COMPARISON OF THE RESOURCE ALLOCATION
CAPABILITIES OF PROJECT MANAGEMENT SOFTWARE
PACKAGES IN RESOURCE CONSTRAINED PROJECT
SCHEDULING PROBLEMS

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ÖZGE HEKIMOĞLU

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Approval of the Graduate School of Natural and Applied Sciences.

<div align="right">

_____

Prof. Dr. Canan Özgen

Director
</div>

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

<div align="right">

_____

Prof. Dr. Çağlar Güven

Head of Department
</div>

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

<div align="right">

_____

Assoc. Prof. Dr. Canan Sepil

Supervisor
</div>

Examining Committee Members

Prof. Dr. Gülser Köksal   (METU, IE)   _____

Assoc. Prof. Dr. Canan Sepil   (METU, IE)   _____

Assoc. Prof. Dr. Levent Kandiller (METU, IE)   _____

Assoc. Prof. Dr. Yasemin Serin   (METU, IE)   _____

Nilgün Ortaç Bilir   (ASELSAN)   _____

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Name, Last name: Özge HEKİMOĞLU

Signature   :

ABSTRACT

COMPARISON OF THE RESOURCE ALLOCATION CAPABILITIES OF PROJECT MANAGEMENT SOFTWARE PACKAGES IN RESOURCE CONSTRAINED PROJECT SCHEDULING PROBLEMS

HEKIMOĞLU, Özge

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Supervisor: Assoc. Prof. Dr. Canan SEPIL

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In this study, results of a comparison on benchmark test problems are presented to investigate the performance of Primavera V.4.1 with its two resource allocation priority rules and MS Project 2003. Resource allocation capabilities of the packages are measured in terms of deviation from the upper bound of the minimum makespan. Resource constrained project scheduling problem instances are taken from PSPLIB which are generated under a factorial design from ProGen. Statistical tests are applied to the results for investigating the significance effectiveness of the parameters.

Key Words: Project Scheduling, Project Management Software Packages, Resource Allocation, Experimental Design

ÖZ

SINIRLI KAYNAK KULLANIMLI PROJE ÇİZELGELEMESİ PROBLEMLERİNDE PROJE YÖNETİMİ YAZILIM PAKETLERİNİN KAYNAK ATAMA KABİLİYETLERİNİN KARŞILAŞTIRILMASI

HEKİMOĞLU, Özge

Yüksek Lisans Tezi, Endüstri Mühendisliği Bölümü

Tez Yöneticisi: Doç. Dr. Canan SEPİL

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Bu çalışmada, kaynak atamada kullandığı iki öncelik kuralı ile Primavera V.4.1'in ve MS Project 2003'ün performans değerlendirmesi, referans kabul edilen test problemleri bazında karşılaştırmalı olarak sonuçları sunulmuştur. Yazılımların kaynak atama kabiliyetleri bulunan en iyi değerden sapma miktarına bağlı olarak kaynak atama kabiliyetleri ölçülmüştür. PSPLIB'den alınan kısıtlı kaynaklarla proje çizelgeleme problemleri, ProGen tarafından faktörel tasarım altında üretilmiştir. Elde edilen Sonuçlara istatistiksel testler uygulayarak parametrelerin etkinliği araştırılmıştır.

Anahtar Kelimeler : Proje Çizelgelemesi, Proje Yönetimi Yazılım Paketleri, Kaynak Ataması, Deneysel Tasarım

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CHAPTER I

INTRODUCTION

A project can be defined as a combination of interrelated activities that must be performed in a certain sequence. Until 1950's, the management of projects was done by the use of Gantt charts, which specify the start and finish times of each activity on a horizontal time scale. The disadvantage of this technique is that the interdependency between different activities can not be represented.

In the late 1950's, namely 1956-1958, two techniques for project planning and control were developed almost simultaneously. These techniques are the Critical Path Method (CPM) and the Project Evaluation and Review Technique (PERT). Both of these techniques make use of the network idea in planning and scheduling projects. They are both time-oriented methods in the sense that they both deal with the determination of a time schedule for the project. The difference is that the durations of activities are assumed to be deterministic in CPM, whereas they are described to be probabilistic in PERT.

Generally, project management consists of three phases; the planning phase, the scheduling phase and the control phase. These phases can be summarized as follows:

a) The planning phase: The activities which make up the project are defined and then technological dependencies upon one another are shown explicitly in the form of a network diagram. Estimates of the time required to perform each of the activities are

made. These time estimates are based on a stated resource level (manpower, machinery, etc.) for each activity.

b) The scheduling phase: The basic scheduling computations are commonly called Forward-Pass rules and Backward-Pass rules. These computations yield the earliest and the latest allowable start and finish times for each activity and identify the critical path through the network. The amount of slack associated with activities on the non-critical paths is also determined. In the scheduling phase, the time-cost tradeoff of activity performance times may be considered if the analyst is interested in determining the cost of reducing the project completion time. Also resource allocation can be done so that the feasibility of each schedule is checked with respect to resource requirements and availabilities.

c) The control phase: When the network plan is generated, the schedule have been developed to a satisfactory extent, they are saved as a baseline. The project is monitored and controlled by a comparison with actual status of the project against the baseline schedule. The monitoring allows for frequent review and when necessary, allows revision of the project plan.

The resources in a project can be classified into different categories. They can be differentiated as follows:

Renewable resources are the resources that have the ability to regenerate at regular intervals or can be defined as a resource that can be used continuously without being used up. Manpower can be given as an example, where working hours and number of available personnel can be a constraint.

Non-renewable resources are the resources which cannot be replaced once they are used up. Funds can be an example for non-renewable resources, where the ceiling amount for the fund in known, and as it is consumed, the usable amount decreases.

Doubly constrained resources are the resources that are constrained with both, period and total capacity of a resource. Funds can be an example for doubly constrained resources, where, as the usable ceiling amount decreases there also can be a constrained amount for a period.

In this study, the basic scheduling phase with resource allocation is considered for the case of renewable resources in limited resource availability.

The problem of scheduling projects with limited resources is referred to resource constrained project scheduling problems (RCPSP). The problem arises when resources required by project activities are available in fixed limited amounts and the demands of concurrent activities cannot be satisfied simultaneously. In real life, most project schedulers are faced with the problem of limited resources, such as fixed manpower availabilities, restricted availability of machines and/or equipment. Under these conditions, activity sequencing decisions are required in scheduling, with a resultant increase in the project completion time. The common objective of the RCPSP is to minimize the project completion time, classical makespan minimization.

RCPSP is an NP-hard problem [Blazewicz, J et al (1983)], and it is difficult or impossible to obtain optimal solutions for real-sized problems. Because of the lack of success with optimization procedures, most of the effort in solving RCPSP has been spent in developing heuristic procedures which produce "good" feasible solutions. By their nature, heuristic procedures generate solutions at different levels of closeness to optimality and computations time vary depending on the problem characteristics.

Commercial project management software packages are preferred to be used in the last decades to solve RCPSP's with a duration minimization objective. There are a large number of project management software packages developed to assist the project manager in project management. These packages support the user in structuring the project, in scheduling the project, and in monitoring and controlling the project.

In order to make resource allocation, the softwares make use of priority rules. The priority rule used by each software is generally not known because of proprietary information with some exceptions, namely last version of Primavera (V.4.1) which gives their users an option to choose the priority rule when scheduling with resource leveling option for resolving the over allocation of resources.

There have been some studies which compare different project management software packages such as Johnson (1992), Maroto and Tormos (1994), Maroto, et al. (1994), Burley (1995), Maroto, et al. (1996), Farid and Manoharan (1996), Kolisch (1999), and Mellentien and Trautmann (2001). However, the software's are continuously improved with new versions coming out frequently. Since 2001, there has been no research for the latest versions of the project management software packages in the literature. A comparison for the performance of the latest versions of commercial project management software package needs to be done.

In this study, two software packages are used: Primavera Enterprise V 4.1-Project Management and Microsoft Office Project 2003. Comparison between these project management softwares will be done in order to give project managers an option for choosing the project management software that fits best to their project environment. The reason for selecting these packages is that these two are the most popular packages in Turkey. Primavera Enterprise V 4.1-Project Management has ability to convert

Microsoft Office Project 2003 data to Primavera Enterprise V 4.1-Project Management data and there is no easy access to the other packages like Acos Project, CA Super Project, CS Project Professional, Scitor PS, Artemis Schedule Publisher, Project Scheduler, etc.

The rest of the thesis is organized as follows: Chapter II summarizes the related literature on RCPSP's with renewable resources, with emphasis on studies for duration minimization objective and mostly used heuristic rules. The RCPSP is formulated in Chapter III. Chapter IV discusses the experimental setting that is used in comparing the project management software packages. The results and conclusion is given in Chapter V.

CHAPTER II

LITERATURE REVIEW

In project scheduling, most of the common objectives of the several researches are about time phased resource constrained project scheduling problems (RCPSP). RCPSP takes precedence constraints and resource availability constraints into account with a duration minimization objective. RCPSP is an NP-hard problem. Because of the complexity and importance, there are a large number of studies in the literature. These are summarized in the surveys by Özdamar and Ulusoy (1995) and Brucker, et al. (1999).

Özdamar and Ulusoy (1995) gave a general review of the studies on RCPSP's for various objectives. They have pointed out and briefly explained the studies about optimization techniques and heuristics for single mode RSPSP's with renewable resources which have duration minimization objective in the literature. Brucker, et al. (1999) introduced a common notation for project scheduling and machine scheduling to increase the similarities between these two scheduling areas.

We categorized the RCPSP studies in the literature into five groups as; studies on exact algorithms, heuristic procedures, the quality of the commercial project management software packages, instance generators, specific attention is given to the size of the problems solved with different approaches.

2.1   Exact Algorithms

Schrage (1970) was the first to propose a branch and bound method which implicitly enumerates all schedules for determining the optimum solution (job shop problem).

Davis and Heidorn (1971) introduced a bounded enumeration based optimization method for resource constrained problems with multi resource type. They used feasible subsets and target duration in their method where large amount of feasible subsets are generated even for small networks. They proposed two procedures for reducing large amounts of feasible subsets. They tested their method with 65 artificially generated problems which consists of 30 jobs and three different resource types and managed to reach the optimal for 48 of them with an average of 0.94 minutes of computational time on IBM 7094.

Hastings (1972) introduced a branch and bound method with dominance rules. He tested his method on an example with 21 activities.

Patterson and Huber (1974) proposed a bounding technique combined with a binary search algorithm and examined the project scheduling problem when their bounding method is used. Minimum bound method finds a lower bound for the problem solution and seeks a feasible value starting from this point to obtain optimal solution. They tested minimum bound method with the one without using bounds in on 0-1 algorithm and concluded that minimum bound method has mostly show better performance on computational time and finding the optimal results. They have proposed another method which is the maximum bound method which first finds a feasible solution by using a priority rule and than seeks for optimality while preserving the feasibility. Maximum bound method has shown similar results to the minimum bound method with a higher computational time. Finally they have used both bounding methods for

performing a binary search method and could not reach a better computational value from both methods at one time.

Willis and Hastings (1976) have adapted their branch and bound optimization routine into project scheduling computer package Netcode. They have solved four 25 activity networks by using Netcode and compared the results with 14 different priority rules which are time based, resource based and random procedures which all use parallel activity allocations. Netcode gave better or same results compared to the various priority rules.

Stinson, Davis and Khumawala (1978) introduced a branch and bound method which uses extension alternatives for obtaining partial schedules. The partial schedules are then extended by using the subset of the eligible activities.

Talbot and Patterson (1978) have presented an integer programming algorithm which consists of an enumeration of all possible end times for each activity and they also proposed to use network cuts with their algorithm which removes the candidate evaluations that do not ensure any reduction in project completion time. Network cuts help to fathom partial schedules. By using the schedule elimination technique inessential effort is avoided. In order to check the efficacy of their algorithm, they solved 50 multi resource constrained problem of Davis (1968), which of 22 includes 22 jobs and the other 28 includes 27 jobs, and compared the results with Patterson and Roth's (1976) implicit enumeration method and Stinson's (1975) branch and bound method. They investigated the results for their algorithm with using cuts and without using cuts. Results for the computational effort shown that, their algorithm with cuts outperformed all the other tested alternative methods.

Christofides, et al. (1987) proposed a branch and bound algorithm based on the idea of using disjunctive arcs for resolving conflicts for the resource scarce environments. They introduced four lower bounds. Their first lower bound is based on the longest path computations. The second bound is derived from a relaxed integer programming formulation which includes cutting planes. The third bound is derived from a time based Lagrangean relaxation of integer programming formulation. The last bound uses disjunctive arcs for representing the problem as a graph. They have tested their bounds efficiency with problems containing 25 activities and 3 resources.

Bell and Park (1990) introduced an exact method which tends to overcome resource conflicts rather than constructing detailed schedules by dispatching activities. Their method first detects the resource conflicting activities are and then resolves resource conflicts by defining a precedence constraint to sequence two activities in such a resource-violating set.

Demeulemeester and Herroelen (1992) introduced an implicit enumeration procedure of a branch-and-bound method for multiple resource constrained single mode project scheduling problem to minimize the makespan duration. The procedure depends on a search process called depth-first search type contrast to the breadth-first search used by Bell and Park (1990). The nodes in the solution tree stands for resource and precedence feasible partial schedules. Dominance pruning rules, both the left-shift dominance rule and cutset dominance rule is used and this helps us to fathom more amounts of nodes when backtracking. Resource conflicts in the solution tree are handled with delaying alternatives which are in progress or in eligible set. They solved 110 Patterson instances categorizing by activity numbers and compared the CPU time of the branch and bound and its three different methods ((i) the left-shift dominance rule and cutest dominance rule, (ii) the dominance rule and (iii) without both rules) with the Stinson's (1978) method. The average CPU time for the branch and bound

method with the three methods were obtained as 0.215, 1.345, 2.548 seconds respectively, where the average CPU time for Stinson method was 2.494 seconds.

Demeulemeester and Herroelen (1997) modified their algorithm DH by using a new code and called their new method as new DH-procedure (1992). By using the new DH-procedure they compared depth-first method, with two search methods; best-search method (Stinson 1978) and hybrid search method in which branching occurs among the best node obtained from the created ones. They used 110 Patterson problem sets for investigating computational efficiency and used 480 KSD (Kolisch, Sprecher and Drexl) sets to explore optimality efficiency. The results showed that depth-first method outperformed the other two methods in the computational time where the other two methods failed to solve most of the 480 ProGen instances which KSD has generated, because of the need of memory storage. They also implemented their version of the lower bound method LB3, which Mingozzi (1994) introduced, and LB0 to their new DH-procedure. They have found out that truncated new DH-procedure gave better results than MINSLK for many problems when a first solution is obtained. They proposed to use truncated branch and bound algorithms for commercial project planning software.

Mingozzi, et al. (1998) presented a 0-1 linear programming formulation requiring exponential number of variables, corresponding to all feasible subsets of activities that can be simultaneously executed without violating resource or precedence constraints. Their new 0-1 linear programming formulation is used to obtain a lower bound that dominates the commonly used LB0 and is tighter than Stinson's (1978) lower bound (LBS). They proposed various lower bounds by relaxing some of the constraints. They also proposed a tree search algorithm based on their formulation that uses lower bounds and dominance rules. For the experimental study they first compared their proposed lower bounds with the existing ones by using the Patterson instances and

Kolisch, Sprecher and Drexl (KSD) instances. Second they compared four branch and bound methods by using the KSD instances. The first method is the DH method, another branch and bound method is which uses the existing lower bound method LB0. The last two branch and bound methods uses their proposed lower bounds. The results show that their branch and bound method, which uses the so called lower bound LB3, is competitive with DH procedure for the hard problems where in the easier problems it does not repeat the same success.

2.2 Heuristic Methods

Since the optimization methods and exact algorithms do not show their success in finding the optimal values with a reasonable computational effort for large projects, the researchers tend to make studies on heuristics methods. There are various kinds of heuristics proposed for solving the RCPSP. Studies for the heuristic methods in the literature are described below.

Wiest (1964) introduced the topic "critical sequence" which is the sequence of critical jobs that does not represent a technological sequence; critical sequence rather appears because of resource limitations. They also defined a procedure to find the slack amounts which leads one to identify the critical sequence.

Davis and Patterson (1975) compared the priority rules results, by using 83 problems including number of activities between 20 and 27, with optimality durations. They used eight priority rules for observation. Some of the widely used priority rules as Patterson defined are as follows:

Minimum Total Slack (MINSLK): Total Slack is the excess time available for an activity to be expanded or delayed without affecting the project finish time. Minimum total slack method gives priority to an activity which has lower total slack value when a resource conflict occurs.

Minimum Latest (Earliest) Finish Time (LFT (EFT)): Possible late (early) finish time of an activity without causing any delay in the project time. Minimum latest (earliest) finish time method gives priority to an activity which has a lower latest (earliest) finish time when a resource conflict occurs.

Shortest Imminent Operation (SIO): schedules the activities in the basis of their processing times. Activity with the lower duration will be selected in case of resource conflicts.

Resource Scheduling Method (RSM): This method gives priority to the minimum value of d_{ij} where d_{ij} is the increase in project duration when activity j is processed after activity i.

Greatest Resource Demand (GRD): This priority rules gives most resource demanding activity the priority.

Randomness (RAN): this method gives priority to an activity in complete random basis.

Davis and Patterson's (1975) study revealed that MINSLK rule performed the best with 5,6% deviation from the optimal duration where LFT and RSM ranked as the second and third.

Patterson (1976) developed a guideline for project scheduling. He introduced new parameters which are; time, network and resource based independent variables. He investigated average percent increase in critical path duration by using priority rules and made a step-down multiple regression analysis, for the duration minimization problem, with his newly defined independent variables. He found that MINSLK and LFT shown the best result on the criteria for the increase in critical path duration and they are effective in the environments that shows variability in activity durations and has an higher average free slack per activity and both priority rules should be used with the objective duration minimization.

Cooper (1976) proposed two heuristic methods which uses priority rules. The first method composed of parallel methods where series of partial schedules are created. The second heuristic is the sampling method where set of feasible schedules are created with the randomizing techniques. Priority rules are adapted to the schedules obtained by two heuristic methods. For the parallel methods 26 priority rules are used for investigation and they conducted an experimental design for the parallel methods with four levels of order strength, two levels of density, and two levels of resource factors. To obtain a full factorial experimental design with two replications for every combination of the factor levels 32 problems containing 60 activities are used. Significant effectiveness of the factors is investigated with ANOVA and the results gave that priority rule and its interactions have significant effect on the results. They have also conducted an experimental design for the sampling method with 14 priority rules and less factor levels. Priority rules effects and their interactions did not have any significance according to ANOVA results.

Thesen (1976) presented a heuristic that uses sub optimizing algorithm to select activities to start at different points in time. He also introduced a new hybrid urgency

factor which is the combination of eligible activities which has the largest combined urgency.

