	4,1 Tage	0,51
33	Aushub	1 Tag	1	2 Tage	1,3 Tage	0,04
34	Aushub Fund.	2 Tage	2	4 Tage	2,75 Tage	0,04
35	Fundamente	5 Tage	4	8 Tage	6,85 Tage	0,04
36	Sauberkeitsschicht	1 Tag	2	3 Tage	1,8 Tage	0,04
37	Bodenplatte	6 Tage	3	10 Tage	7,95 Tage	0,04
38	split Bodenplatte	6 Tage	3	10 Tage	8 Tage	0,04
39	Montage Schalung	1 Tag	2	6 Tage	2,85 Tage	0
40	Wände/Stützen	14,5 Tage	4	19 Tage	17,25 Tage	0
41	split Wände/Stützen	14,5 Tage	4	19 Tage	17,3 Tage	0
42	Treppen	2 Tage	3	8 Tage	4,9 Tage	0
43	Montage Schalung	10 Tage	2	13 Tage	11,2 Tage	0,04
44	Wandvorlauf	8 Tage	3	12 Tage	9,95 Tage	0
45	Decke U3	10,5 Tage	4	13 Tage	12,05 Tage	0,04
46	split Decke U3	10,5 Tage	4	13 Tage	12,1 Tage	0,04
47	Mauerwerk	5 Tage	2	10 Tage	6,85 Tage	0
48	Wände/Stützen	9 Tage	4	10,5 Tage	9,9 Tage	0
49	split Wände/Stützen	9 Tage	4	10,5 Tage	9,95 Tage	0
50	Treppen	2 Tage	3	6 Tage	3,95 Tage	0
51	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0
52	Decke U2	8 Tage	4	11 Tage	9,85 Tage	0,04
53	Split Decke U2	8 Tage	4	11 Tage	9,85 Tage	0,04
54	Mauerwerk	5 Tage	2	10 Tage	6,9 Tage	0
55	Wände/Stützen	17 Tage	4	21 Tage	19,55 Tage	0
56	Demontag. Schalung	1 Tag	2	3 Tage	1,7 Tage	0
57	Treppe	2 Tage	3	4 Tage	3 Tage	0
58	Wandvorlauf	8 Tage	3	12 Tage	10 Tage	0
59	Decke U1	5,75 Tage	3	6,25 Tage	6 Tage	0,04
60	Split Decke U1	5,75 Tage	3	6,25 Tage	6 Tage	0,04
61	Split Decke U1	5,75 Tage	3	6,25 Tage	6 Tage	0,04
62	Split Decke U1	5,75 Tage	3	6,25 Tage	6 Tage	0,04
63	Demontag. Schalung	9 Tage	3	11 Tage	10 Tage	0,04
64	Mauerwerk	5 Tage	2	10 Tage	6,9 Tage	0
65	Wandabdichtung	2 Tage	3	4 Tage	3 Tage	0
66	Deckenabdichtung	2 Tage	3	4 Tage	3,05 Tage	0
67	Verfüllen Baugr.	4 Tage	2	7 Tage	5,1 Tage	0
68	Aushub	1 Tag	1	2 Tage	1,25 Tage	0
69	Aushub Fund.	2 Tage	2	4 Tage	2,75 Tage	0
70	Fundamente	5 Tage	4	10 Tage	8,05 Tage	0
71	Sauberkeitsschicht	1 Tag	2	3 Tage	1,75 Tage	0
72	Bodenplatte	6 Tage	3	14 Tage	10 Tage	0
73	Montage Schalung	2 Tage	2	5 Tage	3,15 Tage	0
74	Wände/Stützen	18 Tage	4	24 Tage	21,8 Tage	0
75	Treppen	2 Tage	3	6 Tage	3,95 Tage	0
76	Montage Schalung	8 Tage	2	11 Tage	9,15 Tage	0
77	Wandvorlauf	8 Tage	3	12 Tage	9,95 Tage	0
78	Decke U3	18 Tage	4	23 Tage	21,25 Tage	0
79	Wände/Stützen	17 Tage	4	20 Tage	18,9 Tage	0
80	Treppen	2 Tage	3	4 Tage	3 Tage	0
81	Wandvorlauf	8 Tage	3	12 Tage	9,95 Tage	0
82	Decke U2	13 Tage	4	19 Tage	16,8 Tage	0
83	Wände/Stützen	15 Tage	4	21 Tage	18,75 Tage	0
84	Demontag. Schalung	1 Tag	3	3 Tage	2 Tage	0
85	Treppen	2 Tage	3	4 Tage	2,95 Tage	0
86	Wandvorlauf	8 Tage	3	12 Tage	10,05 Tage	0
87	Decke U1	18 Tage	4	26 Tage	23,05 Tage	0
88	Demontag. Schalung	4 Tage	3	8 Tage	6,05 Tage	0
89	Wandabdichtung	3 Tage	3	5 Tage	4 Tage	0
90	Deckenabdichtung	3 Tage	3	5 Tage	3,95 Tage	0
91	Verfüllen Baugr.	3 Tage	2	6 Tage	4,1 Tage	0
92	TDK abbauen	1 Tag	4	4 Tage	2,85 Tage	0
93	Gleise abbauen	5 Tage	3	7 Tage	6 Tage	0,49
94	Baustellenräumung	4 Tage	3	6 Tage	5 Tage	1
95	Ende	0 Tage	1	0 Tage	0 Tage	0