Ulusoy and Özdamar (1989) introduced a priority rule called weighted resource utilization and precedence (WRUP), which takes precedence and resource relations into account when giving priority and they compared it with the other priority rules MINSLK, LFT, RSM, GRD, SIO and RAN. They conducted an experimental design with four factors, two levels each. Used factors for the design are the aspect ratio (*ASP*), the complexity (*CPX*), the resource utilization (*UF*) and the dominant obstruction value (*DOV*) where the first two give indications on the network topology and the latter two represent the resource constraint characteristics of the project. They used Thesen's (1976) method for solving 64 test problems with up to 33 activities and adapted a priority rule when resource conflict occurs instead of solving the knapsack problem in Thesen's algorithm. These seven priority rules were all used to solve these test problems with the defined algorithm and WRUP gave the best results for all tested areas. They have investigated significance of the factors and their interactions for 1% and 5% levels. They have also made a comparison with 111 test problems where 47 are added to the previous ones. These 47 test problems represent larger size problems which have been created randomly. The factors vary in a defined range randomly. WRUP resulted 2.04% better than the best priority rule MINSLK for the 111 test problems.

Khattab and Choobineh (1991) have implemented eight new priority rules, which have precedence and resource attributes, into their new heuristic procedure for RCPSP and evaluated five performance measures results. The performance measures are resource utilization, average deviation from the best known duration, frequency of obtaining the shortest duration, and relatively used two measures resource range and project delay. They used the 14 networks used by Elsayed and Nasr (1986) with 7 to 48 activities and

5 to 23 events in their experimental design, and seen that none of the priority rule show significance on the performance from each other. Finally they have compared their search procedure and some of the existing heuristics in the performance measure basis.

Ulusoy and Özdamar (1994) proposed a local constraint base analysis (LCBA) in a single-pass parallel scheduling algorithm. In LCBA, the local essential conditions are used to overcome resource conflicts in order to determine the activity progress sequence. First they used eight priority rules defined in Khattab and Choobineh (1990-1991) for comparing LCBA and tested the 101 test problems of Ulusoy and Özdamar (1989). They managed to obtain a better result of 2% compared to the best priority method WRUP. Then they used priority rules MINSLK, LFT, WRUP and Khattab and Choobineh (1991)'s best priority rules 2 (ACTIM, Bedworth and Bailey (1982)), 3 (ACTRES, Bedworth and Bailey (1982)), and 4 (ACROS, Elsayed and Nasr (1986)) to compare with their LCBA method. This time they used 78 problem sets where 40 is optimally solved by Christofides et al (1987) and 38 is solved by Alvarez-Valdes and Tamarit (1989). The results show that LCBA outperformed the best priority rule ACROS about 1.81% in the average deviation from the optimal duration with obtaining better solutions in the 80% of the problems.

2.3 Instance Generators

Another category for RCPSP researches on literature is about instance generators. Numerous studies have been conducted on instance generating and as a consequence on instance generators to obtain benchmarks for RCPSP's.

Kolisch, Sprecher and Drexl (1995) introduced a random network generator ProGen to generate problem instances for different network topology and to obtain wide ranges of resource availability measures. Main ProGen parameters are Network Complexity

(*NC*), Resource Strength (*RS*) and Resource Factor (*RF*) which will be defined in further sections. They have developed single and multi mode case of RCPSP's with using renewable, nonrenewable and doubly constrained resources. They have used Patterson's 110 problem instances for single mode makespan minimization problems. They solved 43 problem instances including 27-activities with the exact algorithm of Demeulemeester and Herroelen (1992) with an average computation time of 1.06 seconds when coded in C. They conducted an experimental design with four *RS* levels, four *RF* levels and three complexity levels with 10 replications for each treatment. 480 instances were solved using the exact algorithm with an average computation time of 461.25 seconds. Parameter effects on the solution times were statistically analyzed by using mean value analysis and ANOVA. By the ANOVA analysis, it is understood that complexity is marginally significant effective on computational time and also negatively correlated. *RF* and activity number (*J*) is significantly effective with positive correlation and *RS* is also significantly effective but with a negative correlation. They did not find significant effectiveness of renewable resource numbers and number of starting activities. Generally they have shown that mostly used problem instances in the literature only introduced the easy problems and also they have interpreted that when harder parameters are set, in some conditions optimality may not be reached with any computational effort. They have used wide range (easy to hard) of factor levels and shown the effects of this parametric characterization for computational study in single and multi mode cases of RCPSP.

Kolisch and Sprecher (1996) have presented new instances generated from ProGen to the ones they have introduced in the study Kolisch et al. (1995). They have generated instances systematically for fixed, base and variable parameters for single and multi mode RCPSP with full factorial design using parameters *NC*, *RS* and *RF* to obtain a benchmark for RCPSP's. Their generated instances are according to the parameters of four *RS* levels, four *RF* levels, three complexity levels and two number of activity

levels with 10 replications for each treatment. These problems are set in the project scheduling problem library (PSPLIB) and can be downloaded from site 129.187.106.231/**psplib** to be used as a benchmark for factorial design studies.

Demeulemeester, Vanhoucke and Herroelen (2003) introduced RanGen, Random Network Generator for activity-on-the-node networks. RanGen produces problem instances under different network and resource parameters for obtaining data to be used in resource constrained project scheduling problems. RanGen gives a choice to use alternative types of resource parameters which are resource usage (*RU*), which can be used alternatively to resource factor (*RF*), and resource constrainedness (*RC*), which can be an alternative of resource strength (*RS*). RanGen can generate wide ranges of problem complexity with the help of its network topology measures order strength (*OS*) and complexity index (*CI*) (introduced in Bein, Kamburowski, Matthias, Stallmann (1992)), where previous studies have shown *CI* is an essential parameter for random AoN generators. They have shown the advantages of RanGen over ProGen and ProGen/Max where the latter two can not generate networks with lower *OS* values. They have defined number of starting activities and maximum number of successors/predecessors in ProGen as superfluous parameters and asserted that these parameters are used to detain the problem instances from representing the harder instances.

Debels and Vanhoucke (2005) generated instances from "RanGen" (RanGen1) for parameter levels; Order Strength = 0.25, 0.50 or 0.75; Resource Use = 1, 2, 3 or 4; Resource Constrainedness = 0.2, 0.4, 0.6 or 0.8

Their generated problem instances can be found in site http://www.projectmanagement.ugent.be/RG300Instances.php.

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Vanhoucke, et al. (2004) has extended "RanGen1" to "RanGen2" which makes use of six topological measures to describe the structure of a network. 1800 generated test instances for RanGen2 can be found in the site http://www.projectmanagement.ugent.be/rangen.php.

2.4 Comparison of the Quality of Commercial Project Management Software Packages

Last type of research is comparing the quality of commercial project management software packages under limited resource environments. There are several commercial project management software packages to be used. Every project management software package has different capability to schedule different projects for different parameter settings under resource constrained and unconstrained environments with the objective of makespan minimization. Choosing the best commercial project management software package that will give the minimum deviation from the optimal solution for the desired environment (factor level) is an important issue. For this reason several researches have been made to compare the resource allocation capabilities of the software packages as it was mentioned previously.

Johnson (1992) compared the 13 versions of seven commercial project management software packages, using Patterson's 110 instances, with activity number differing from 7 to 51 and resource amount differing from 1 to 3. He compared Super Project Expert 1.0 and Super Project 2.0, Timeline 2.0 and 4.0, Primavera 4.00, 4.1 and 5.0 for DOS, Harvard Total Project Manager II and Harvard Project Manager 3.0, Hornet, Pertmaster and Microsoft Project for Windows 1.0 and 3.0's results with the optimal results of Talbot and Patterson (1978). The software package that gave the best result was Timeline 2.0 with 5.03 percent deviation from the optimal value and the software

package that gave the worse result was Microsoft Project 1.0 with 25.6 percent deviation from the optimal value on average terms.

As Kolisch (1999) discussed in his literature review part, Maroto and Tormos (1994) compared CA Super Project 2.0 A, Instaplan 3.0B, Micro Planner for Windows 6.24A, Micro Planner Professional 7.3B, Microsoft Project for Windows 1.0 and 3.0 and Project Scheduler 1.0 with respect to solve a 51 activities and 3 resources problem. They found the deviation between software results of constrained resource environment and minimum makespan of the unlimited resource condition. CA Super Project 2.0 and Microsoft Project for Windows 3.0 gave the best results while Microsoft Project for Windows 1.0 gave the worse result. In a subsequent study of Maroto and Tormos (1994), Maroto, et al. (1994) compared CA Super Project 2.0 and Microsoft Project in the three versions: V.2.0 for DOS and V.2.0 and V.3.0 for Windows. They made a full factorial design with three level of number of constrained resources and two level of resource overload. Eight instances were generated for every treatment, leading to solve the 48 generated problem instances with an activity number varying from 30 to 100. The results were compared to the unconstrained environment schedule as it was in Maroto and Tormos (1994). The statistical effects of the parameters and the software programs were investigated with ANOVA. The other researches made for comparison of the quality of software packages are Burley (1995) compared Microsoft Project 3.0, Project Manager Workbench/w, and Timeline 6.0 and Maroto, et al. (1996) compared CA Super Project 4.0 and Microsoft Project 4.0, Farid and Manoharan (1996) compared Microsoft Project 3.0, Primavera Project Planner, Project Scheduler 5.0 and TimeLine. Kolisch (1999) compared seven commercial project management software packages in his study. He used instances generated from ProGen to compare project management software packages Artemis Schedule Publisher, CA Super Project, Microsoft Project, Primavera Project Planner, Project Manager Workbench, Project Scheduler 6 and Time Line. He conducted an

experimental design with three activity levels (10,20,30), three resource levels (1,2,3) three *RS* levels (0.2,0.5,0.7), two *RF* levels (0.5,1) and two complexity levels with 10 replications for each treatment. 1080 instances should be solved in order to make a full factorial design for each combination of the factor levels. To avoid this much of effort Kolisch used fractional design based on the orthogonal matrices to reduce the parameter levels to 16 and instance number to 160. Kolisch used Demeulemeester and Herroelen's [1992] optimal branch and bound algorithm to solve the instances with a limited CPU time of 3600 CPU-seconds. Then he conducted single factor analysis of variance (ANOVA) for each problem parameter. Observing that the solutions violated the homogeneity and normally distributed assumption of the ANOVA, Kolisch applied nonparametric U test of Mann and Whitney for two level parameters and the nonparametric H test of Kruskal Wallis for the three level parameter levels. He observed that resource factor is significantly effective for all softwares, resource strength is insignificant only for Time Line, number of scarce resources and number of activities have significance effect on some of the softwares where, network complexity has no significance effect on any software. Kolisch applied the nonparametric Friedmann test for testing significant distinction between the project management software packages. Finally he performed the nonparametric Wilcoxon Test for a pairwise comparison between packages and concluded that five pairs of software packages are insignificant in performance where the other two differs.

Mellentien and Trautmann (2001) presented results of a benchmark test evaluating the resource allocation capabilities of the project management software packages Acos Plus.1 8.2, CA Super Project 5.0a, CS Project Professional 3.0, MS Project 2000, and Scitor Project Scheduler 8.0.1. They used PSPLIB single-mode resource constrained problem instances which were generated by ProGen. They made an experimental design by four level *RS*, four levels *RF* and three levels *NC* for number of activities 30 and 60. For conducting number of activities 120, he used same *RF* and *NC* and used

five level *RS* which of two are common with the lower activity number levels, as it is in PSPLIB. By 10 instances for every combination of the factor levels the tests are based on 1560 instances. They have not made any statistical analysis in order to investigate the significance of the factor effects. They have only observed instance results by using the deviation of the makespan obtained by the software packages from the best feasible makespan known for the problem sets. Among the tested software packages, Acos Plus.1 and Scitor Project Scheduler performance shown the best resulted for resource allocation. Moreover, they have outlined that especially for large-sized problems, their numerical analysis shown a considerable performance difference between the software package results and the results of the state-of-the-art project scheduling algorithms. Acos Plus has shown the best results for instances with 30, 60 and 120 activities with a percent deviation of 3.87, 4.05 and 9.69 respectively to the makespan obtained from state-of-the-art project scheduling algorithms.

CHAPTER III

PROBLEM STATEMENT

3.1 RCPSP Formulation

In project scheduling, most of the common objectives of the numerous researches are about minimizing project duration. Minimizing the duration of the project can be essential for the organizations which wants to handle more projects with the same amount of resources and also for the projects that have to be completed before its due date.

When the project time exceeds the due date there can be significant amounts of tardiness costs. In some circumstances tradeoff between reducing the duration of project and paying the tardiness cost for the delay should be done very carefully. To make this tradeoff, it is important to find the minimum project completion time. RCPSP achieves this objective when there are limited amounts of renewable resources. RCPSP can be stated as follows;

There are j interrelated activities where $j = 1,...,J$ and $j = 1$ and $j = J$ are the dummy activities which represents the source and the sink for the network. Activities $j= 2,...,J-1$ has a set of predecessors P_j where an activity's process can not start until all of its predecessors are completed. Duration for an activity j is d_j units of time. There are R renewable resources with limited capacity. The objective is to schedule the activities in order to obtain the possible earliest completion time for the project.

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Main assumptions are listed below:

(i) Since there is precedence relation between activities, an activity should not be started before all of its predecessors are finished. Precedence relations between the activities are finish-to-start relation.

(ii) No preemption allowed. When an activity is started, it should be finished within its duration without any interruption.

(iii) Activity durations are known, deterministic and integer.

(iv) Each task requires one or more resource types during its processing time.

(v) Maximum resource availability is known and fixed for every resource type during the entire project duration.

(vi) The objective is to minimize the project duration without violating resource constraints.

The following notation will be used in the formulation: The decision variables, f_j and K_{jr} are defined as finish time of processing activity j and unit of resource r demanded by activity j during its processing time, respectively. The parameters are as follows; R is the number of resource type, K_r is the capacity of resource r in unit duration, P_j is the set of immediate predecessors of activity j, A_t is the set of activities which are processed at period t, d_j is the unit of time needed to complete activity j (duration), and T is the number of time periods.

Under these assumptions, parameters and the decision variables, the mathematical formulation is given as follows as in Kolisch (1999);

(3.1) The objective has to be a makespan minimization problem.

$$Min\ f_J$$

(3.2) An activity can not start until all of its immediate predecessors are completed.

$$f_i + d_j \leq f_j \qquad\qquad j = 1,...,J,\ \ i \in P_j$$

(3.3) In every period, only an activity which is being processed can use resources within the available resource capacity.

$$\sum_{j \in A_t} K_{jr} \quad \leq K_r \qquad\qquad r = 1,...,R, \quad t = 1,....,T$$

(3.4) Project starts at time zero.

$$f_1 = 0$$

3.2 Software Packages

Most project management software packages use activity-on-node network representations for visualizing the project structure, in which each node represents an activity and arcs represent the precedence relationships between the activities. Product

architecture of a project can be structured by a Work Breakdown Structure (WBS) in any project management software package.

All software packages perform the basic scheduling calculations. That is, by the help of activity durations and precedence relations they can derive the earliest and latest start and finish of the activities by using both a backward and a forward pass. In an unlimited resource environment, a resource and precedence feasible schedule is obtained by these scheduling calculations and program depicts a resource usage profile and represents them by means of a graph in a time-phased sheet. Resource allocation is mainly done with the following methodology after resource profiles are defined in the project management software;

1) By the loading direction method, the software derives earliest and latest possible schedule times of the activities. Here, front loading helps to schedule the activities within their earliest possible schedule time and the backward loading helps to schedule the activities within their latest possible schedule time.

2) By the help of the scheduling scheme, ability of more than one activity to be processed at the same time is identified for that project. The serial scheduling gives only a selection of one activity to be processed within the several candidates and the parallel schedule where more than one candidate can be chosen to be processed as long as feasibility of resource and precedence constraints is not violated.

3.3 Comparison of the Performance of Software Packages

RCPSP as defined above is an NP-Hard problem [Blazewicz, J et al. (1983)]. It is difficult or impossible to obtain an optimal solution of realistic-size problems. It takes large amounts of computational time for a program to solve RCPSP's. Project

management software packages manage to obtain a result for RCPSP's in few seconds while their performances for finding close results to the optimal are not as promising. The importance of using commercial project management software packages in according to find a feasible schedule for duration minimization problems with resource constraints, were explained in previous chapters. The goal of this research is to compare the resource allocation capabilities of commercial project management software packages. Their performance will be considered according to their duration minimization capabilities. Generated networks will be taken as benchmark instances, for testing the deviation from the benchmark results in resource capacitated environments. For this reason an experimental design will be conducted in the next chapter for investigating resource allocation capabilities of commercial project management software packages for single mode RCPSP's under different parameter settings.

First, choosing set of instances to be used for the experimental design must be performed. The two candidate instance generators for our experimental design are ProGen and RanGen. ProGen instances are used in various studies where RanGen instances are started to be used in recent researches. RanGen is said to represent harder ranges of problem parameters and dominate ProGen in this area. In our experiment, we choose to use ProGen instances which were used in various studies. Mainly because these instances can easily be reached from PSPLIB and optimal solutions or best known solutions of these instances are available in this library. Moreover, earlier comparisons [Kolisch (1999)] and [Mellentien and Trautmann (2001)] used ProGen and results of our study can be compared easily on these instances.

 ProGen data was obtained from the PSPLIB under the topic of single-mode RSPSP. Parameter settings for ProGen will be analyzed in Chapter IV.

Selecting which commercial project management software packages for making a comparison is another issue. The chosen project management software package should have a widespread usage. Since they have a wide usage in Turkey as well as their older versions has been used in similar researches, the selected programs for our study are MS Project Office 2003 and Primavera Enterprise V.4.1-Project Management. From now on, we will briefly refer to these two programs as MS and PV. Brief explanations about both programs specifications are given below;

MS shows compatibility with Windows and MS-Office tools. Individual views can be defined using filter and sort functions. A resource usage diagram can be visualized in a separate view. It automatically schedules the project as the project information is entered. The program uses its default leveling option which is not known with respect to its proprietary characteristic.

PV has a widespread usage especially in the management of construction companies. It gives leveling options by letting the user select one of the various priority rules for leveling resources. Since [Davis and Patterson (1975)] and [Patterson (1976)] has found MINSLK and LFT as the most efficient heuristic priority rules, we decide to use MINSLK (as total float in PV) and LFT in our experimental studies. PV also gives its users a chance to import MS data with the scheduling option. So by the use of this characteristic, MS data which represents the instances taken from the PSPLIB can be imported in PV with less amount of effort.

RCPSP's will be solved by PV and MS. By using the result of the RCPSP's obtained by MS, PV MINSLK and PV LFT will be used in order to make a comparison between the performances of software packages. Softwares and its versions are developing continuously. New instance generators and new factors are represented in the literature. Until today several researches have been done on the comparison of the

softwares for testing their scheduling abilities under resource limited environments. These studies mostly do not cope with nowadays conditions. They mostly lack the following; Patterson's (1976) 110 instances parameters were not generated by using controlled design, Resource factor was taken lower values and Resource Strength was taken higher values which represent easy problems. By this reason it can be said that Patterson instances does not represent wide ranges of factors. Versions of software packages from Johnson (1992), Maroto and Tormos (1994), Maroto, Tormos, Capilla and Crespo (1994), Burley (1995), Maroto, Tormos, Lova and Crespo (1996), Farid and Manoharan (1996), Kolisch (1999) and Mellentien and Trautmann (2001) are old for meeting the requirements of today's circumstances. For the latest researches Mellentien and Trautmann (2001) did not perform statistical analysis on the results. Kolisch (1999) have not investigated the effects of interactions of the factors. Instead of performing a full factorial design he has conducted a fractional design in his study. Also he solved small sized problems which are up to 30 activities.

3.4 Network Generation

Creating networks for obtaining test problems is another issue for making full factorial design. There are several benchmark problems used by researches. Most of the researchers have taken Patterson instances. After Kolisch, Sprecher and Drexl (1995) had introduced networks generated from their instance generator ProGen; these instances have been accepted as benchmarks for new studies since ProGen represent wide ranges of factors with also hard problems included. Some of the instances can not be solved optimally for hard problems. These problems have lower bound and upper bound values reported in PSPLIB, whose data are kept updated.

One of the recently developed recommended random generator is RanGen and details of RanGen and its two version were mentioned in Chapter II. It generates wide ranges of problem complexity with the help of its network topology measures. Recently there are several studies on generating benchmark instances from RanGen. These benchmark problems can be downloaded from the relevant sites for RCPSP studies.

CHAPTER IV

EXPERIMENTAL DESIGN

4.1 Factors and Factor Levels

An experimental design is conducted in order to observe and identify corresponding changes in the output response under different factor settings, where factor of an experiment is a controlled independent variable; a variable whose levels are set by the experimenter.

Factors of ProGen and all of the factor levels and replications of single-mode RCPSP in the PSPLIB will be included in this research. Brief definitions of the factors are as follows:

Number of activities is estimated to affect the objective function value. Effect of the change in the number of activities is to be tested in four levels to represent various activity levels. The levels are 30, 60, 90 and 120.

Network Complexity (*NC*): Network complexity is the structural complexity of a network which means the average number of precedence relations per activity. It depends on the amount of predecessor/successors relationship in a network. It is defined as

$$NC: \quad \frac{1}{J}\sum_{j=1}^{J}\left|P_j\right|$$

Low (high) *NC* means there are few (many) precedence relations between activities. The *NC* is examined in three levels which are 1.5, 1.8 and 2.1.

Resource Factor (*RF*): Resource factor reflects the average portion of resource types requested per activity.

$$RF: \quad \frac{1}{(J-2)*R}\sum_{j=1}^{J}\sum_{r=1}^{R} \qquad \begin{cases} 1 & if \quad K_{jr}>0 \\ 0 & else \end{cases}$$

Low (high) *RF* means activities uses less (more) of the resource types. For example, if the resource factor is 1, all activities require all types of resources on the average. *RF* will contain four levels in this experimental design. The levels are 0.25, 0.50, 0.75, and 1.0.

Resource Strength (*RS*): Resource strength is the proportion of resource demand and availability. It represents the amount of availability for each resource type on average.

$$RS_r: \quad \frac{K_r - K_r^{\,min}}{K_r^{\,max} - K_r^{\,min}} \qquad\qquad r = 1,...,R$$

Where $K_r^{\,max}$ is the peak demand of resource *r* for resource unconstrained makespan and $K_r^{\,min}$ is the minimum availability of resource *r* to process each activity.

For example if the resource strength is 1, then each of the resource type is available at any time during the project duration and the all resource constraints are redundant. For

each resource type *r*, the RS values are the same in all problems generated by PROGEN. Four *RS* levels will be used for the design, which are 0.2, 0.5, 0.7 and 1 for the first three choices of activity levels (*J*=30, 60 and 90) and levels 0.1, 0.2, 0.3, 0.4, 0.5 for the last choice of activity level (*J*=120).

The last factor will be the program used to observe that if the chosen program has an effect on the results. As mentioned before MS, PV (with two priority rules MINSLK and LFT) will be compared and we will denote these as a factor with three levels.

Resource factors and its levels are given below in Tables 4.1.1 and 4.1.2.

Table 4.1.1 Factors and Factor Levels (*J*=120) excluded

Factors	Factor Levels			
	Level 1	Level 2	Level 3	Level 4
J	30	60	90	-
NC	1.5	1.8	2.1	-
RS	0.2	0.5	0.7	1.0
RF	0.25	0.50	0.75	1.00
Program	MS	PV-MINSLK	PV-LFT	

Table 4.1.2 Factor Levels of *RS* for (*J*=120)

Factors	Factor Levels				
	Level 1	Level 2	Level 3	Level 4	Level 5
J	120	-	-	-	-
NC	1.5	1.8	2.1	-	-
RS	0.1	0.2	0.3	0.4	0.5
RF	0.25	0.50	0.75	1.00	-
Program	MS	PV-MINSLK	PV-LFT	-	-

Moreover duration of an activity is generated from a uniform distribution [1, 10]. Number of resource types is selected as 4. The maximum number for usage of a resource type can not exceed 10.

There are 10 generated instances for every treatment, so there are 4*4*3*10=480 instances for number of activity levels 30, 60 and 90. There are 4*5*3*10=600 instances for number of activity level 120. The total leads us to number of instances of 480*3+600=2040.

A makespan value will achieved by using the program MS and the program PV with its leveling option priority rules MINSLK and LFT which will lead to 2040*3=6120 results to be analyzed.

MS and PV results will be observed with the makespan of the instances. The PSPLIB results are obtained from the heuristics and the optimization methods used. For the instances representing first level of number of activities (*J*=30) optimal makespan has

been reached. However, for the other levels of number of activities, a lower bound and an upper bound has been found for the projects duration where the lower bound of a problem is obtained by relaxing the RCPSP and upper bound of the problem is obtained by using an heuristic.

To make an observation between MS and PV makespan results the response values should be analyzed. Our sole response variable is the percent deviation of the project management software value from the benchmark makespan. The calculation methodology will be as following;

The 2040 problem instances which were generated from ProGen will be represented as; $g = 1,...,2040$. There will be 2 type of project management software packages used which is MS and PV and two types of priority rules will be used for PV. These will be represented as; $p = 1,2,3$. Thus the response variable for $g = 1,..., 2040$ and $p = 1,2,3$ can be represented as;

$$\Psi_{gp} = \frac{Z_{gp} - Z_g}{Z_g} * 100$$

where Z_{gp} is the makespan obtained for problem instance g found by project management software type p and Z_g is the benchmark makespan value of the problem instance g.

In what follows we first report the results of 2040 replications for all program types by giving the mean and the standard deviation of the percent deviations from the benchmark values in Table 4.1.3.

Table 4.1.3 Mean and standard deviation from the optimal values for programs

MS		PV-MINSLK		PV-LFT	
Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
8.60	8.68	13.03	11.07	7.61	7.84

In further analysis responses will be the mean of ten replications of a treatment.

When we take a general look at the results it can be said that PV-LFT gives the minimum values when the means and the standard deviation are analyzed where PV-MINSLK method gives the highest values. The maximum deviation from the benchmark values can increase up to 53%.

When we take a general look at the results shown in Table 4.1.4 we can say that a significant difference occurs at PV-LFT success at the lowest *RS* value 0.1 compared to the others.

By the analyze of the factor number of activities in Table 4.1.4, PV-LFT gives the best results for the problems 60, 90 and 120 activities where MS has the second ranking and PV-MINSLK takes the last. In the problems with 30 activities this time MS takes the lead where PV-LFT gives close values.

There does not seem to be much difference at the results of the factor levels for factor *NC* when Table 4.1.4 is analyzed.

RS results will be considered separately as using first three levels of *J* and the last level of *J* since *RS* levels are not common in these *J* levels. When the *RS* results are considered in tables 4.1.5 and 4.1.6 it can be said that as the *RS* value reduces the deviation from the makespan increases. MS seems to have trouble with finding good results when *RS* value reaches to 0.1.

When Table 4.1.4 is analyzed it is seen that, when factor *RF* takes the smallest value 0.25, programs seems to show better results than the other levels of *RF*. The results obtained for the other levels of *RF* shows similar results to each other.

As a results are analyzed it can be said that except for the environment where *J*=30, PV-LFT shows the best performance for other levels of *J* and in every combination of the other factors. MS is the most successful program in solving problems with 30 activities. PV-MINSLK has shown poorer results for every combinations of each factor.

Table 4.1.4 Percent deviations from the benchmark values

Factor	Level	MS		PV-MINSLK		PV-LFT	
		Mean	Max	Mean	Max	Mean	Max
NC	1.5	8.33	47.74	11.90	49.21	7.31	33.90
	1.8	8.81	44.71	12.77	52.87	7.68	43.90
	2.1	8.58	41.20	13.41	50.00	7.63	35.56
RS	0.1	26.46	47.74	29.74	47.17	21.08	32.41
	0.2	17.20	38.03	24.70	52.87	16.14	35.56
	0.3	13.80	27.05	21.80	43.81	12.63	23.01
	0.4	9.79	35.37	16.51	41.46	8.96	43.90
	0.5	5.24	28.71	10.80	43.42	4.71	25.74
	0.7	2.15	15.38	3.80	35.71	1.11	18.42
	1.0	0.00	0.00	0.00	0.00	0.00	0.00
RF	0.25	4.94	38.03	8.66	45.46	3.89	43.90
	0.50	9.68	47.74	15.04	52.87	8.63	33.85
	0.75	10.35	41.20	14.70	50.00	9.15	35.56
	1.00	9.44	35.46	13.71	42.11	8.77	27.35
J	30	5.24	31.03	9.64	49.21	5.69	33.90
	60	6.53	38.03	10.23	52.87	5.79	35.56
	90	6.32	32.26	9.66	50.00	5.18	33.33
	120	14.78	47.74	20.67	49.25	12.55	43.90

Table 4.1.5 Percent deviations from the benchmark values (*RS* for *J*=30,60,90)

Factor	Level	MS		PV-MINSLK		PV-LFT	
		Mean	Max	Mean	Max	Mean	Max
RS	0.2	16.64	38.03	24.08	52.87	16.07	35.56
	0.5	5.33	15.84	11.48	43.42	5.03	23.73
	0.7	2.15	15.38	3.80	35.71	1.11	18.42
	1	0.00	0.00	0.00	0.00	0.00	0.00

Table 4.1.6 Percent deviations from the benchmark values (*RS* for
** *J*=120)**

Factor	Level	MS		PV-MINSLK		PV-LFT	
		Mean	Max	Mean	Max	Mean	Max
RS	0.1	26.46	47.74	29.74	47.17	21.80	32.41
	0.2	18.89	35.37	26.53	49.25	16.34	33.33
	0.3	13.80	27.05	21.80	43.81	12.63	23.01
	0.4	9.79	35.37	16.51	41.46	8.96	43.90
	0.5	4.97	28.71	8.76	27.38	3.74	25.74

Comparison of percent deviations from the benchmark value results with other studies: In Kolisch's (1999) (his results has shown in Table 4.1.9) the results show that as *J* levels increase mean deviation form makespan increases with one exception. Also in his study higher *NC* levels gave better results compared to the lower levels for all tested softwares including MS Project V.4.0. In our experiment and in Mellentien and Trautmann (2001) (results shown in Table 4.1.8), results do not support this comment. In both studies [Kolisch's (1999)] and [Mellentien and Trautmann's (2001)] and in our study, *RS* levels give better values as the *RS* levels gets higher. For *RF*, opposite to the *RS*, when *RF* levels gets lower, better values can be obtained and this also coincides with the Kolisch's (1999) and Mellentien and Trautmann's (2001) results. In both studies, Kolisch's (1999) and Mellentien and Trautmann's (2001) with one exception, lower *J* levels give better results than the higher *J* levels. In our experiment, for all program types *J*, level 90 gives better results than 60. Also when an observation is made from Table 4.1.6 with two common levels of *RS*, *J* level 120 gives better results than 90. Finally, when Table 4.1.4 and Table 4.1.8 are observed, it can be seen that Mellentien and Trautmann's (2001) results for MS Project 2000 is slightly better than our experimental study for MS Project 2003 for the same instances solved. The reason

for this slight difference must come from the difference for the chosen options. This supports the fact that the resource leveling option of MS Project has not been changed in versions 2000 and 2003.

Table 4.1.7 Percent deviations from the benchmark values (*J* for *RS*=0.2, 0.5)

Factor	Level	MS		PV-MINSLK		PV-LFT	
		Mean	Max	Mean	Max	Mean	Max
J	30	8.77	31.03	15.99	49.21	10.09	33.90
	60	12.18	38.03	18.93	52.87	11.25	35.56
	90	12.01	32.26	18.43	50.00	10.30	33.33
	120	11.93	35.37	17.65	49.25	10.04	33.33

Table 4.1.8 Results of [Mellentien and Trautmann (2001)]. Percent deviations from the benchmark values (*J*).

Programs	*J* Levels		
	30	**60**	**120**
Acos Plus.1	3.87	4,05	9.69
Super Project	5.39	6.37	13.99
CS Project	3.50	5.28	13.70
MS Project 2000	5.18	6.23	14.02
Scitor PS	4.85	4.98	11.15

Table 4.1.9 Results of [Kolisch (1999)]. Percent deviations from the benchmark values (*J*).

Programs	*J* Levels		
	10	**20**	**30**
Artemis SP	7.79	10,73	9.79
CA Super Project	1.83	4.85	6.11
MS Project V.4.0	2.36	6.08	6.91
PV Project Planner	3.67	4.59	4.73
PM Workbench	5.21	6.88	7.79
Project Scheduler 6	2.17	6.10	7.34
Time Line	2.60	4.52	6.30

4.2 Experimental Design Model

A factorial design is used to evaluate two or more factors simultaneously. The treatments are combinations of levels of the factors. The advantages of factorial designs over one-factor-at-a-time experiments are that they are more efficient and they allow interactions to be detected.

A factorial design should be made to investigate the factor effects. Every combination of the factor levels should be tested. Several replications for each factor level should be generated in order to obtain a sufficient amount of tested instances for a treatment. An experimental design in which every setting of every factor appears with every setting of every other factor is called a full factorial design.

In our experiment there are five factors. Two of factors (*NC* and *Program*) have three levels, two of factors have four levels (*J* and *RF*) and the last factor *RS* levels vary according to the number of activity levels. For the first three levels of *J, RS* has four levels, for the remaining level of *J; RS* has five levels for which two levels are common with the ones for the previous case. *RS* has seven different levels to be analyzed.

A full factorial design can not be made with the problem sets solved from the PSPLIB since the problem sets do not have every combination of the levels of *J* and *RS*. For this reason the interaction effect of *RS* and *J* can not be analyzed by using ANOVA.

A statistical analysis will be done for the full model without including the interaction effect of *RS* and *J*. This model will give results for all level combinations used in our experimental design. This models result will not be reliable by itself because of the absence of the chance to investigate the interaction between *RS* and *J*. Interaction of the *RS* and *J* can affect other interactions and other factors significances. For this reason a second experiment should be performed in order to investigate *RS*J* interaction effects on the results *J*. To see the other factors behavior on the problem results, another experiment will be conducted for the last level of *J*.

When we are implementing these three methods, the program effects will be investigated by taking the program as a factor. Additional to investigating the program effects, program levels also will be considered one by one. By making another investigation for the program levels separately, the factor effects on the programs used in this research can be identified. During the analysis of the effects of the factors to the programs, four factor experimental design will be performed by removing the program from the factors. As a result twelve different statistical analyses will be conducted in

our experiment. Three different models with four different analysis will be made, for simplicity twelve different analyze will be defined as models and models will be abbreviated as in Table 4.2.1. We will briefly refer to these models, by abbreviations used in Table 4.2.1.

Table 4.2.1 Model Abbreviations

Model	Program			
	All Program	MS	PV-MINSLK	PV-LFT
All J	M1AllProgs	M1AllMS	M1AllPV-1	M1AllPV-2
J=30,60,90	M2SmallProgs	M2SmallMS	M2SmallPV-1	M2SmallPV-2
J=120	M3LargeProgs	M3LargeMS	M3LargePV-1	M3LargePV-2

Statistical analysis of the experiment should contain two main steps. First step is investigating the factor effects by a factorial design and the second part is analyzing the residuals for checking the adequacy of the model.

In our model there will be 5 factors. The linear statistical model will include both, the terms for main effects and the interactions.

$$y_{ijklm} = \mu + \sigma_i + \beta_j + \alpha_k + \gamma_l + \Omega_m +$$

$$(\sigma\beta)_{ij} + (\sigma\alpha)_{ik} + (\sigma\gamma)_{il} + (\sigma\Omega)_{im} + (\beta\alpha)_{jk} +$$

$(\beta\gamma)_{jl} + (\beta\Omega)_{jm} + (\alpha\gamma)_{kl} + (\alpha\Omega)_{km} + (\gamma\Omega)_{lm} + \varepsilon_{ijklm}$

where

μ : Overall mean

σ_i : Effect of the *NC* factor level *i*   *i=1,2,3*

β_j : Effect of the *RF* factor level *j*   *j=1,2,3,4*

α_k : Effect of the *RS* factor level *k*   *k=1,2,3,4,(5,6,7)*

γ_l : Effect of the *J* factor level *l*   *l=1,2,3,(4)*

Ω_m : Effect of the program type *m*   *m=1,2,3*

and

ε_{ijklm} : is the usual NID $(0,\sigma^2)$ random error term.   for $\forall i,j,k,l,m$

y_{ijklm} : Percent deviation.   for $\forall i,j,k,l,m$

4.3 Model Adequacy Checking

For testing the hypothesis, model errors are assumed to be normally and independently distributed random variables with mean zero and variance σ^2. The variance is assumed to be constant for every level of the factors. If these assumptions hold, then the Analysis of Variance (ANOVA) procedure is an exact test for verifying the hypothesis of no difference between the factor levels.

However, generally these assumptions are not satisfied exactly. Therefore, ANOVA results can not be reliable until these assumptions have been satisfied. Violation of the specified assumptions can be checked by examination of the residuals. The description of the residuals for the model can be stated as;

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Residual = Response – Fitted Value

For obtaining an adequate model, our aim will be obtaining structureless residuals, meaning that the residuals should not show any patterns. Residuals of mean deviation from the makespan should be checked in order to see if they satisfy the ANOVA assumptions or not.

4.4 Hypothesis Testing

All of the factors in the design are fixed and factor effects are defined as the deviation from the overall mean. So sum of the factor means should be zero;

$$\sum_{i=1}^{3} \sigma_i = 0 \qquad (NC \text{ effect})$$

$$\sum_{j=1}^{4} \beta_j = 0 \qquad (RF \text{ effect})$$

$$\sum_{k=1}^{7} \alpha_k = 0 \qquad (RS \text{ effect})$$

$$\sum_{l=1}^{4} \gamma_l = 0 \qquad (J \text{ effect})$$

$$\sum_{m=1}^{3} \Omega_m = 0 \qquad (Program \text{ effect})$$

Interaction effects are also fixed and their summation equals to zero.

The aim of this statistical analysis is to test significant effectiveness of the factor levels. To say that there is no significant difference between factor levels the hypothesis that there should be no difference between the factor level means should be tested. Remembering that the factor effects were defined as the deviations from the overall mean, hypothesis written below should hold;

$$H_o : \mu_o = \mu_1 = \mu_2 = \ .... \ \mu_z = 0 \qquad \text{for every factor.}$$

For testing this hypothesis it is assumed that errors ε_{ijklm} are normally and independently distributed with $(0, \sigma^2)$, the responses y_{ijklm} are also normally and independently distributed with $(\mu + \sigma_i + \beta_j + \alpha_k + \gamma_l + \Omega_m, \sigma^2)$.