Cachadinha and Kulkarni, Inst.für Planungsverfahren im Baubetrieb, RWTH Aachen

Fig. 9.11: Bridge over the Lister Dam - Original Topology

Bridge over the Lister Dam — Original Topology — Variance: 0,933

Nr.	Vorgangsname	OD	c	PD	Beta-D	K. Grad
1	Anfang	0 Tage	1	0 Tage	0 Tage	0
2	Strasse Brücke	3 Tage	4	8 Tage	6,15 Tage	1
3	Strasse 1a	3 Tage	4	8 Tage	6,15 Tage	0
4	Strasse 2a	3 Tage	4	8 Tage	6,1 Tage	0
5	Strasse 1b	8 Tage	4	16 Tage	13 Tage	0
6	Strasse 2b	4 Tage	4	8 Tage	6,45 Tage	0
7	Strasse 3b	6 Tage	4	12 Tage	9,7 Tage	0
8	Strasse 3a	1 Tag	4	3 Tage	2,25 Tage	0
9	Strasse 1c	3 Tage	4	8 Tage	6,1 Tage	0
10	ÖN Fundament	2 Tage	2	6 Tage	3,45 Tage	0
11	ÖN Wände	6 Tage	2	8 Tage	6,75 Tage	0
12	ÖN Treppe	1 Tag	2	1 Tag	1 Tag	0
13	ÖN Decken	2 Tage	2	5 Tage	3,15 Tage	0
14	ÖN Isolierarbeiten	2 Tage	3	4 Tage	3 Tage	0
15	ÜS Fundament	3 Tage	2	6 Tage	4,1 Tage	1
16	ÖS Wände	6 Tage	2	9 Tage	7,1 Tage	1
17	ÖS Treppe	1 Tag	2	1 Tag	1 Tag	1
18	ÖS Decken	2 Tage	2	5 Tage	3,15 Tage	1
19	ÖS Isolierarbeiten	2 Tage	3	4 Tage	3 Tage	1
20	ÖN Aushub	1 Tag	4	3 Tage	2,25 Tage	0
21	ÖN Andecken	1 Tag	3	1 Tag	1 Tag	0
22	ÖS Aushub	1 Tag	4	3 Tage	2,2 Tage	0
23	ÖS Andecken	0,5 Tage	3	1,5 Tage	1 Tag	1
24	WLN Fundament	4 Tage	2	8 Tage	5,5 Tage	0
25	WLN Wände	13 Tage	2	18 Tage	14,85 Tage	0
26	WLN Kontrollgang	1 Tag	2	4 Tage	2,1 Tage	0
27	FWNW Fundament	2 Tage	2	5 Tage	3,1 Tage	0
28	FWNW Wände	2 Tage	2	5 Tage	3,15 Tage	0
29	FWNO Fundament	3 Tage	2	6 Tage	4,15 Tage	0
30	FWNO Wände	5 Tage	2	8 Tage	6,15 Tage	0
31	WLS Fundament	2 Tage	2	5 Tage	3,1 Tage	0
32	WLS Wände	6 Tage	2	8 Tage	6,75 Tage	0
33	WLS Kontrollgang	1 Tag	2	1 Tag	1 Tag	0
34	FWSO Fundament	1 Tag	2	1 Tag	1 Tag	0
35	FWSO Wände	1 Tag	2	4 Tage	2,1 Tage	0
36	FWSW Fundament	1 Tag	2	1 Tag	1 Tag	0
37	FWSW Wände	1 Tag	2	4 Tage	2,2 Tage	0
38	ÜB 1	25 Tage	3	35 Tage	30 Tage	1
39	ÜB 2	25 Tage	3	35 Tage	30,05 Tage	1
40	ÜB 3	20 Tage	3	30 Tage	25,15 Tage	1
41	ÜB 4	20 Tage	3	30 Tage	24,95 Tage	1
42	ÜB 5	20 Tage	3	30 Tage	24,9 Tage	1
43	ÜB 6	20 Tage	3	30 Tage	25 Tage	1
44	ÜB 7	15 Tage	3	25 Tage	20,1 Tage	1
45	ÜB 8	15 Tage	3	25 Tage	19,9 Tage	1
46	PF 1 Fundament	1 Tag	2	1 Tag	1 Tag	0
47	PF 1 Schaft	10 Tage	2	14 Tage	11,45 Tage	0
48	PF 1 Pfeilerkopf	6 Tage	2	8 Tage	6,75 Tage	0
49	PF 2 Fundament	1 Tag	2	1 Tag	1 Tag	0
50	PF 2 Schaft	10 Tage	2	14 Tage	11,55 Tage	0
51	PF 2 Pfeilerkopf	6 Tage	2	9 Tage	7,15 Tage	0
52	PF 3 Fundament	1 Tag	2	1 Tag	1 Tag	0
53	PF 3 Schaft	10 Tage	2	14 Tage	11,45 Tage	0
54	PF 3 Pfeilerkopf	6 Tage	2	9 Tage	7,15 Tage	0
55	PF 4 Fundament	1 Tag	2	1 Tag	1 Tag	0
56	PF 4 Schaft	10 Tage	2	14 Tage	11,5 Tage	0
57	PF 4 Pfeilerkopf	6 Tage	2	9 Tage	7,1 Tage	0
58	PF 5 Fundament	1 Tag	2	1 Tag	1 Tag	0
59	PF 5 Schaft	10 Tage	2	14 Tage	11,5 Tage	0
60	PF 5 Pfeilerkopf	6 Tage	2	9 Tage	7,15 Tage	0
61	PF 6 Fundament	1 Tag	2	1 Tag	1 Tag	0
62	PF 6 Schaft	10 Tage	2	14 Tage	11,5 Tage	0
63	PF 6 Pfeilerkopf	6 Tage	2	9 Tage	7,05 Tage	0
64	PF 7 Fundament	1 Tag	2	1 Tag	1 Tag	0
65	PF 7 Schaft	10 Tage	2	14 Tage	11,5 Tage	0
66	PF 7 Pfeilerkopf	6 Tage	2	9 Tage	7,15 Tage	0
67	BGS Aushub	1 Tag	4	4 Tage	2,8 Tage	0
68	BGN Aushub	2 Tage	4	6 Tage	4,5 Tage	0
69	BGN Verfüllen	2 Tage	4	6 Tage	4,45 Tage	0
70	BGS Verfüllen	2 Tage	4	5 Tage	3,85 Tage	0
71	PF 1 Spundwände	1 Tag	5	4 Tage	3,2 Tage	0
72	PF 2 Spundwände	1 Tag	5	4 Tage	3,2 Tage	0
73	PF 3 Spundwände	1 Tag	5	5 Tage	3,95 Tage	0
74	PF 4 Spundwände	2 Tage	5	6 Tage	5 Tage	0
75	PF 5 Spundwände	2 Tage	5	6 Tage	4,95 Tage	0
76	PF 6 Spundwände	1 Tag	5	5 Tage	3,9 Tage	0
77	PF 7 Spundwände	1 Tag	5	4 Tage	3,15 Tage	0
78	ÜB Ausbau	70 Tage	3	90 Tage	80 Tage	1
79	BE	3 Tage	3	9 Tage	5,9 Tage	0
80	Baustrasse	2 Tage	4	7 Tage	5,1 Tage	0
81	Drag BB	2 Tage	1	2 Tage	2 Tage	0
82	Behelfsbrücke	3 Tage	2	6 Tage	4,1 Tage	0
83	BE Entfernen	8 Tage	3	12 Tage	10 Tage	0
84	Abriss Brücke	50 Tage	3	70 Tage	59,8 Tage	1
85	Baustrasse entf.	4 Tage	3	6 Tage	4,95 Tage	1
86	Ende	0 Tage	1	0 Tage	0 Tage	0