Null and alternative hypothesis of each factor for the design is written as follows:

$$H_o : \sigma_i = 0 \qquad \text{for all i}$$
$$H_1 : \text{at least one } \sigma_i \neq 0 \ ,$$

$$H_o : \beta_j = 0 \qquad \text{for all j}$$
$$H_1 : \text{at least one } \beta_j \neq 0$$

$$H_o : \alpha_k = 0 \qquad \text{for all k}$$
$$H_1 : \text{at least one } \alpha_k \neq 0$$

$$H_o : \gamma_l = 0 \qquad \text{for all l}$$

$$H_1 : \text{ at least one } \gamma_l \neq 0$$

$$H_o : \Omega_m = 0 \qquad \text{for all m}$$

$$H_1 : \text{ at least one } \Omega_m \neq 0$$

These hypothesis and interaction effects are tested by using general linear model in ANOVA. The confidence level will be taken as 95%.

4.5 Models and Results

In the further models defined level *RS=1* will be excluded from the analysis of the results of the factorial design. Since all the results for *RS=1* is obtained as zero, the independency of the residuals will not be satisfied unless this *RS* level is excluded. No matter of the combinations of the other factors, *RS=1* instances results are always zero. *RS=1* means resource constraints are not violated at any time so it can be said that MS, PV-MINSLK and PV-LFT always schedules the project to the optimal completion time when there is no resource constraints. In the further analysis level *RS=1* will be excluded so, *RS* will be investigated for three levels for (*J=30, 60, 90)* and will be investigated for five levels which is common with the previous ones. As a result *RS* will be investigated for total of six different levels.

Types of the models were explained before in the experimental design model topic. Models including all levels of *J* (M1All), model with first three level of *J* (M2Small), and model with the last level of *J* (M3Large), will be presented. These three experiments will be conducted with the three program levels separately and with an

experiment that all program levels are included. We will investigate the results under twelve different approaches.

4.5.1 Analysis of models containing all *J* factor levels

4.5.1.1 Analysis of M1-All-Progs. Model

Residuals versus the fitted values are given in the Appendix A as Figure A.1.1.1. The normal probability of residuals and histogram of residuals are given in the Appendices as Figure A.1.1.2 and Figure A.1.1.3 respectively. Figures indicate the inequality of variance and so residuals versus each factor is plotted to support the decision. Residuals versus each factor plot are given in the Appendix B.1.1. In figure Program vs. residual violation of constant variance can easily be visualized. A transformation must be done to the data in order to meet constant variance assumption.

Arcsine transformation is done with the formulation

$$y^* = \text{arcsine } y^{0.5}$$

After the arcsine transformation residuals versus the fitted values are given in Appendix A as Figure A.1.2.1. The normal probability of residuals and histogram of residuals are given in Appendix A as Figure A.1.2.2 and Figure A.1.2.3 respectively. Residuals versus each factor plot are given in the Appendix B.1.2.

After arcsine transformation it can be said that equality of variance is secured. The ANOVA results of responses for significance level 0.05 are in Table 4.5.1.1.1 In the tables the abbreviations of ANOVA are as follows:

DF: Degree of Freedom.

Seq. SS: Sequential sum of square.

Adj. SS: Adjusted sum of square.

Adj. MS: Adjusted expected mean square of factor.

F: Ratio of adjusted expected mean square factor to expected mean square of error.

P: Observed significance level.

R-Sq: Ratio of regression variance to total variance.

R-Sq (Adj.): Adjusted R-Sq.

According to the ANOVA table except for *NC* rest of the main effects (program type, *RS, RF* and *J*) are significant for duration minimization in RCPSP. *RS* seems to be the most affective factor on the results compared to the others. Looking for the ANOVA results, when the interactions are investigated *NC*RS, NC*J, RF*RS, RF*J, RS*Program* and *Program*J* are significant effective. Interaction *NC*Program* shows weak significance where *NC*RF* can be defined as insignificant. Interaction *RF*Program* can be defined as insignificant without any doubt.

Table: 4.5.1.1.1 ANOVA Table of Responses after arcsine transformation for M1-All-Progs. Model

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Main Effects						
NC	2	0.06404	0.00749	0.00374	1.65	0.193
RF	3	0.96430	0.56474	0.18825	83.07	0.000
RS	5	8.62172	7.04790	1.40958	622.04	0.000
Program	2	1.14097	0.45790	0.22895	101.03	0.000
J	3	0.03348	0.03348	0.01116	4.93	0.002
Two-Way Interactions						
NC*RF	6	0.02745	0.02745	0.00458	2.02	0.062
NC*RS	10	0.08464	0.09406	0.00941	4.15	0.000
NC*Program	4	0.02631	0.02631	0.00658	2.90	0.022
NC*J	6	0.10962	0.10962	0.01827	8.06	0.000
RF*RS	15	0.32229	0.32612	0.02174	9.59	0.000
RF*Program	6	0.01247	0.01247	0.00208	0.92	0.482
RF*J	9	0.07637	0.07637	0.00849	3.74	0.000
RS*Program	10	0.06311	0.06939	0.00694	3.06	0.001
Program*J	9	0.04554	0.04554	0.00759	3.35	0.003
Error	416	0.94268	0.94268	0.00227		
Total	503	12.53500				
R-Sq = 92,47%				R-sq(adj.)= 90,91%		

4.5.1.2 Analysis of M1-All-MS Model

Residuals versus the fitted values, the normal probability of residuals and histogram of residuals are given in Appendix A.2.1. Figures indicate the inequality of variance and so residuals versus each factor is plotted to support the decision. Residuals versus each factor plot are given in the Appendix B.2.1. In figures *J* vs. residual and *RS* vs. residual violation of constant variance can easily be visualized. A transformation must be done to the data in order to meet constant variance assumption.

Arcsine transformation is conducted in to MS responses for all levels of number of activity factor. After the transformation residuals versus the fitted values, the normal probability of residuals and histogram of residuals are given in Appendix A.2.2. Residuals versus each factor plot are given in the Appendix B.2.2.

After arcsine transformation it can be said that equality of variance is secured with some exceptions. The ANOVA table of responses for significance level 0.05 is in Table 4.5.1.2.1. According to the ANOVA table *RF* and *RS* is significant effective in MS responses where *RS* seems to be much more affective compared to *RF*. Factors *NC* and *J* are insignificant on the responses. When the interactions are examined, it is seen that interactions of *NC* with any factor does not have any significance where *RF*RS* interaction is highly significant. *RF*J* interaction seems to be significant effective.

Table: 4.5.1.2.1 ANOVA Table of Responses after arcsine transformation for M1-All-MS Model

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Main Effects						
NC	2	0.005450	0.005450	0.000257	0.14	0.866
RF	3	0.275755	0.171102	0.057034	32.05	0.000
RS	5	2.619574	2.067991	0.413598	232.44	0.000
J	3	0.013534	0.013534	0.004511	2.54	0.061
Two-Way Interactions						
NC*RF	6	0.010032	0.010032	0.001672	0.94	0.470
NC*RS	10	0.016418	0.017437	0.001744	0.98	0.465
NC*J	6	0.020443	0.020443	0.003407	1.91	0.085
RF*RS	15	0.159668	0.158370	0.010558	5.93	0.000
RF*J	9	0.038583	0.038583	0.004287	2.41	0.016
Error	108	0.192176	0.192176	0.001779		
Total	167	3.351632				
R-Sq = 94,26%				R-sq(adj.)= 91,13%		

4.5.1.3 Analysis of M1-All-PV-1 Model

Residuals versus the fitted values, the normal probability of residuals and histogram of residuals are given in Appendix A.3.1. Figures indicate the inequality of variance and so residuals versus each factor is plotted to support the decision. Residuals versus each factor plot are given in the Appendix B.3.1. In figures J vs. residual and RS vs. residual violation of constant variance can easily be visualized. A transformation must be done to the data in order to meet constant variance assumption.

Arcsine transformation is conducted in to PV-MINSLK responses. After the transformation residuals versus the fitted values, the normal probability of residuals and histogram of residuals are given in Appendix A.3.2. Residuals versus each factor plot are given in the Appendix B.3.2.

After arcsine transformation it can be said that equality of variance is secured with some exceptions. The ANOVA table of responses for significance level 0.05 is in Table 4.5.1.3.1. According to the ANOVA table RF and RS is significant effective where RS seems to be much more affective compared to RF. NC and J is insignificant to PV-MINSLK. Interactions of $NC*J$ and $RF*RS$ can be said to be significant. The other interactions have no significance effect.

Table: 4.5.1.3.1 ANOVA Table of Responses after arcsine transformation for M1-All-PV-1 Model

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Main Effects						
NC	2	0.072109	0.014312	0.007156	2.28	0.108
RF	3	0.325938	0.196830	0.065610	20.86	0.000
RS	5	3.032173	2.500379	0.500076	159.02	0.000
J	3	0.016469	0.016469	0.005490	1.75	0.162
Two-Way Interactions						
NC*RF	6	0.018328	0.018328	0.003055	0.97	0.448
NC*RS	10	0.042099	0.049001	0.004900	1.56	0.129
NC*J	6	0.056662	0.056662	0.009444	3.00	0.009
RF*RS	15	0.111315	0.115330	0.007689	2.44	0.004
RF*J	9	0.030378	0.030378	0.003375	1.07	0.388
Error	108	0.339639	0.339639	0.003145		
Total	167	4.045111				
R-Sq = 91,60%				R-sq(adj.)=87,02%		

4.5.1.4 Analysis of M1-All-PV-2 Model

Residuals versus the fitted values, the normal probability of residuals and histogram of residuals are given in Appendix A.4.1. Figures indicate the inequality of variance and so residuals versus each factor is plotted to support the decision. Residuals versus each factor plot are given in the Appendix B.4.1. In figures *J* vs. residual and *RS* vs. residual violation of constant variance can easily be visualized. A transformation must be done to the data in order to meet constant variance assumption.

Arcsine transformation is conducted in to PV-LFT responses. After the transformation residuals versus the fitted values, the normal probability of residuals and histogram of

residuals are given in Appendix A.4.2. Residuals versus each factor plot are given in the Appendix B.4.2.

After arcsine transformation it can be said that equality of variance is secured with some exceptions. The ANOVA table of responses for significance level 0.05 is in Table 4.5.1.4.1. According to the ANOVA table only *NC* is insignificant where the other factors *RS, RF* and *J* are significant effective. *RS* seems to be much more significant compared to other factors. Interactions are mostly insignificant except for the *RS*RF* interaction showing a high significant effect and *NC*J* interaction can be defined as weakly significant.

Table: 4.5.1.4.1 ANOVA Table of Responses after arcsine transformation for M1-All-PV-2 Model

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Main Effects						
NC	2	0.012790	0.000465	0.000233	0.09	0.917
RF	3	0.375076	0.200820	0.066940	25.10	0.000
RS	5	3.033083	2.548922	0.509784	191.16	0.000
J	3	0.049017	0.049017	0.016339	6.13	0.001
Two-Way Interactions						
NC*RF	6	0.006422	0.006422	0.001070	0.40	0.877
NC*RS	10	0.041417	0.044014	0.004401	1.65	0.102
NC*J	6	0.040311	0.040311	0.006719	2.52	0.025
RF*RS	15	0.130885	0.130886	0.008726	3.27	0.000
RF*J	9	0.020276	0.020276	0.002253	0.84	0.577
Error	108	0.288007	0.288007	0.002667		
Total	167	3.997284				
R-Sq = 92,79%				R-sq(adj.)=88,86%		

4.5.2 Analysis of models containing small *J* factor levels

4.5.2.1 Analysis of M2-Small-Progs. Model

Residuals versus the fitted values, the normal probability of residuals and histogram of residuals are given in Appendix A.5.1. Figures indicate the inequality of variance and so residuals versus each factor is plotted to support the decision. Residuals versus each factor plot are given in the Appendix B.5.1. In figures *RF* vs. residual and *RS* vs. residual violation of constant variance can easily be visualized. A transformation must be done to the data in order to meet constant variance assumption.

Arcsine transformation is conducted in to the responses. After the arcsine transformation residuals versus the fitted values, the normal probability of residuals and histogram of residuals are given in Appendix A.5.2. Residuals versus each factor plot are given in the Appendix B.5.2

After arcsine transformation it can be said that equality of variance is secured. The ANOVA table of responses for significance level 0.05 is in Table 4.5.2.1.1. According to the ANOVA table all of the factors show significant effectiveness where *RS* has much more significance on the results compared to the others. Interactions seems to be significant except for *RF*Program* interaction and interactions *NC*RF* and *NC*Program* seems to be weakly significant.

Table: 4.5.2.1.1 ANOVA Table of Responses after arcsine transformation for M2-Small-Progs. Model

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Main Effects						
NC	2	0.02203	0.02203	0.01102	7.46	0.001
RF	3	0.53254	0.53254	0.17751	120.28	0.000
RS	2	5.18576	5.18576	2.59288	1756.85	0.000
Program	2	0.71813	0.71813	0.35906	243.29	0.000
J	2	0.03335	0.03335	0.01667	11.30	0.000
Two-Way Interactions						
NC*RF	6	0.02200	0.02200	0.00367	2.48	0.024
NC*RS	4	0.06535	0.06535	0.01634	11.07	0.000
NC*Program	4	0.01657	0.01657	0.00414	2.81	0.026
NC*J	4	0.09157	0.09157	0.02289	15.51	0.000
RF*RS	6	0.28568	0.28568	0.04761	32.26	0.000
RF*Program	6	0.00821	0.00821	0.00137	0.93	0.476
RS*Program	4	0.05637	0.05637	0.01409	9.55	0.000
RF*J	6	0.04571	0.04571	0.00762	5.16	0.000
RS*J	4	0.33805	0.33805	0.08451	57.26	0.000
Program*J	4	0.03807	0.03807	0.00952	6.45	0.000
Error	264	0.38963	0.38963	0.00148		
Total	323	7.84902				
R-Sq = 95,04%				R-sq(adj.)=93,93%		

4.5.2.2 Analysis of M2-Small-MS Model

Residuals versus the fitted values, the normal probability of residuals and histogram of residuals are given in Appendix A.6.1. Figures indicate the inequality of variance and so residuals versus each factor is plotted to support the decision. Residuals versus each factor plot are given in the Appendix B.6.1. In figure *RS* vs. residual violation of constant variance can be visualized. A transformation must be done to the data in order

to meet constant variance assumption. Box and Cox transformation is made on the responses.

Box and Cox formulation is given below;

$$y^* = (y^\lambda - 1)/\lambda \qquad\qquad \lambda \neq 0$$
$$y^* = \ln y \qquad\qquad\qquad\quad \lambda = 0$$

Where y is the positive response variable and y^* is the transformed response variable.

Transformation parameter which makes $SSE(\lambda)$ minimum will be used for transformation. For this reason transformation parameter λ is taken from Figure 4.5.2.2.1 as estimate 0,07.

After the Box and Cox transformation residuals versus the fitted values, the normal probability of residuals and histogram of residuals are given in Appendix A.6.2. Residuals versus each factor plot are given in the Appendix B.6.2.

After the transformation it can be said that equality of variance is secured. The ANOVA table of responses for significance level 0.05 is in Table 4.5.2.2.1. According to the ANOVA table *RS* and *RF* show significant effectiveness where *RS* has great effectiveness on the results. *NC* and *J* are insignificant on MS results. Interactions seems to be significant except for *NC*RF* interaction and interaction *NC*RS* seems to be weakly significant.
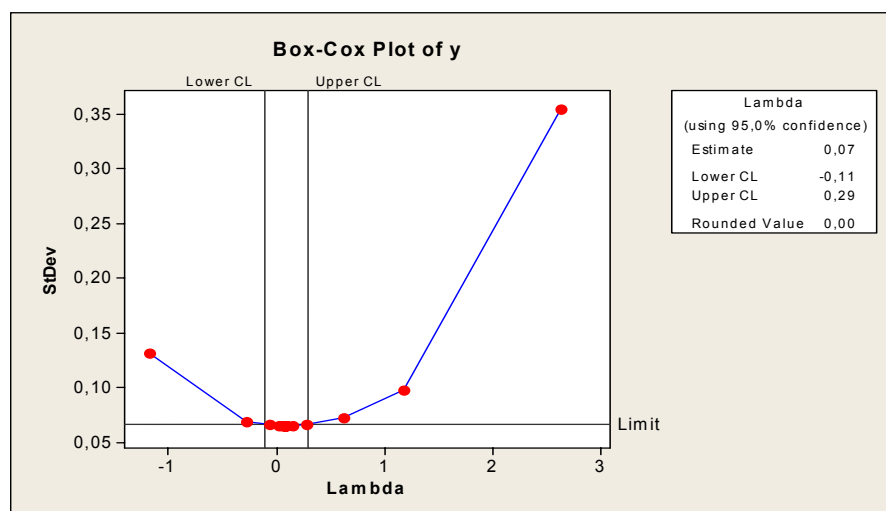
Figure: 4.5.2.2.1 Box and Cox plot for M1-Small-MS Model

Table: 4.5.2.2.1 ANOVA Table of Responses after Box and Cox transformation for M2-Small-MS Model

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Main Effects						
NC	2	0.3837	0.3837	0.1919	1.71	0.188
RF	3	6.9358	6.9358	2.3119	20.62	0.000
RS	2	95.1179	95.1179	47.5589	424.21	0.000
J	2	0.3883	0.3883	0.1942	1.73	0.185
Two-Way Interactions						
NC*RF	6	1.2615	1.2615	0.2103	1.88	0.098
NC*RS	4	1.5805	1.5805	0.3951	3.52	0.011
NC*J	4	1.8794	1.8794	0.4698	4.19	0.004
RF*RS	6	7.0329	7.0329	1.1721	10.46	0.000
RF*J	6	4.2437	4.2437	0.7073	6.31	0.000
RS*J	4	8.8003	8.8003	2.2001	19.62	0.000
Error	68	7.6236	7.6236	0.1121		
Total	107	135.2477				
R-Sq = 94,36%			R-sq(adj.)=91,13%			

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4.5.2.3 Analysis of M2-Small-PV-1 Model

Residuals versus the fitted values, the normal probability of residuals and histogram of residuals are given in Appendix A.7.1. Residuals versus each factor plot are given in the Appendix B.7.1. In figure *RS* vs. residual violation of constant variance can be visualized. A transformation must be done to the data in order to meet constant variance assumption. Arcsine transformation is made to the residuals.

After the arcsine transformation residuals versus the fitted values, the normal probability of residuals and histogram of residuals are given in Appendix A.7.2. Residuals versus each factor plot are given in the Appendix B.7.2. After the transformation it can be said that equality of variance is secured.

The ANOVA table of responses for significance level 0.05 is in Table 4.5.2.3.1. According to the ANOVA table except for *J* other factors show significance on the results, *J* shows weak significance. *RS* seems to have high effect on the results compared to the other factors. All interactions seems to be significant except for *NC*RF* and *RF*J* interactions.

Table: 4.5.2.3.1 ANOVA Table of Responses after arcsine transformation for M2-Small-PV-1 Model

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Main Effects						
NC	2	0.034058	0.034058	0.017029	9.98	0.000
RF	3	0.195252	0.195252	0.065084	38.15	0.000
RS	2	1.918794	1.918794	0.959397	562.34	0.000
J	2	0.015390	0.015390	0.007695	4.51	0.014
Two-Way Interactions						
NC*RF	6	0.013146	0.013146	0.002191	1.28	0.276
NC*RS	4	0.031818	0.031818	0.007955	4.66	0.002
NC*J	4	0.045603	0.045603	0.011401	6.68	0.000
RF*RS	6	0.078759	0.078759	0.013127	7.69	0.000
RF*J	6	0.017145	0.017145	0.002857	1.67	0.141
RS*J	4	0.153197	0.153197	0.038299	22.45	0.000
Error	68	0.116014	0.116014	0.001706		
Total	107	2.619176				
R-Sq = 95,57%				R-sq(adj.)=93,03%		

4.5.2.4 Analysis of M2-Small-PV-2 Model

Residuals versus the fitted values, the normal probability of residuals and histogram of residuals are given in Appendix A.8.1. Figures indicate the inequality of variance and so residuals versus each factor is plotted to support the decision. Residuals versus each factor plot are given in the Appendix B.8.2. In figure *RS* vs. residual violation of constant variance can be visualized. A transformation must be done to the data in order to meet constant variance assumption. Arcsine transformation is made to the residuals.

After the arcsine transformation residuals versus the fitted values, the normal probability of residuals and histogram of residuals are given in Appendix A.8.2.

Residuals versus each factor plot are given in the Appendix B.8.2. With the analyses of the figures it can be said that equality of variance is secured.

The ANOVA table of responses for significance level 0.05 is in Table 4.5.2.4.1. According to the ANOVA table *NC* is insignificant, while other factors show significance on the results. *RS* seems to have high effect on the results compared to the other factors. Interactions mostly seems to be significant except for *NC*RF* and *RF*J* interactions. Interaction *NC*RS* shows weak significance according to the ANOVA table.

Table: 4.5.2.4.1 ANOVA Table of Responses after arcsine transformation for M2-Small-PV-2 Model

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Main Effects						
NC	2	0.002523	0.002523	0.001261	0.66	0.520
RF	3	0.209977	0.209977	0.069992	36.64	0.000
RS	2	1.943382	1.943382	0.971691	508.70	0.000
J	2	0.046457	0.046457	0.023229	12.16	0.000
Two-Way Interactions						
NC*RF	6	0.006560	0.006560	0.001093	0.57	0.751
NC*RS	4	0.025600	0.025600	0.006400	3.35	0.015
NC*J	4	0.033048	0.033048	0.008262	4.33	0.004
RF*RS	6	0.109283	0.109283	0.018214	9.54	0.000
RF*J	6	0.013418	0.013418	0.002236	1.17	0.332
RS*J	4	0.107639	0.107639	0.026910	14.09	0.000
Error	68	0.129889	0.129889	0.001910		
Total	107	2.627776				
R-Sq = 95,06%			R-sq(adj.)=92,22%			

4.5.3 Analysis of models containing large *J* factor level

4.5.3.1 Analysis of M3-Large-Progs. Model

Residuals versus the fitted values, the normal probability of residuals and histogram of residuals are given in Appendix A.9. Residuals versus each factor plot are given in the Appendix B.9. The assumption of equality of variances holds with the exceptions in figure *RF* vs. residual.

The ANOVA table of responses for significance level 0.05 is in Table 4.5.3.1.1. According to the ANOVA table all factors show significance on the results. *RS* seems to be more effective on the results compared to the other factors. Interactions mostly seems to be significant except for *RF*Program* and *NC*RS* interactions showing insignificance on the responses. Interaction *NC*RF* shows weak significance according to the ANOVA table.

Table: 4.5.3.1.1 ANOVA Table of Responses for M3-Large-Progs. Model

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Main Effects						
NC	2	0.020076	0.020076	0.010038	21.02	0.000
RF	3	0.206259	0.206259	0.068753	144.00	0.000
RS	4	0.856389	0.856389	0.214097	448.41	0.000
Program	2	0.210985	0.210985	0.105492	220.95	0.000
Two-Way Interactions						
NC*RF	6	0.006758	0.006758	0.001126	2.36	0.034
NC*RS	8	0.007179	0.007179	0.000897	1.88	0.069
NC*Program	4	0.007506	0.007506	0.001877	3.93	0.005
RF*RS	12	0.037899	0.037899	0.003158	6.61	0.000
RF*Program	6	0.003711	0.003711	0.000618	1.30	0.264
RS*Program	8	0.019667	0.019667	0.002458	5.15	0.000
Error	124	0.059205	0.059205	0.000477		
Total	179	1.435634				
R-Sq = 95,88%				R-sq(adj.)=94,05%		

4.5.3.2 Analysis of M3-Large-MS Model

Residuals versus the fitted values, the normal probability of residuals and histogram of residuals are given in Appendix A.10.1. Residuals versus each factor plot are given in the Appendix B.10.1. In figure *NC* vs. residual violation of constant variance can be visualized. A transformation must be done to the data in order to meet constant variance assumption. Arcsine transformation is made to the residuals.

After the arcsine transformation residuals versus the fitted values, the normal probability of residuals and histogram of residuals are given in Appendix A.10.2. Residuals versus each factor plot are given in the Appendix A.10.2.

After transformation with the analyses of the figures it can be said that equality of variance is secured. The ANOVA table of responses for significance level 0.05 is in Table 4.5.3.2.1. According to the ANOVA table factors *RS* and *RF* show significance on the results while factor *NC* shows weak significance. Interactions mostly seems to be insignificant except for *RF*RS* showing significance on the responses.

Table: 4.5.3.2.1 ANOVA Table of Responses after arcsine transformation for M3-Large-MS Model

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Main Effects						
NC	2	0.004369	0.004369	0.002185	3.61	0.043
RF	3	0.153692	0.153692	0.051231	84.56	0.000
RS	4	0.696070	0.696070	0.174017	287.22	0.000
Two-Way Interactions						
NC*RF	6	0.002971	0.002971	0.000495	0.82	0.567
NC*RS	8	0.006403	0.006403	0.000800	1.32	0.280
RF*RS	12	0.034092	0.034092	0.002841	4.69	0.001
Error	24	0.014541	0.014541	0.000606		
Total	59	0.912138				
R-Sq = 98,41%			R-sq(adj.)=96,08%			

4.5.3.3 Analysis of M3-Large-PV-1 Model

Residuals versus the fitted values, the normal probability of residuals and histogram of residuals are given in Appendix A.11.1. Residuals versus each factor plot are given in the Appendix B.11.1. In figure *RF* vs. residual violation of constant variance can be

visualized. A transformation must be done to the data in order to meet constant variance assumption. Arcsine transformation is made to the residuals.

After the arcsine transformation residuals versus the fitted values, the normal probability of residuals and histogram of residuals are given in Appendix A.11.2. Residuals versus each factor plot are given in the Appendix B.11.2.

After transformation with the analyses of the figures it can be said that equality of variance is secured. The ANOVA table of responses for significance level 0.05 is in Table 4.5.3.3.1. According to the ANOVA table factors are significant effective on the responses where RS seems to be the most significant. Interactions mostly seems to be insignificant except for *RF*RS* showing significance on the responses.

Table: 4.5.3.3.1 ANOVA Table of Responses after arcsine transformation for M3-Large-PV-1 Model

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Main Effects						
NC	2	0.042208	0.042208	0.021104	20.35	0.000
RF	3	0.139904	0.139904	0.046635	44.98	0.000
RS	4	0.609665	0.609665	0.152416	147.00	0.000
Two-Way Interactions						
NC*RF	6	0.013070	0.013070	0.002178	2.10	0.091
NC*RS	8	0.017999	0.017999	0.002250	2.17	0.068
RF*RS	12	0.045332	0.045332	0.003778	3.64	0.003
Error	24	0.024884	0.024884	0.001037		
Total	59	0.893062				
R-Sq = 97,21%				R-sq(adj.)=93,15%		

4.5.3.4 Analysis of M3-Large-PV-2 Model

Residuals versus the fitted values, the normal probability of residuals and histogram of residuals are given in Appendix A.12. Residuals versus each factor plot are given in the Appendix B.12. From the figures residuals it can be said that equal variance assumption holds with some exceptions

The ANOVA table of responses for significance level 0.05 is in Table 4.5.3.4.1. According to the ANOVA table factors are significant effective on the responses while *NC* showing weak significance. Interactions mostly seems to be insignificant except for *RF*RS* showing weak significance on the responses.

Table: 4.5.3.4.1 ANOVA Table of Responses for M3-Large-PV-1 Model

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Main Effects						
NC	2	0.0034186	0.0034186	0.0017093	5.35	0.012
RF	3	0.0563888	0.0563888	0.0187963	58.79	0.000
RS	4	0.2132217	0.2132217	0.0533054	166.71	0.000
Two-Way Interactions						
NC*RF	6	0.0013791	0.0013791	0.0002299	0.72	0.638
NC*RS	8	0.0022918	0.0022918	0.0002865	0.90	0.535
RF*RS	12	0.0106198	0.0106198	0.008850	2.77	0.016
Error	24	0.0076739	0.0076739	0.003197		
Total	59	0.2949937				
R-Sq = 97,40%				R-sq(adj.)=93,60%		

4.5.4 General evaluation of the ANOVA results

MS: Factor *RS* has great significance on the MS results. Likewise *RF* is found to be significant on MS results though as not much as *RS*. The other two main effects *NC* and *J* seem to be insignificant on the responses. When the interactions are investigated it can be said that *NC*RF* interaction is insignificant on the results. Interaction *RS*J* and *RF*RS* has significance on the results. Interaction *RF*J* can be defined as significant. *NC*RS* seems to be weakly significant in the model when the first three levels of *J* is included. When interaction *NC*J* is investigated, two different results are obtained from ANOVA tables for all *J* levels included model and the model with first three levels are included. *NC*J* seems to be significant on the model with first three levels of *J*. When the full model is observed *NC*J* seems insignificant but this can occur from both situations first it can be the effect of the last level of *J* or the absence of *RS*J* interaction.

PV-MINSLK: Factors *RS* and *RF* has the same effects on PV-MINSLK as the MS results. *RS*J* and *RF*RS* interactions seems to be significant on the responses. Interactions *NC*RF* and *RF*J* can be defined as insignificant on the results without any doubt. Interaction *NC*J* seems to show significance on the results. *NC* and *J* can be defined as significant. When interaction *NC*RS* is investigated different results are obtained for significance. This interaction seems to be significant for the model that the first three levels of *J* are included and not very significant in the model for the last level of *J*. *NC*RS* interaction seems to be clearly insignificant for the full model without *RS*J* interaction. This shows the lack in affect of *RS*J* interaction on *NC*RS* interaction.

PV-LFT: Factors *RS* and *RF* has the same effects with PV-MINSLK and MS for PV-LFT. Factor *J* seems to be significant on the PV-LFT results. *NC* is insignificant on the

PV-LFT responses. Interactions *RS*J* and *RF*RS* are shows significance. *NC*RF* and *RF*J* are clearly insignificant. *NC*RS* can be defined as insignificant. *NC*J* can be defined as weakly significant on the results.

General Factor Effects: These effects are obtained by investigating the results when all the program levels are included in the model. We generally investigate these results in order to observe the significance of the *Program.* Selected *Program* for solving RCPSP's seems to be significant according to the responses. Further comments for investigating the results when all programs are included will be done in order to show general significance of factors. Significance of any tested factor and its interaction will show the need for using that factor or its interaction in the experimental design. When the main effects of the factors are analyzed *RS, RF* and *J* seems to be significant effective on the results. *NC* seems to be significant when *J* levels are separately analyzed and when all *J* levels are included *NC* seems to be insignificant. *RS* seems to be the most effective factor on the results. *RS*J* is not included for that model and this can be the reason of *NC* being insignificant in the full model without *RS*J*. By analyzing the main effects in the full model it can be said that all the factors investigated should be included in the experiments for investigations of the effects. Any of the programs or their priority rules results may not have any significant effect of *NC* and *J* but if these factors have significance on only one program, it is sensible to include these factors in the experimental designs.

Interaction *NC*RS* seems to be significant on the first three levels of *J*. We can say that *NC*RF* does not effect the responses much. *NC*Program* interaction seem to show weak significance. Last interaction with *NC* is the *NC*J* interaction which shows significance on the results and should be included in the investigations. Interaction *RF*RS* and *RF*J* seems to be significant on the responses where the other *RF* interaction *RF*Program* is insignificant. *RS*Program* and *RS*J* seems to be

significant similarly as the other *RS* interactions. Finally *Program*J* interactions seems to be significant.

Comparing results with literature: As the results of [Kolisch (1999)], RF has significance on three different program levels. His results have shown significance for six softwares out of seven for RS. Similarly results have shown that, RS have serious significance on all responses. Likewise his statistical test results, J has significance on some programs (MS) while has no significance on the others (Both PV methods). He did not find any significance of NC to the results while according to our research; NC has significance on PV-MINSLK results.

CHAPTER V

CONCLUSION

Resource constrained project scheduling problems (RCPSP) are an important topic for the researchers for several decades considering several objective such as minimizing project duration, efficient utilization of resources. For scheduling the RCPSP's generally optimization methods and heuristics are used to obtain a feasible solution. Nowadays in most of the projects, project management software's are used for scheduling. These software's provide project planning, tracking and controlling besides the simplicity and quickness of obtaining a schedule.

In our study, resource allocation capabilities of project management software's are tested with resource constrained project scheduling problems generated from the instance generator ProGen. ProGen instances and optimal or best known solutions to these instances are taken from the PSPLIB.

MS Project 2003 (MS) and Primavera Enterprise V.4.1-Project Management (PV) with its two priority rules minimum total slack (MINSLK) and latest finish time (LFT) are used for solving 2040 instances generated from ProGen under different parameter settings. The responses are found as the percentage mean deviation from the benchmark makespan.

Experimental design is made with different levels of network complexity (NC), different number of activities (J), different levels of resource factor (RF) and different

levels of resource strength (*RS*) in order to test the packages performances in different settings of topology and resource scarcity measures.

The results of our benchmark test problems show that only one out of 6120 instances was solved better than the state-of-the-art algorithms by using project management software packages. This better solution was obtained from PV-LFT. It can be seen from the results that the quality of the project management software's decrease under the environments with resource scarcity. New algorithms should be implemented in these softwares in order to obtain better results.

The mean and the standard deviations of the deviations for all instances indicated that PV-LFT gave the best results for every factor combinations except for the instances that have 30 activities. In those instances MS outperformed PV results. PV-MINSLK ranked last for all treatments. From these results it can be said that only for small problems MS should be preferred to PV-LFT, for the larger size problems PV-LFT should be used in order to obtain better results for RCPSP's. PV-MINSLK method is not the proper choice for RCPSP's.

In order to test the significance of the factors and their interactions, analysis of variance (ANOVA) is conducted. Twelve different models are used for testing the *Program* (Program is MS, PV-MINSLK, PV-LFT) effects and factors effects on the software results under different settings for the size of the problems. ANOVA results indicated that *Program* factor is significant on the results. For this reason it can be said that choosing the right program is important for obtaining a better result for a RCPSP. According to the results *RS* has highly significance on the results compared to the other factors. Also *RF* has significance on RCPSP's. Significance of *RS* and *RF* has shown parallelism to the results of previous researches. Results showed us that other factors *NC* and *J* significance seem to be dependent on the program and the levels of

the factor used. When the significance of interactions are analyzed, it can be said that *RF*RS* and *RS*J* interactions have significance on the results. The significance of the other interactions differ from program to program where interactions *RF*Program* and *NC*RF* are insignificant on the results.

This study also gives the project manager a chance to know the approximate percent deviations from the optimal solutions that MS and PV will give for his project, when the tested factor levels reflects the project settings. For the future studies some advices can be given as follows;

Project management software packages are continuously evolving. New studies can be made on new coming products of the general used project management software packages. Interactions of *RF*Program* and *NC*RF* can be excluded from the model for this study since these interactions did not show any significance on the results.

Another experiment can be conducted by using RanGen instances. This new experiment will help a project manager to support his decision formed from the results obtained from this study. Since *RS* and *RF* are significant on the results alternatively used parameters of RanGen, resource constrainedness (*RC*) and resource usage can be tested for significance.

Another experiment can be done for comparing the priority rule methods of PV, where the software gives its users different choices with its leveling options. Also while conducting this study PV's priority rules best result can be taken for comparison with the other packages.

Another experiment can be done with the instances generated under different parameter settings. For example number of resource can be increased as well as number of activities.

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APPENDIX A

GENERAL CHARTS

A.1 M1-All-Progs. Model

A.1.1 M1-All-Progs. Model Before Transformation
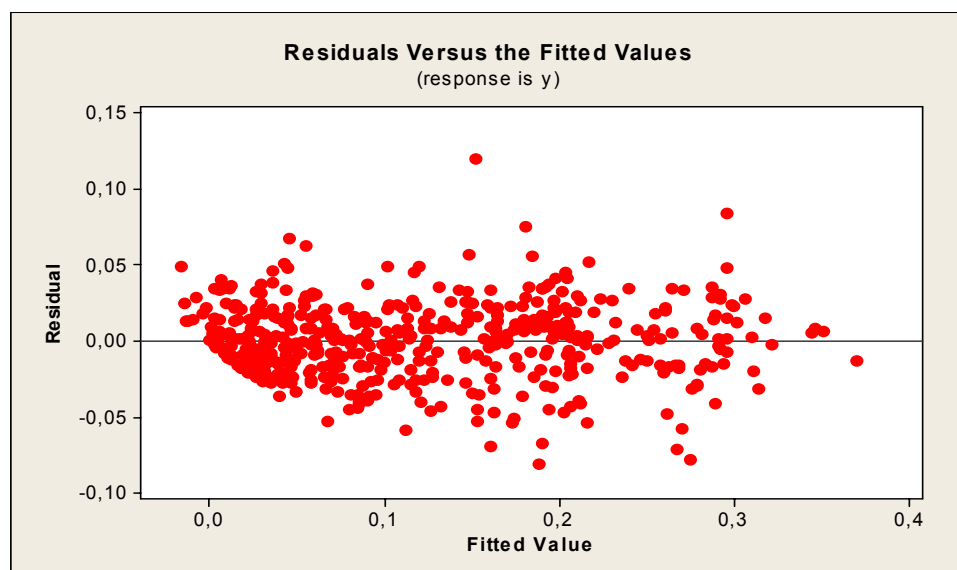
Figure A.1.1.1 Residual versus Fitted Values of M1-All-Progs. Model
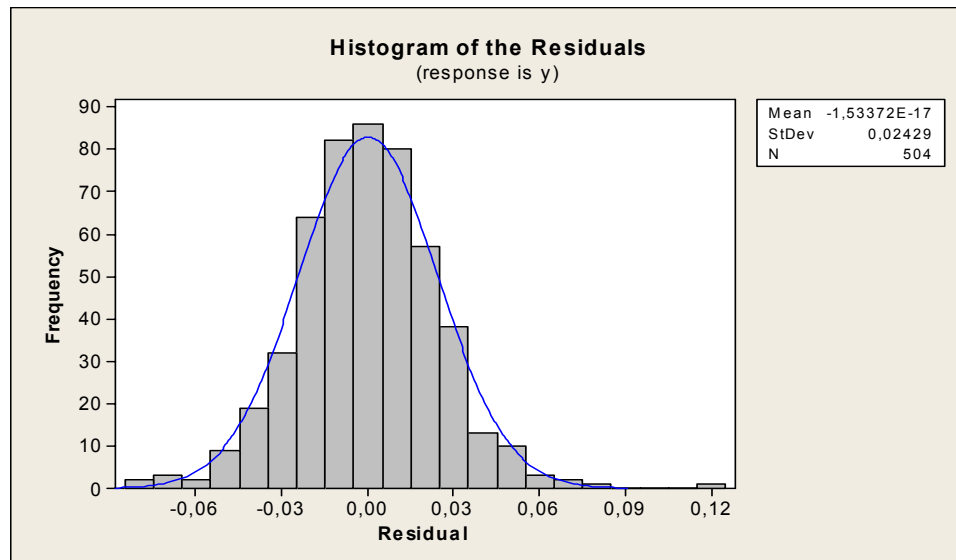
Figure A.1.1.2 Histogram of the Residuals of M1-All-Progs. Model
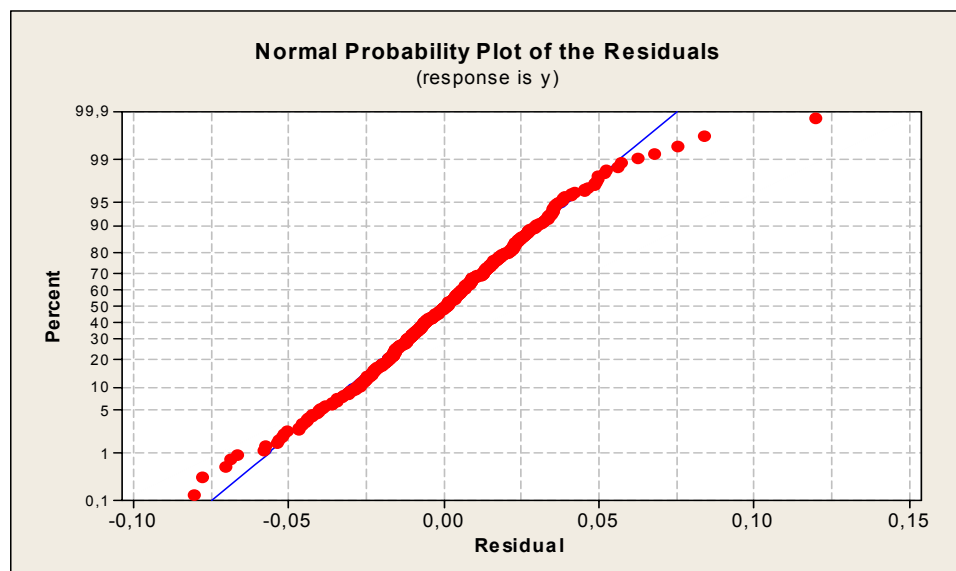
Figure A.1.1.3 Normal Probability Plot of the Residuals of M1-All-
Progs. Model