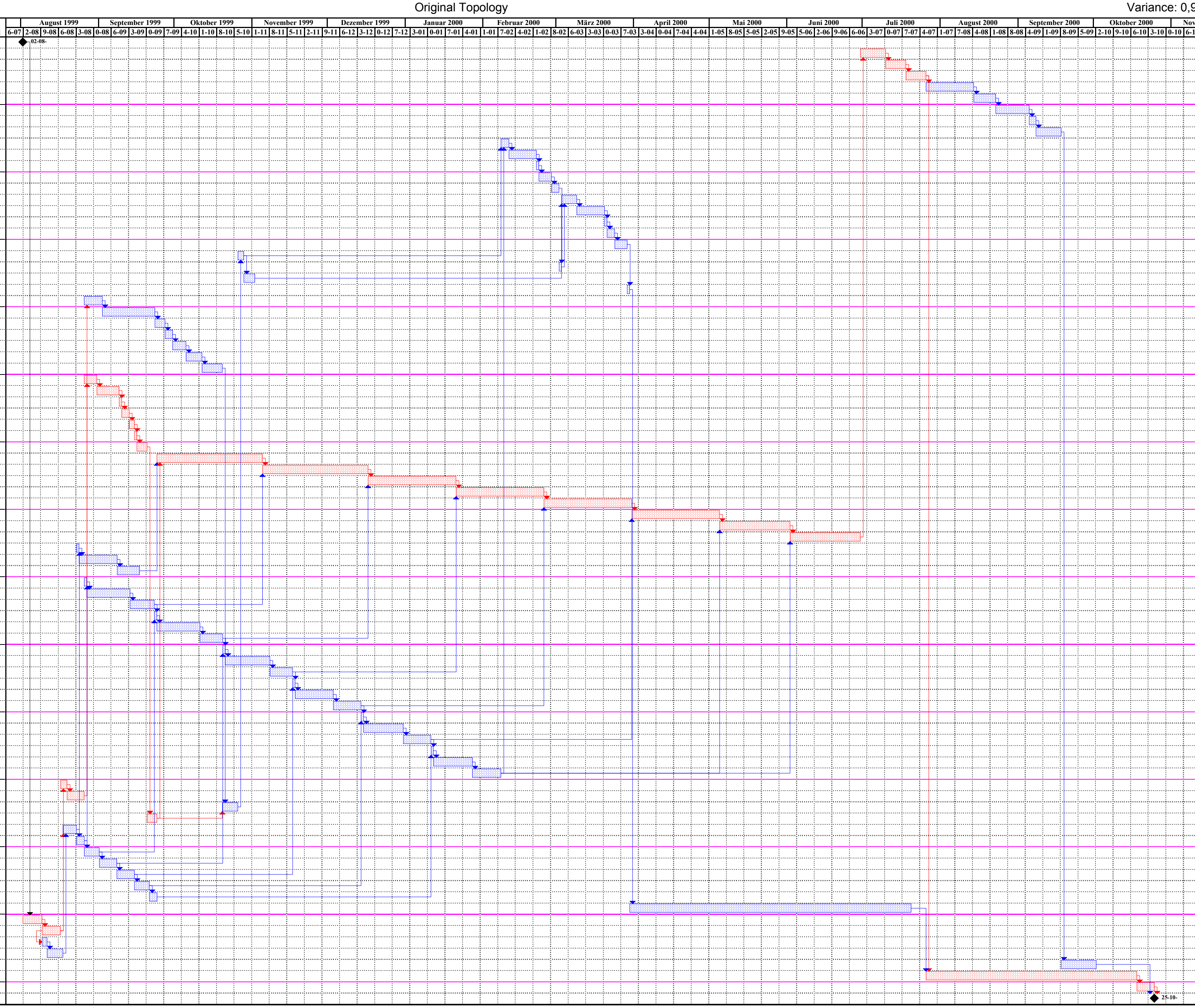


Fig. 9.12: New Convention Center Munich - Original Topology

New Convention Center Munich — Original Topology — Variance: 4,88

Nr.	Vorgangsname	OD	c	PD	Beta-D
1	F/B Platte	5 Wochen	4	10 Wochen	40,5 Tage
2	F/B Platte	5 Wochen	3	8 Wochen	32,5 Tage
3	F/B Platte	5 Wochen	3	8 Wochen	32,25 Tage
4	F/B Platte	5 Wochen	3	8 Wochen	32,35 Tage
5	F/B Platte	5 Wochen	4	8 Wochen	34,6 Tage
6	F/B Platte	5 Wochen	4	8 Wochen	33,95 Tage
7	W WUBeton /UG	6 Wochen	4	13 Wochen	51,8 Tage
8	W WUBeton /UG	6 Wochen	3	10 Wochen	40 Tage
9	W WUBeton /UG	6 Wochen	3	10 Wochen	40,35 Tage
10	W WUBeton /UG	6 Wochen	4	10 Wochen	42,45 Tage
11	W WUBeton /UG	6 Wochen	4	10 Wochen	42,35 Tage
12	W WUBeton /UG	6 Wochen	4	10 Wochen	42,6 Tage
13	W+S /UG	8 Wochen	4	15 Wochen	61,6 Tage
14	W+S /UG	8 Wochen	3	11 Wochen	47,3 Tage
15	W+S /UG	8 Wochen	3	11 Wochen	47,4 Tage
16	W+S /UG	8 Wochen	4	11 Wochen	49,15 Tage
17	W+S /UG	8 Wochen	4	11 Wochen	49,05 Tage
18	W+S /UG	8 Wochen	4	11 Wochen	49,25 Tage
19	D+U /UG	9 Wochen	4	16 Wochen	66,65 Tage
20	D+U /UG	9 Wochen	3	12 Wochen	52,4 Tage
21	D+U /UG	9 Wochen	3	12 Wochen	52,7 Tage
22	D+U /UG	9 Wochen	4	12 Wochen	54,2 Tage