80

A.1.2 M1-All-Progs. Model After Transformation
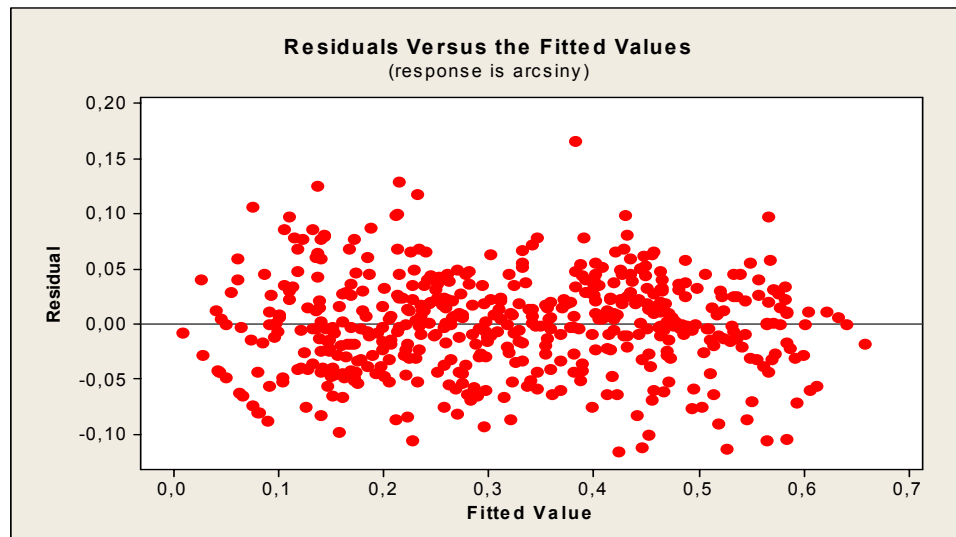
Figure A.1.2.1 Residual versus Fitted Values of M1-All-Progs. Model
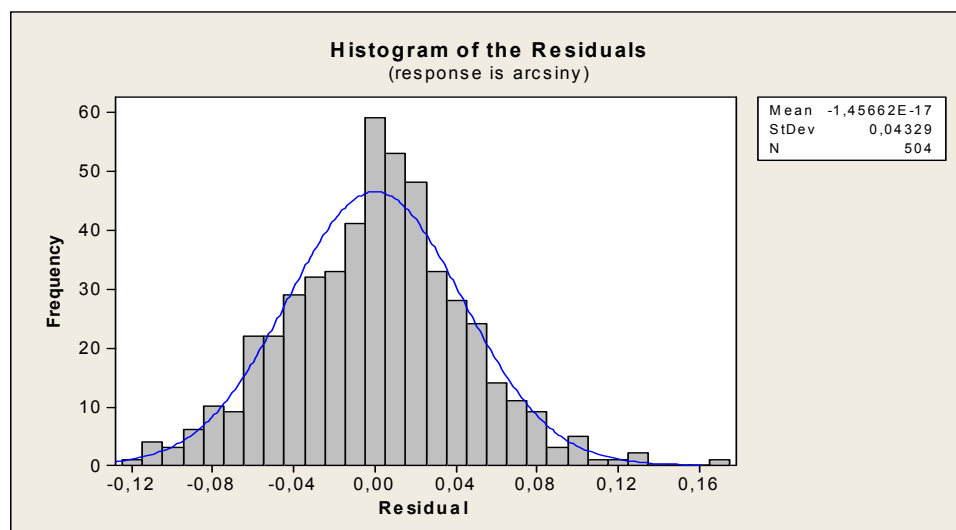
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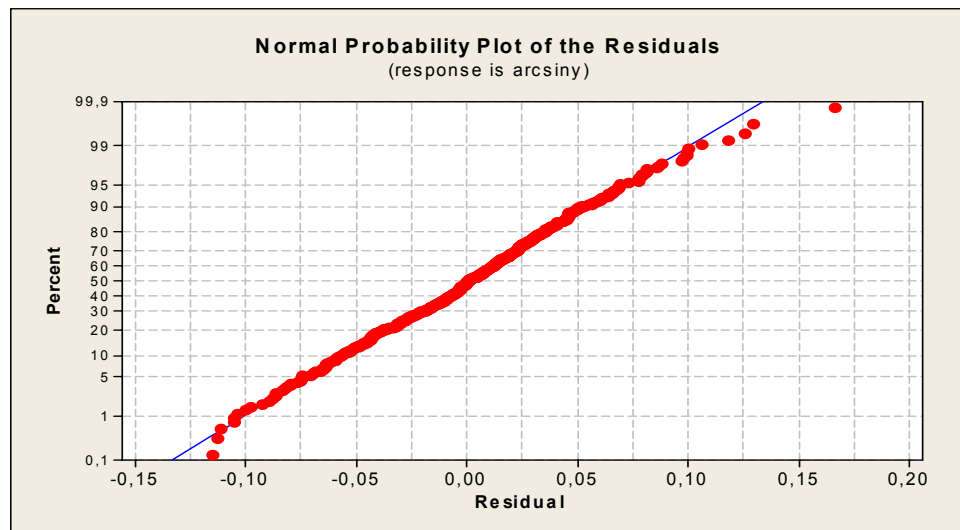
Figure A.1.2.3 Normal Probability Plot of the Residuals of M1-All-

Progs. Model

A.2 M1-All-MS Model

A.2.1 M1-All-MS Model Before Transformation
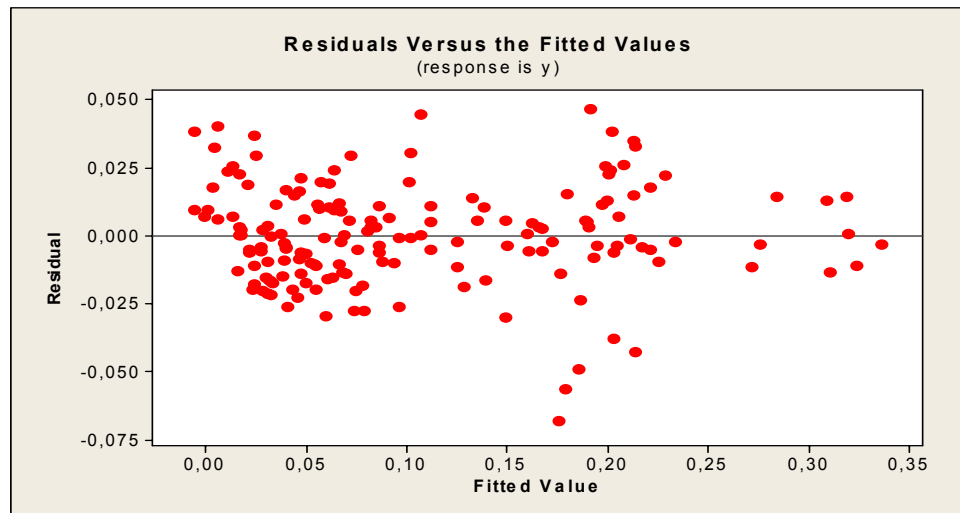
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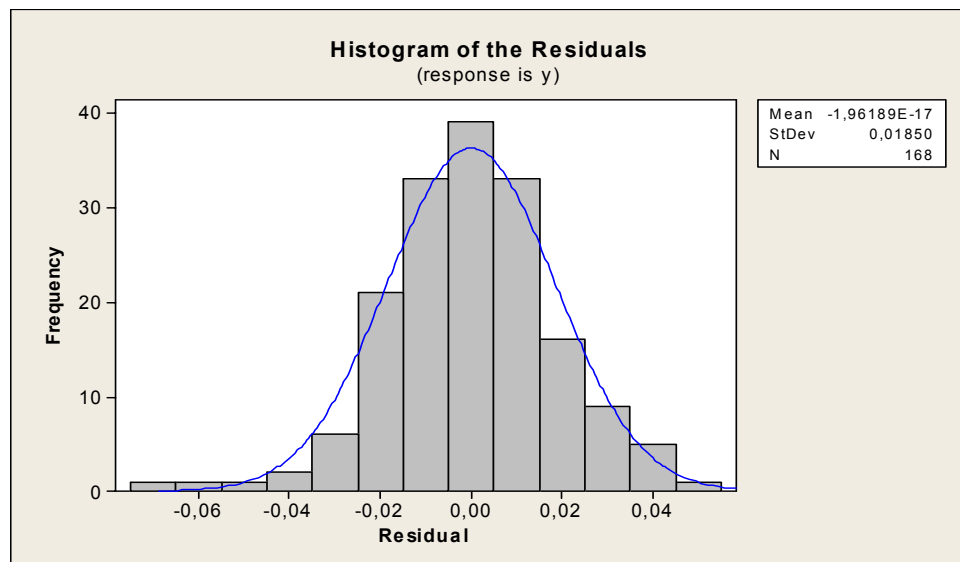
Figure A.2.1.2 Histogram of the Residuals of M1-All-MS Model
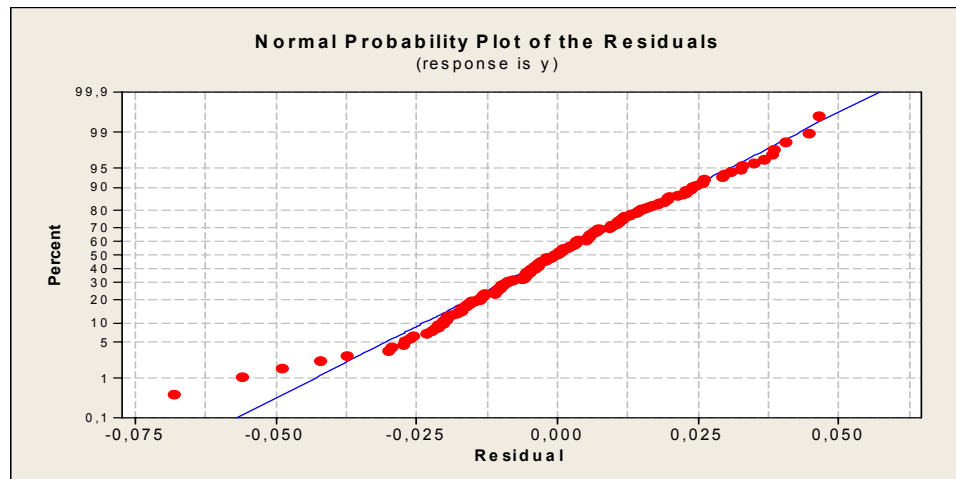
Figure A.2.1.3 Normal Probability Plot of the Residuals of M1-All-MS
Model

A.2.2 M1-All-MS Model After Transformation
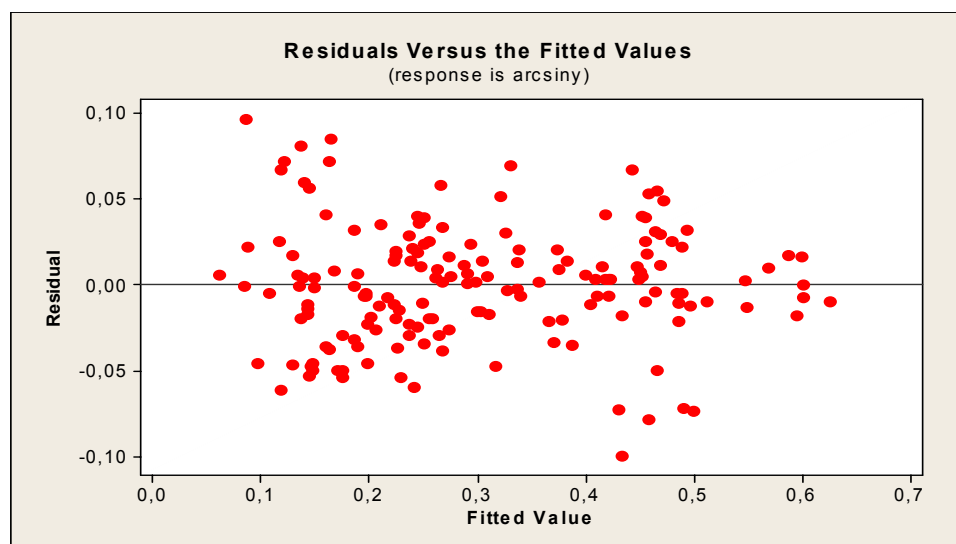
Figure A.2.2.1 Residual versus Fitted Values of M1-All-MS Model
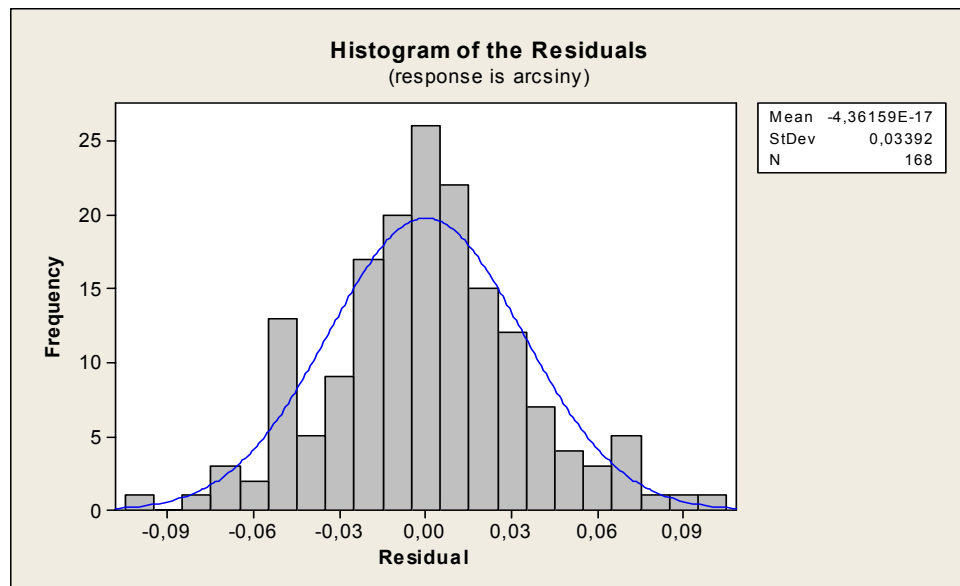
Figure A.2.2.2 Histogram of the Residuals of M1-All-MS Model
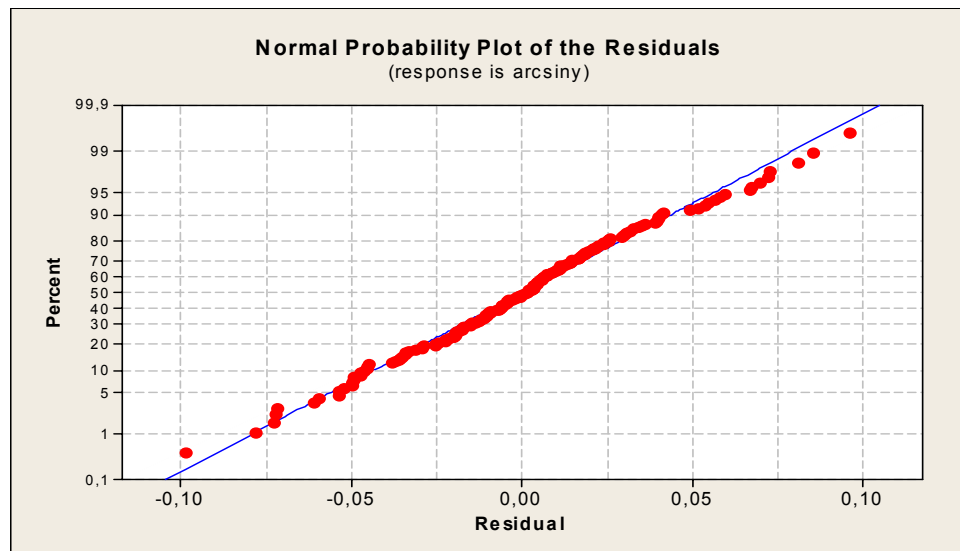
Figure A.2.2.3 Normal Probability Plot of the Residuals of M1-All-MS