23	D+U /UG	9 Wochen	4	12 Wochen	54,55 Tage
24	D+U /UG	9 Wochen	4	12 Wochen	54,35 Tage
25	W+S /EG	9 Wochen	5	19 Wochen	81,8 Tage
26	W+S /EG	9 Wochen	4	13 Wochen	57,05 Tage
27	W+S /EG	9 Wochen	4	13 Wochen	57,15 Tage
28	W+S /EG	9 Wochen	4	13 Wochen	57,6 Tage
29	W+S /EG	9 Wochen	4	13 Wochen	57,85 Tage
30	W+S /EG	9 Wochen	4	13 Wochen	57,3 Tage
31	D+U /EG	9 Wochen	5	24 Wochen	99,45 Tage
32	D+U /EG	9 Wochen	4	13 Wochen	57,35 Tage
33	D+U /EG	9 Wochen	4	13 Wochen	57,7 Tage
34	D+U /EG	9 Wochen	4	13 Wochen	57,55 Tage
35	D+U /EG	9 Wochen	4	13 Wochen	57,45 Tage
36	D+U /EG	9 Wochen	4	13 Wochen	57,65 Tage
37	W+B+S /1.OG	8 Wochen	5	28 Wochen	113,75 Tage
38	W+B+S /1.OG	8 Wochen	4	11 Wochen	49,3 Tage
39	W+B+S /1.OG	8 Wochen	4	11 Wochen	49,45 Tage
40	W+B+S /1.OG	8 Wochen	4	11 Wochen	49,3 Tage
41	W+B+S /1.OG	8 Wochen	4	11 Wochen	49,1 Tage
42	W+B+S /1.OG	8 Wochen	4	11 Wochen	49,5 Tage
43	D+U /1. OG	8 Wochen	5	27 Wochen	109,5 Tage
44	D+U /1. OG	8 Wochen	3	11 Wochen	47,7 Tage
45	D+U /1. OG	8 Wochen	3	11 Wochen	47,6 Tage
46	D+U /1. OG	8 Wochen	3	11 Wochen	47,55 Tage
47	D+U /1. OG	8 Wochen	3	11 Wochen	47,45 Tage
48	D+U /1. OG	8 Wochen	3	11 Wochen	47,4 Tage
49	Ende	0 Tage	3	0 Tage	0 Tage

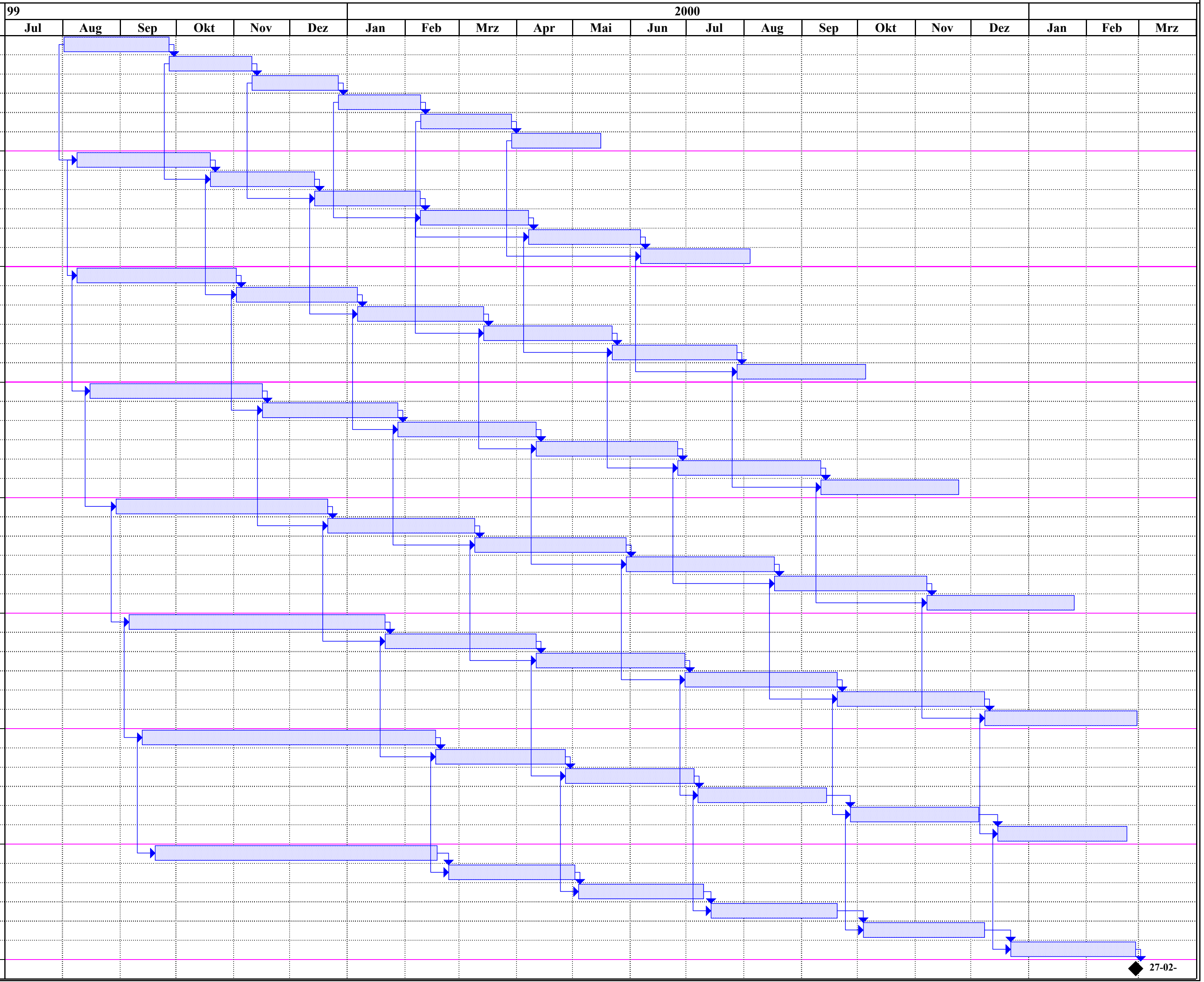
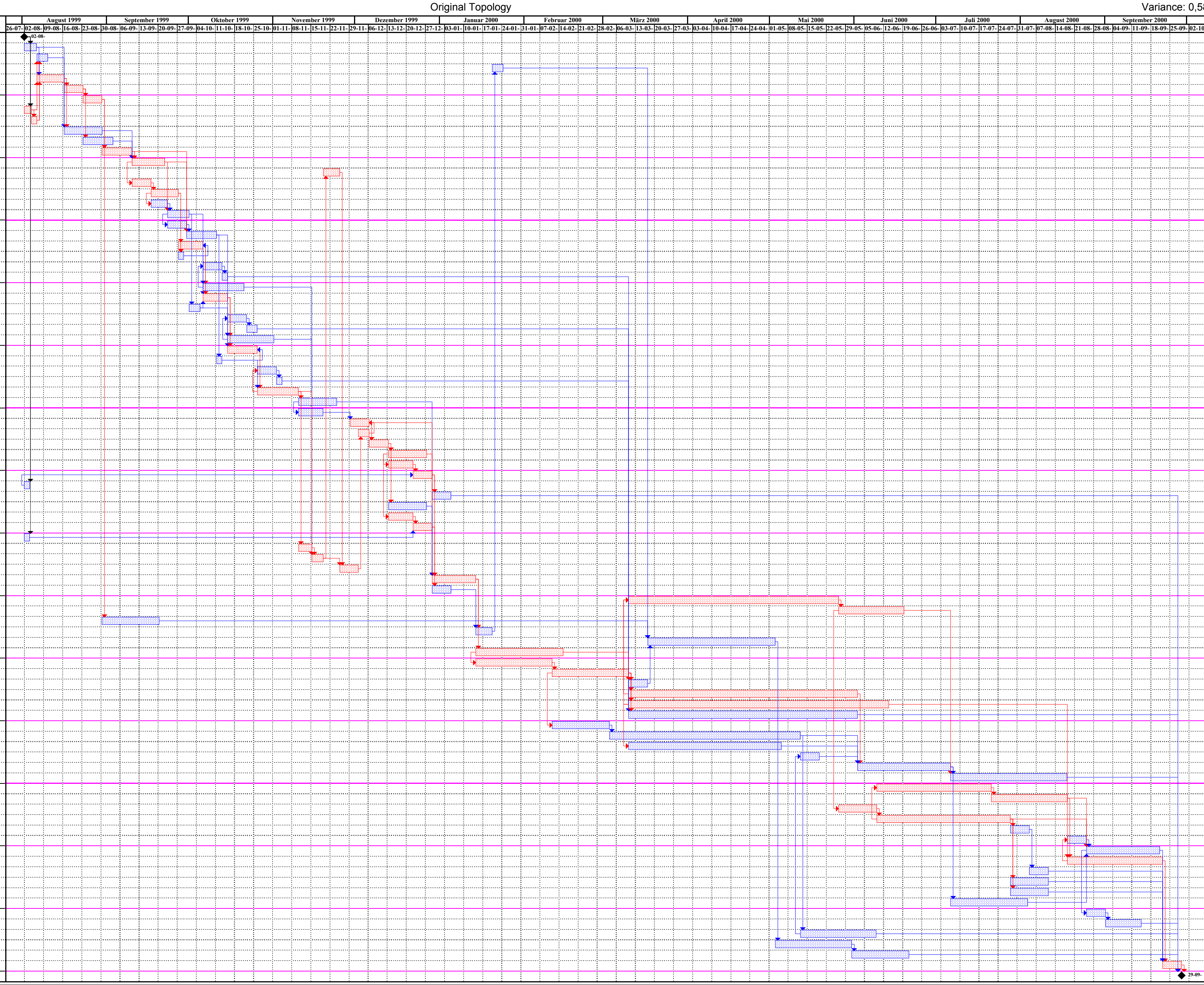