Model

A.3 M1-All-PV-1 Model

A.3.1 M1-All-PV-1 Model Before Transformation
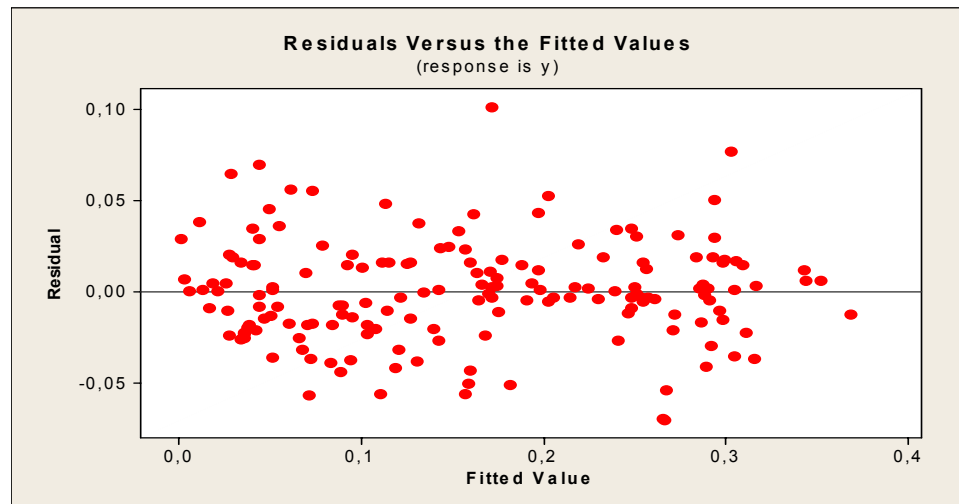
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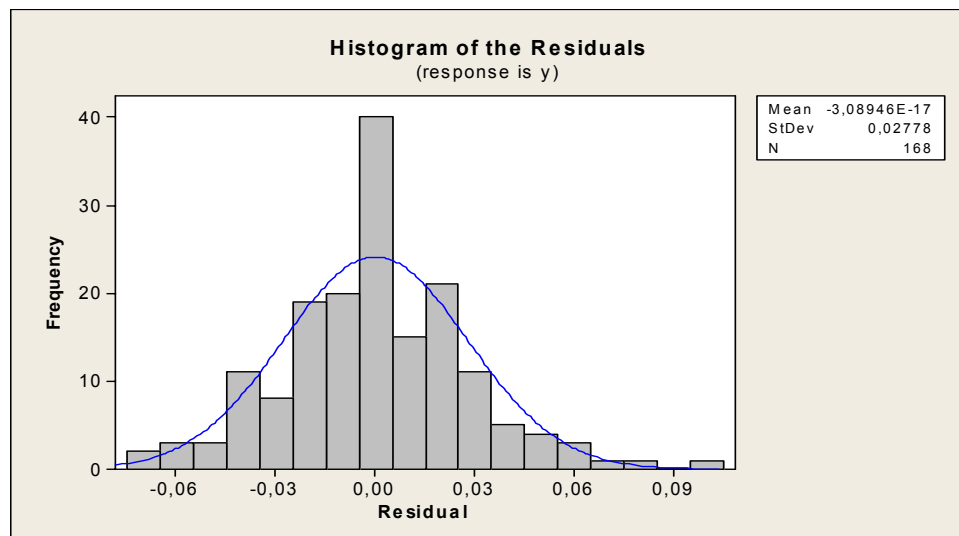
Figure A.3.1.2 Histogram of the Residuals of M1-All-PV-1 Model
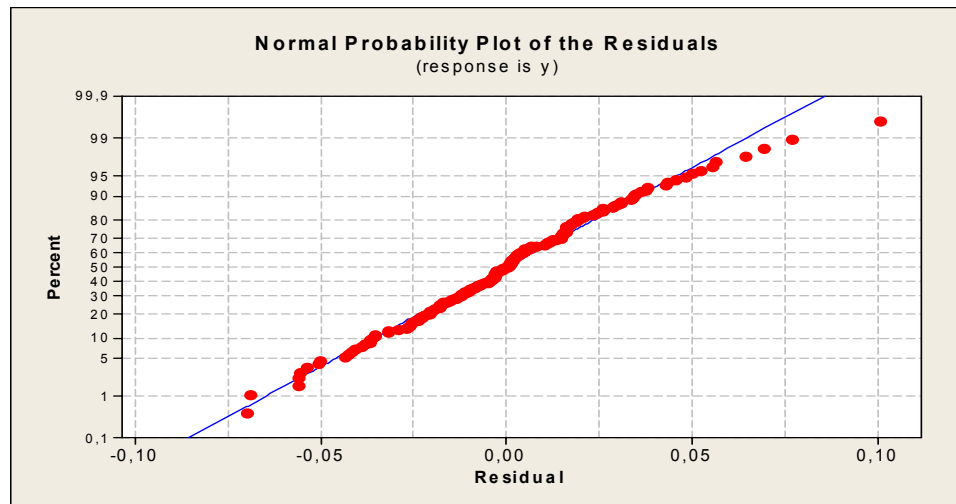
Figure A.3.1.3 Normal Probability Plot of the Residuals of M1-All-PV-1 Model

A.3.2 M1-All-PV-1 Model After Transformation
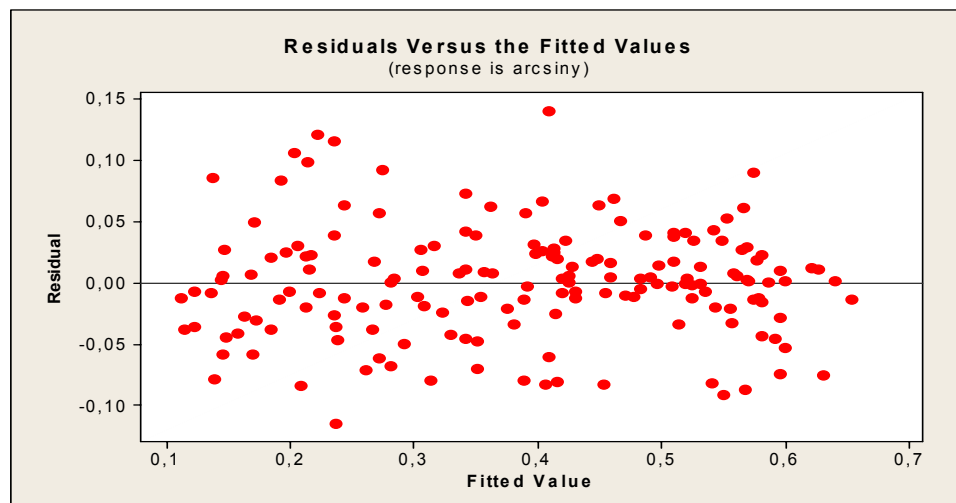
Figure A.3.2.1 Residual versus Fitted Values of M1-All-PV-1 Model
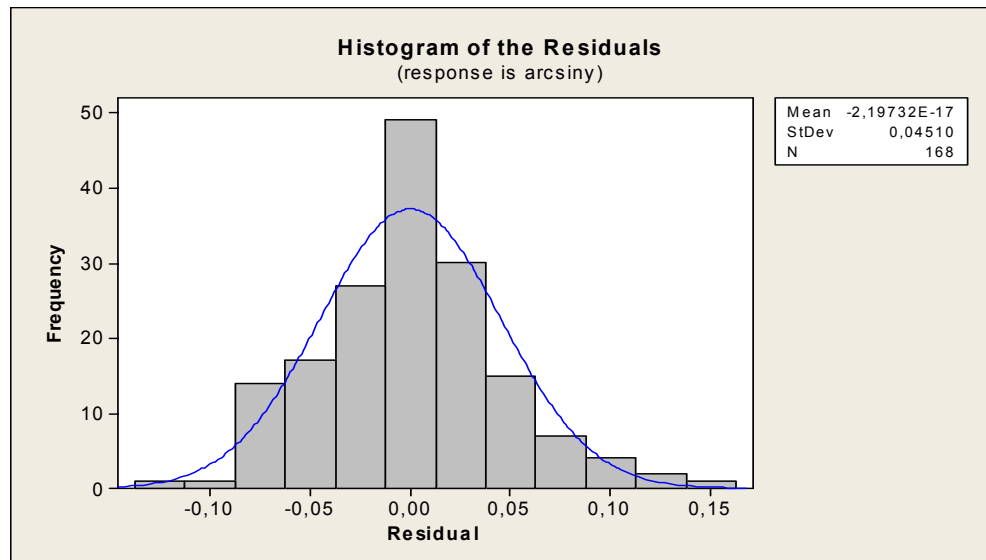
Figure A.3.2.2 Histogram of the Residuals of M1-All-PV-1 Model
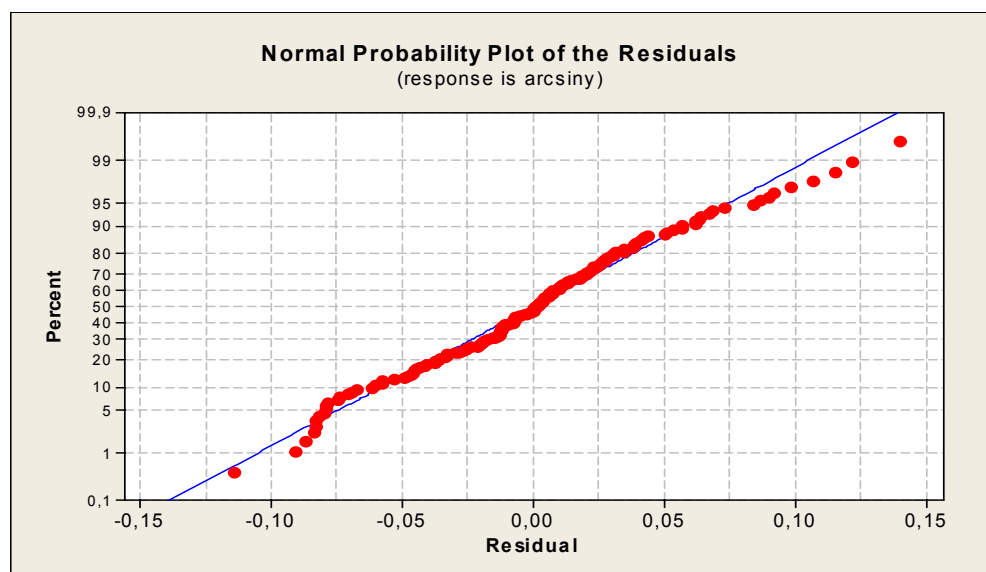
Figure A.3.2.3 Normal Probability Plot of the Residuals of M1-All-PV-
1 Model

A.4 M1-All-PV-2 Model

A.4.1 M1-All-PV-2 Model Before Transformation
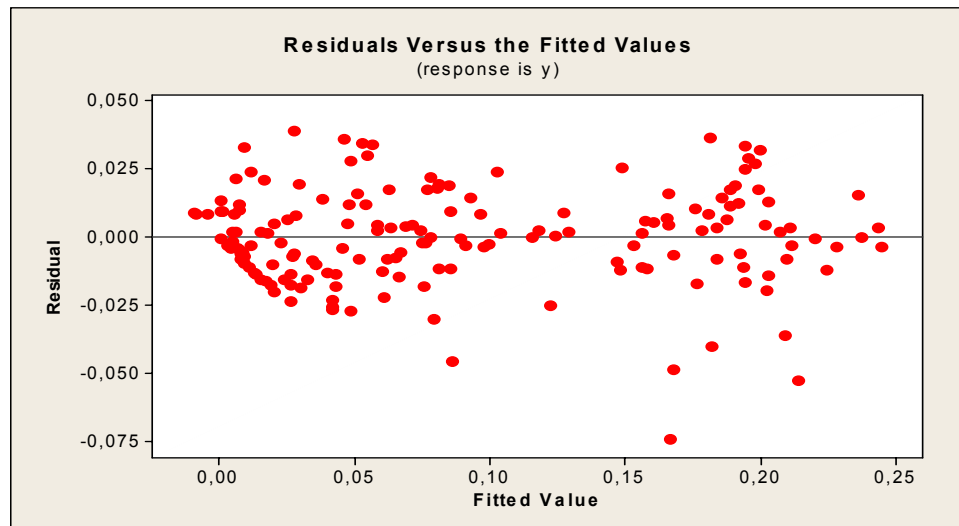
Figure A.4.1.1 Residual versus Fitted Values of M1-All-PV-2 Model
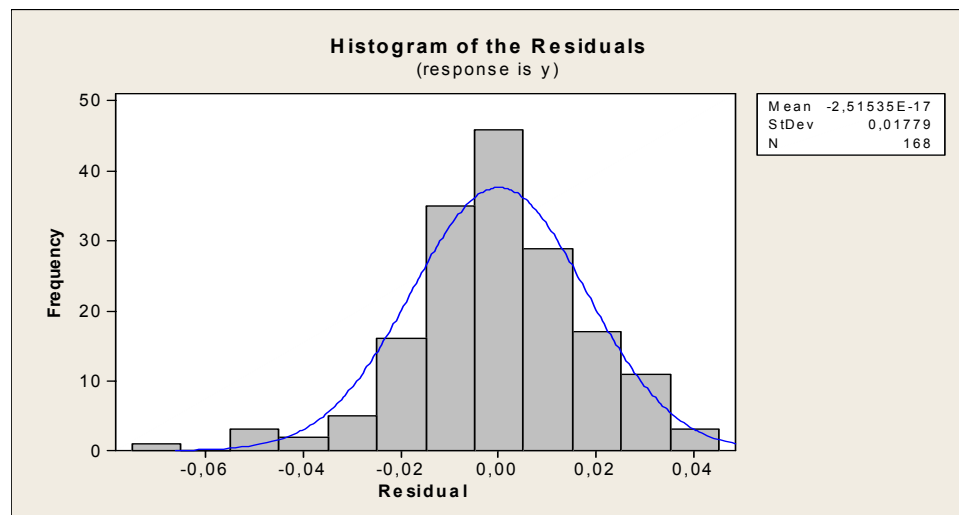
Figure A.4.1.2 Histogram of the Residuals of M1-All-PV-2 Model
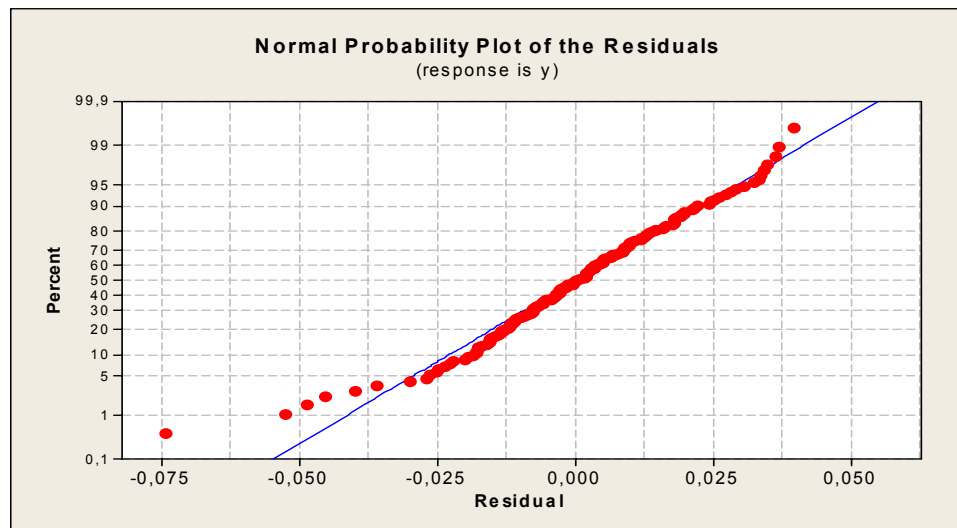
Figure A.4.1.3 Normal Probability Plot of the Residuals of M1-All-PV-2 Model

A.4.2 M1-All-PV-2 Model After Transformation
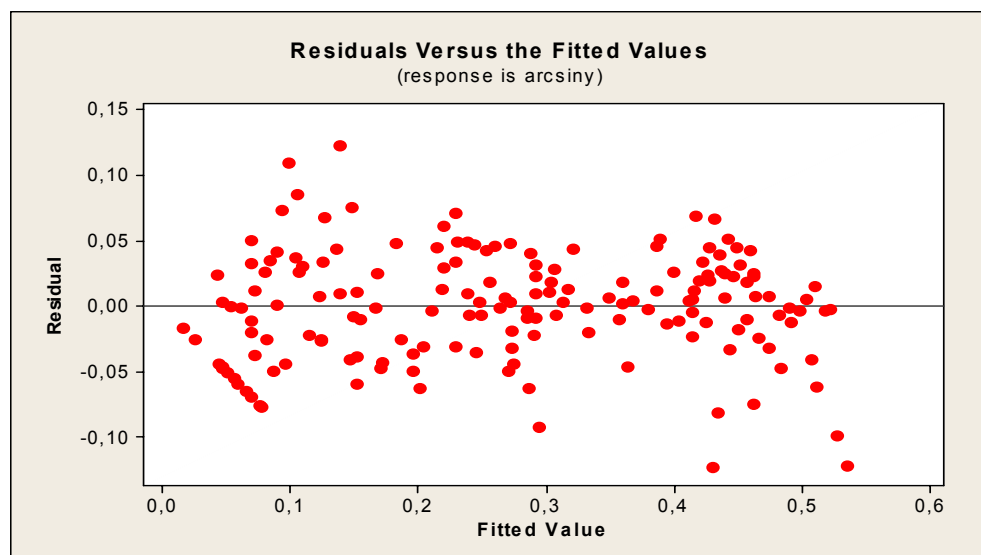
Figure A.4.2.1 Residual versus Fitted Values of M1-All-PV-2 Model
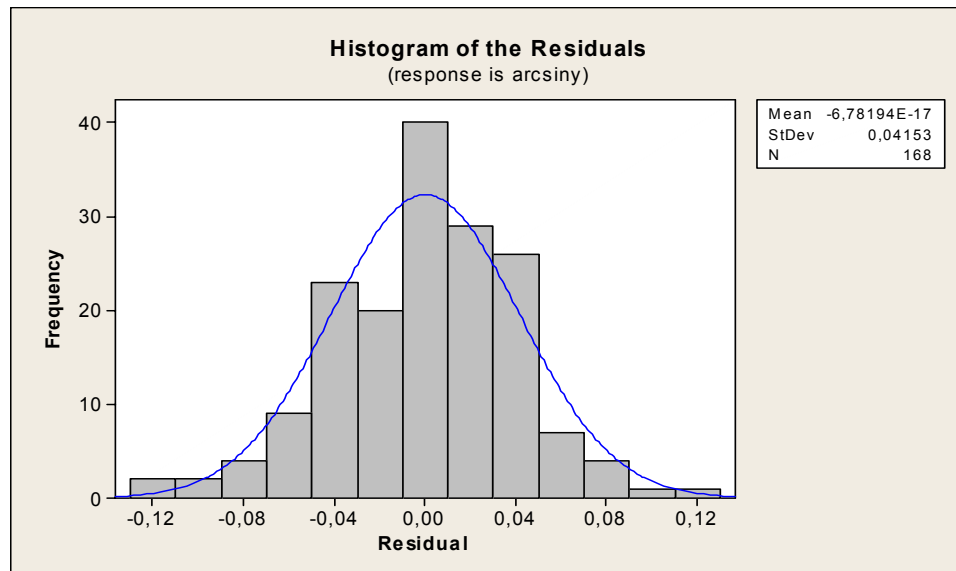
Figure A.4.2.2 Histogram of the Residuals of M1-All-PV-2 Model
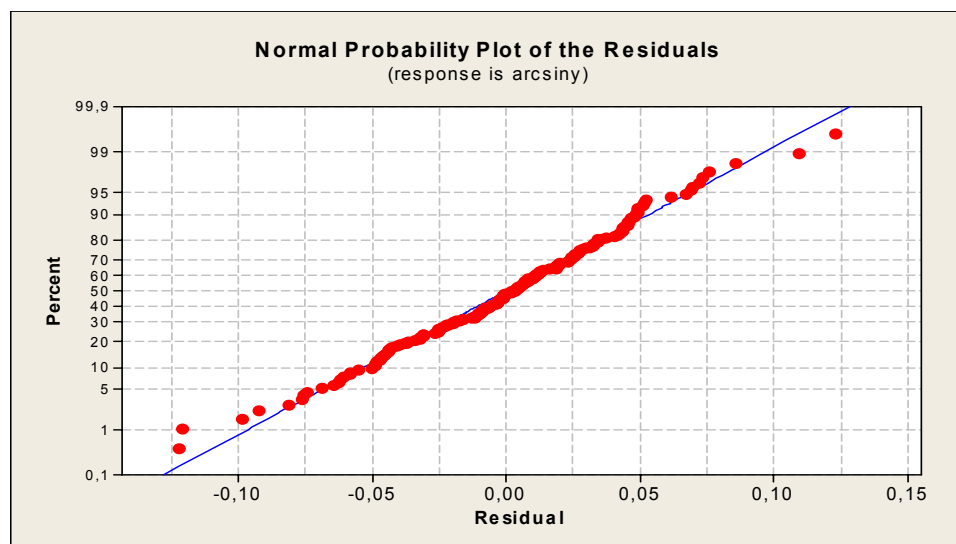
Figure A.4.2.3 Normal Probability Plot of the Residuals of M1-All-PV-2 Model