Fig. 9.13: Workshop - Original Topology

Workshop | Original Topology | Variance: 0,581

Nr.	Vorgangsname	OD	c	PD	Beta-D	K. Grad
1	Anfang	0 Tage	1	0 Tage	0 Tage	1
2	BE	4 Tage	3	5 Tage	4,5 Tage	1
3	Kran aufbauen	1 Tag	3	3 Tage	2 Tage	1
4	Kran abbauen	1 Tag	3	3 Tage	2,05 Tage	1
5	Erdarbeiten A-H	4 Tage	4	7 Tage	5,9 Tage	1
6	Erdarbeiten H-O	3 Tage	4	6 Tage	4,85 Tage	1
7	Erdarbeiten O-V	3 Tage	4	6 Tage	4,9 Tage	1
8	Oberboden abschieben	1 Tag	4	4 Tage	2,85 Tage	0
9	Baustrasse einrichten	1 Tag	3	3 Tage	2 Tage	0
10	Fundamente A-H	8 Tage	3	12 Tage	10 Tage	1
11	Fundamente H-O	7 Tage	3	11 Tage	9 Tage	1
12	Fundamente O-V	7 Tage	3	11 Tage	9 Tage	1
13	Unterbau Bodenplatte	6 Tage	3	10 Tage	8 Tage	1
14	Grundleitungen	3 Tage	3	5 Tage	4 Tage	0
15	Drag Bodenplatte A-H	5 Tage	1	5 Tage	5 Tage	1
16	Bodenplatte A-H	4 Tage	3	8 Tage	6 Tage	1
17	Drag Bodenplatte H-O	4 Tage	1	4 Tage	4 Tage	1
18	Bodenplatte H-O	4 Tage	3	8 Tage	5,95 Tage	1
19	Drag Bodenplatte O-V	5 Tage	1	5 Tage	5 Tage	1
20	Bodenplatte O-V	5 Tage	3	9 Tage	7 Tage	1
21	Stüzen KK A-H	5 Tage	3	9 Tage	7,05 Tage	1
22	tragende Wände KK A-H	2 Tage	1	2 Tage	2 Tage	0
23	Drag nichttr. W KK A-H	5 Tage	1	5 Tage	5 Tage	1
24	nichttrag. Wände KK A-H	1,5 Tage	3	2,5 Tage	2 Tage	0
25	Decke KK A-H	9 Tage	3	13 Tage	11,05 Tage	0
26	Stüzen KK H-O	5 Tage	3	9 Tage	7 Tage	1
27	tragende Wände KK H-O	1,5 Tage	3	2,5 Tage	2 Tage	0
28	Drag nichttr. W KK H-O	5 Tage	1	5 Tage	5 Tage	1
29	nichtrag. Wände KK H-O	1,5 Tage	1	2,5 Tage	1,75 Tage	0
30	Decke KK H-O	9 Tage	3	13 Tage	11 Tage	0
31	Stüzen KK O-V	5 Tage	3	9 Tage	6,95 Tage	1
32	Trag. Wände KK O-V	1,5 Tage	3	2,5 Tage	2 Tage	1
33	Drag Nichttr. W KK O-V	5 Tage	1	5 Tage	5 Tage	1
34	nichttrag. Wände KK O-V	1,5 Tage	3	2,5 Tage	2,05 Tage	0
35	Decke KK O-V	9 Tage	3	13 Tage	11,05 Tage	1
36	Stüzen EG A-H	8 Tage	3	12 Tage	10,05 Tage	1
37	Drag Wände EG A-H	7 Tage	1	7 Tage	7 Tage	1
38	Wände EG A-H	3 Tage	3	7 Tage	4,95 Tage	1
39	Gerüst aufbauen A-H	1,5 Tage	3	2,5 Tage	2 Tage	0
40	Decke Lichtgraben D-E	4 Tage	2	7 Tage	5,15 Tage	1
41	Stüzen EG H-O	8 Tage	3	12 Tage	10,1 Tage	1
42	Drag W EG H-O	7 Tage	1	7 Tage	7 Tage	1
43	Wände EG H-O	4 Tage	3	6 Tage	5 Tage	1
44	Gerüst aufbauen H-O	1,5 Tage	3	2,5 Tage	2 Tage	0
45	Decke Lichtgraben J-K	3 Tage	3	7 Tage	4,95 Tage	0,78
46	Stüzen EG O-V	8 Tage	3	12 Tage	9,95 Tage	1
47	Drag Wände EG O-V	7 Tage	1	7 Tage	7 Tage	1
48	Wände EG O-V	3 Tage	3	7 Tage	5 Tage	1
49	Gerüst aufbauen O-V	1,5 Tage	3	2,5 Tage	2 Tage	0
50	Kellerlichtschächte	1 Tag	4	4 Tage	2,85 Tage	0
51	Abdichtungsarbeiten	2 Tage	4	6 Tage	4,5 Tage	0
52	Arbeitsraum verfülen	2 Tage	4	6 Tage	4,5 Tage	0
53	Ringbalken/Ortgänge	9 Tage	4	14 Tage	12,1 Tage	1
54	Treppen	4 Tage	3	6 Tage	5 Tage	0,99
55	Drag Schutzestrich	55 Tage	1	55 Tage	55 Tage	1
56	Schutzestrich	14 Tage	3	18 Tage	16 Tage	0
57	Kanalarbeiten	13 Tage	3	17 Tage	15 Tage	1
58	Stützmauern	3 Tage	3	5 Tage	4,05 Tage	1
59	Platzbauarbeiten	20 Tage	4	40 Tage	32,55 Tage	1
60	Zimmerarbeiten	20 Tage	3	24 Tage	22,05 Tage	1
61	Drag Dachdecker	20 Tage	1	20 Tage	20 Tage	1
62	Dachdecker	15 Tage	3	25 Tage	20 Tage	1
63	Gerüst abbauen	4 Tage	3	6 Tage	5 Tage	1
64	Heizung	55 Tage	3	65 Tage	59,95 Tage	1
65	Sanitär	55 Tage	4	75 Tage	67,35 Tage	1
66	Elektro/Trafo	55 Tage	3	65 Tage	59,95 Tage	1
67	Drag H/Alufenster	15 Tage	1	15 Tage	15 Tage	1
68	Holz-/Alufenster	45 Tage	3	55 Tage	49,95 Tage	1
69	Drag PA 1	40 Tage	1	40 Tage	40 Tage	1
70	Drag PA2	5 Tage	1	5 Tage	5 Tage	1
71	Putzarbeiten	20 Tage	4	27 Tage	24,3 Tage	1
72	Schlosser/Metall	25 Tage	3	35 Tage	30,15 Tage	1
73	Drag Trockenbau	30 Tage	1	30 Tage	30 Tage	0
74	Trockenbau	10 Tage	3	30 Tage	19,8 Tage	0
75	Drag FF	10 Tage	1	10 Tage	10 Tage	0
76	Fliesen/Fussböden	33 Tage	3	37 Tage	35 Tage	0
77	Türen	4 Tage	3	6 Tage	4,95 Tage	0
78	Drag Maler	5 Tage	1	5 Tage	5 Tage	1
79	Maler	12 Tage	4	23 Tage	18,65 Tage	1
80	Schreiner	20 Tage	3	30 Tage	24,85 Tage	1
81	Schliessanlage	4 Tage	3	6 Tage	5 Tage	0
82	WC-Trennwände	8 Tage	3	12 Tage	9,95 Tage	0
83	bewegliche Trennwände	8 Tage	3	12 Tage	10 Tage	0
84	Absaug-/Druckluft	10 Tage	3	30 Tage	20,1 Tage	1
85	Drag Küchenausgabe	5 Tage	1	5 Tage	5 Tage	0
86	Küchenausgabe	5 Tage	4	12 Tage	9,35 Tage	0
87	Fensterbänke/Naturstein	10 Tage	5	23 Tage	19,55 Tage	1
88	Bepflanzungen	18 Tage	3	22 Tage	20,05 Tage	1
89	Zaunanlage	14 Tage	2	17 Tage	15,05 Tage	1
90	Baustelle räumen	3 Tage	4	6 Tage	4,9 Tage	1
91	Ende	0 Tage	1	0 Tage	0 Tage	0



Cachadinha and Kulkarni, Inst.für Planungsverfahren im Baubetrieb, RWTH Aachen

Lebenslauf

Name: Nuno Manuel Pereira Miguéis Cachadinha
Geburtsdatum und Ort: 19. Juni 1971, Lissabon, Portugal
Familienstand: verheiratet
Staatsangehörigkeit: portugiesisch

Ausbildung:

Jan. 98 - Apr. 98: 4 Kenntnisprüfungen zur Zulassung zur Promotion an der RWTH Aachen
Ergebnis: Zulassung zur Promotion an der Fak. Für Bauingenieur- und Vermessungswesen der RWTH Aachen

Jan. 90 – Jan. 95: Studium des Bauingenieurwesens am Instituto Superior Técnico der TU Lissabon (Portugal)
Abschluss und Prädikat: Licenciado em Eng. Civil (Dipl.-Ing.), 14 Valores

Sep. 89 – Dez. 89: Ausbildung zum Programmierer im Instituto Superior Técnico der TU Lissabon (Portugal)
Abschluss: Programmierer

Sep. 81 – Jun. 89: Gymnasium an der Deutschen Schule Lissabon
Abschluss und Prädikat: Abitur; 1,6

Berufliche Tätigket:

Seit Okt. 97: Forschungsassistent am Inst. Für Planungsverfahren im Baubetrieb der RWTH Aachen

Jan. 95 – Okt. 97: Ingenieur an der Firma Turner Steiner International (Sitz: New York)

Mai. 96 – Okt. 97: Assistant Project Superintendent am Consortium Turner Steiner/ICF Kaiser/Proman/Cinclus. für die Firma Turner Steiner International (New York). Zuständig für die Steuerung, Koordination und Inspektion der Fassaden (Wert: 15 Mio EURO) der Baustelle Colombo in Lissabon (Gesamtwert und –baufläche: 500 Mio EURO, 500 000 m2)

Nov. 95 – Mai 96: Office Engineer am Engineering Dept. des Consortiums TS/K/P/C. Tätig am Design Coordination der Fassaden des Gebäudes Colombo

Nov. 95 – Dez. 95: Offizier am Hauptquartier Lissabon des Portugiesischen Armees. Zuständig für die Fahrzeugslogistik der Einheit

Sep. 95 – Okt. 95: Grundausbildung des allgemeinen Pflichtwehrdienstes

Jan. 95 – Sep. 95: Assistant of the Construction Dept. Manager am Consortium TS/K/P/C

Veröffentlichungen:

"Project Delivery Methods for Large Scale Building Projects", IST Science & Technology Nr. 3 (Dez. 98), zusammen mit Prof. Loforte Ribeiro (IST/TU Lissabon)

"Architettura Prefabbricata –L'obra Colombo a Lisbona Project Management's Point of View", L'Edilizia Nr 11/12 (Dez. 98), De Lettera Editore, Mailand, Vorwort von Prof. F. Finzi (Politecnico di Milano)

Konferenzen:

Mai 99: Specialized Conference on Project Management 1999 in Lissabon, Portugal
Vortrag zum Thema: " Effect of the Schedule Structure in the Impact of Single Activity Delays in the Project Total Duration"

Sept. 99: Deutsch-Litauisch-Polnisches Kolloquium zum Baubetriebswesen in Aachen, Deutschland
Vortrag zum Thema: „Uncertainty in Construction Scheduling"

März 00: Conference of Postgraduate Research in the Built and Human Environment" in Salford, England
Vortrag zum Thema:"Quality in Construction Scheduling and Delivery Date Assurance"

Jan. 01: First International Structural Engineering and Construction Conference in Honolulu, USA
Vortrag zum Thema:" Stochastic Simulation and Schedule Optimization"