A.5 M2-Small-Progs. Model

A.5.1 M2-Small-Progs. Model Before Transformation
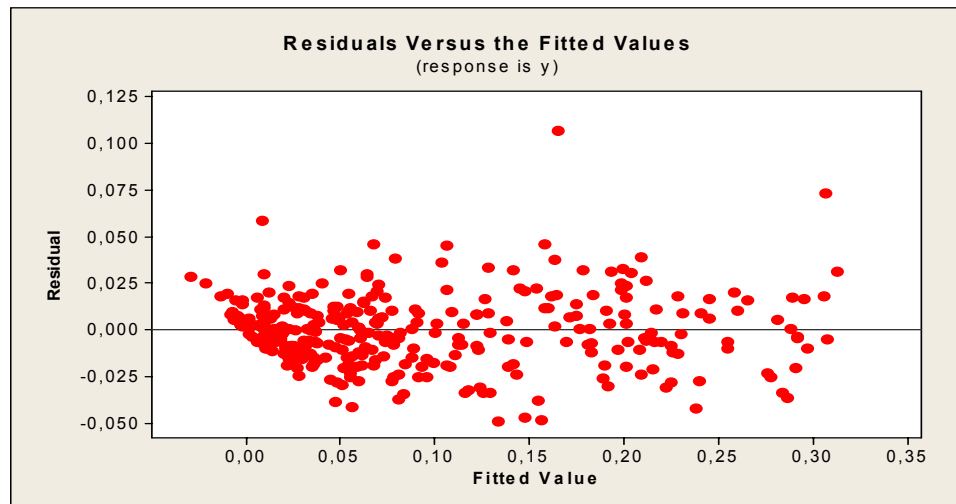
Figure A.5.1.1 Residual versus Fitted Values of M1-Small-Progs.
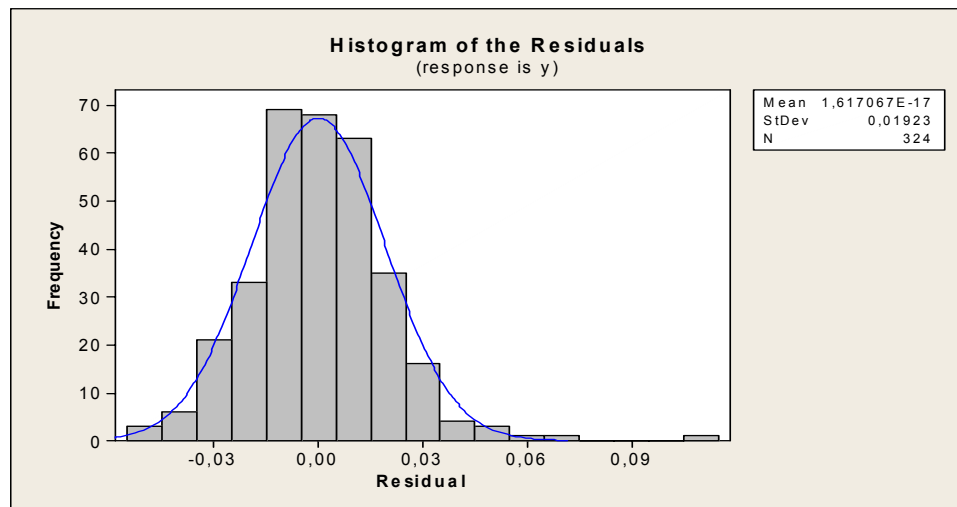
Model

Figure A.5.1.2 Histogram of the Residuals of M1-Small-Progs. Model
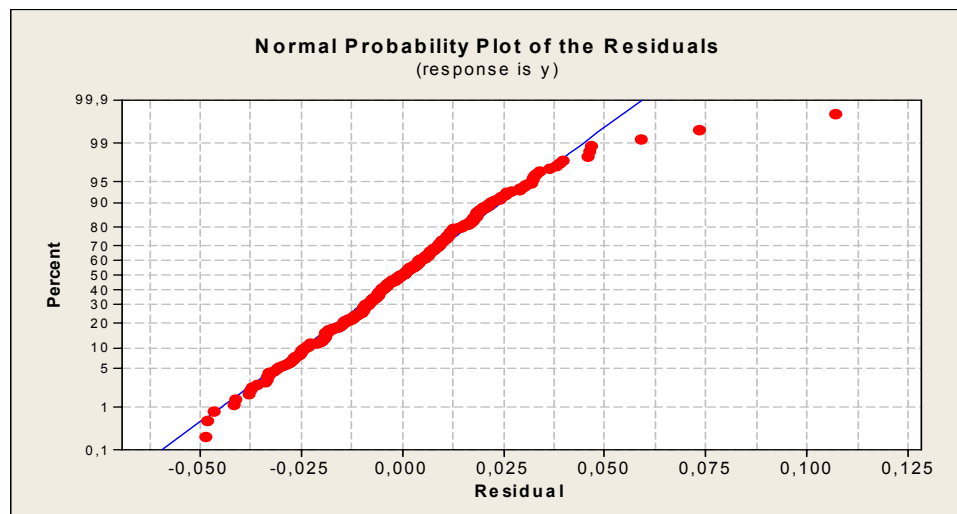
Figure A.5.1.3 Normal Probability Plot of the Residuals of M1-Small-
Progs. Model

A.5.2 M2-Small-Progs. Model After Transformation
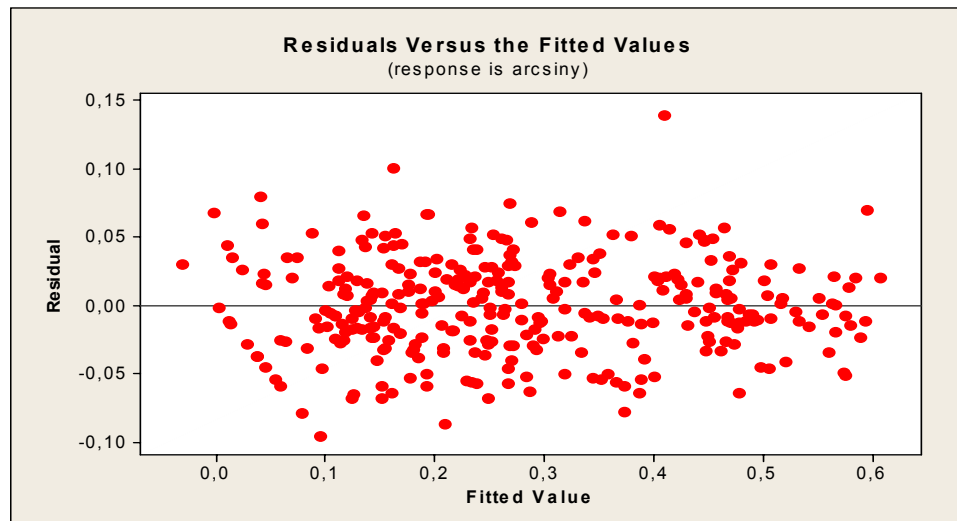
Figure A.5.2.1 Residual versus Fitted Values of M1-Small-Progs.
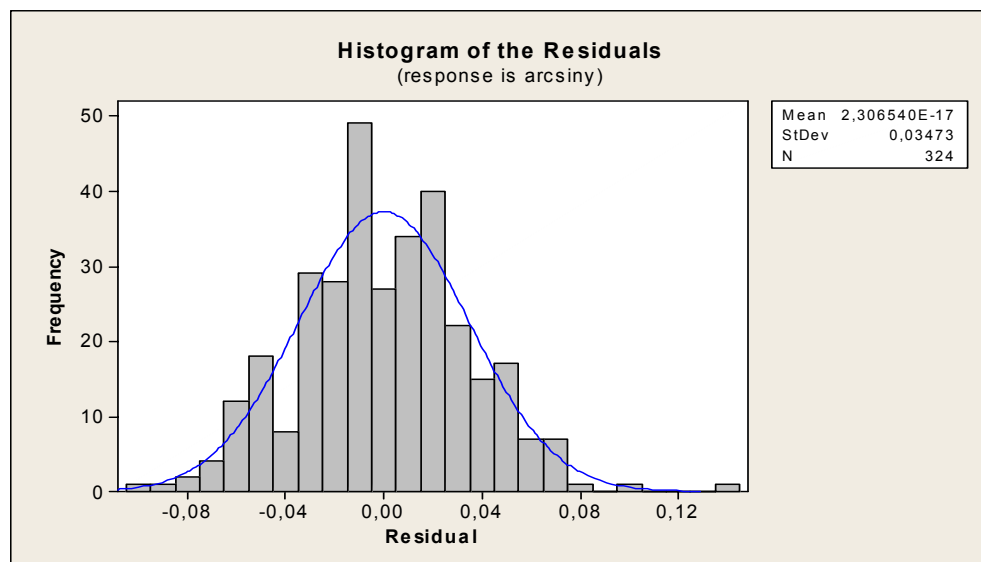
Model

Figure A.5.2.2 Histogram of the Residuals of M1-Small-Progs. Model
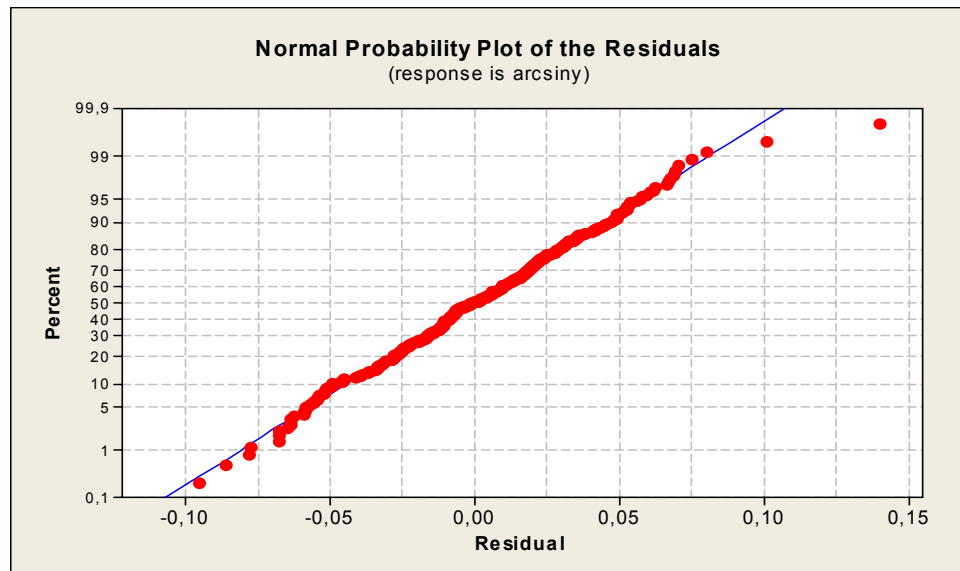
Figure A.5.2.3 Normal Probability Plot of the Residuals of M1-Small-

Progs. Model

A.6 M1-Small-MS Model

A.6.1 M1-Small-MS Model Before Transformation
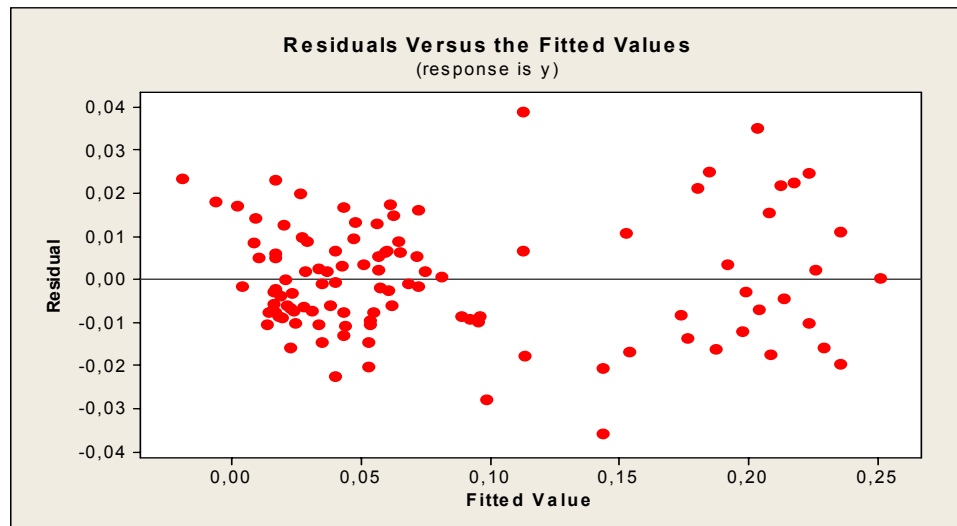
Figure A.6.1.1 Residual versus Fitted Values of M1-Small-MS Model
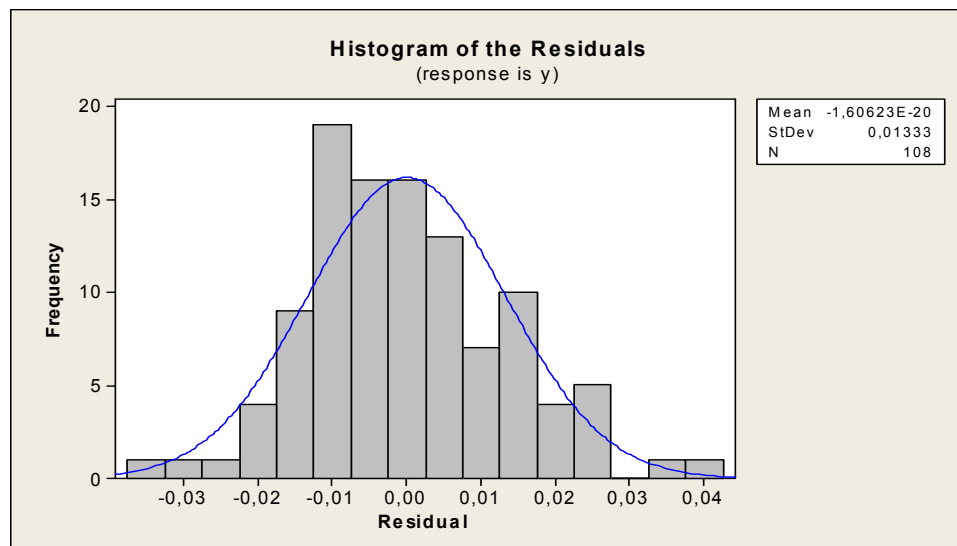
Figure A.6.1.2 Histogram of the Residuals of M1-Small-MS Model
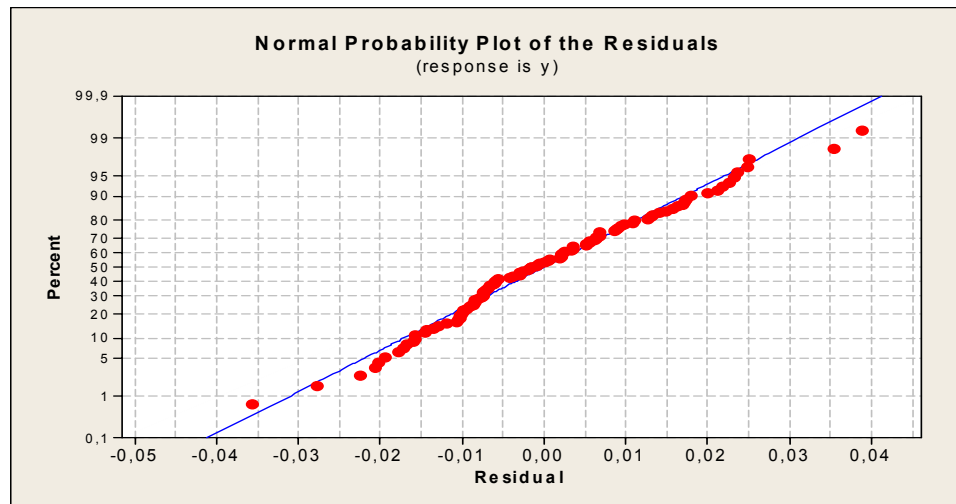
Figure A.6.1.3 Normal Probability Plot of the Residuals of M1-Small-
MS Model

A.6.1 M1-Small-MS Model After Transformation
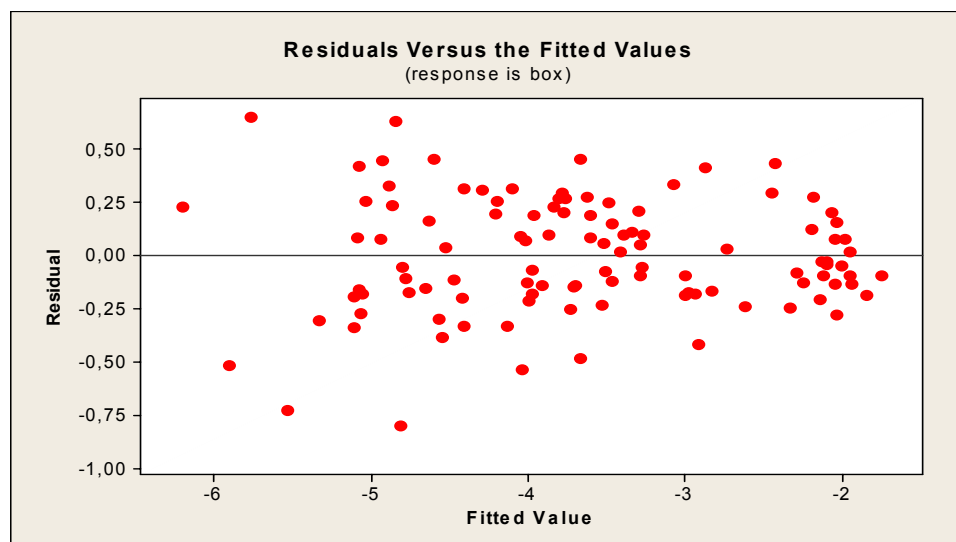
Figure A.6.2.1 Residual versus Fitted Values of M1-Small-MS Model
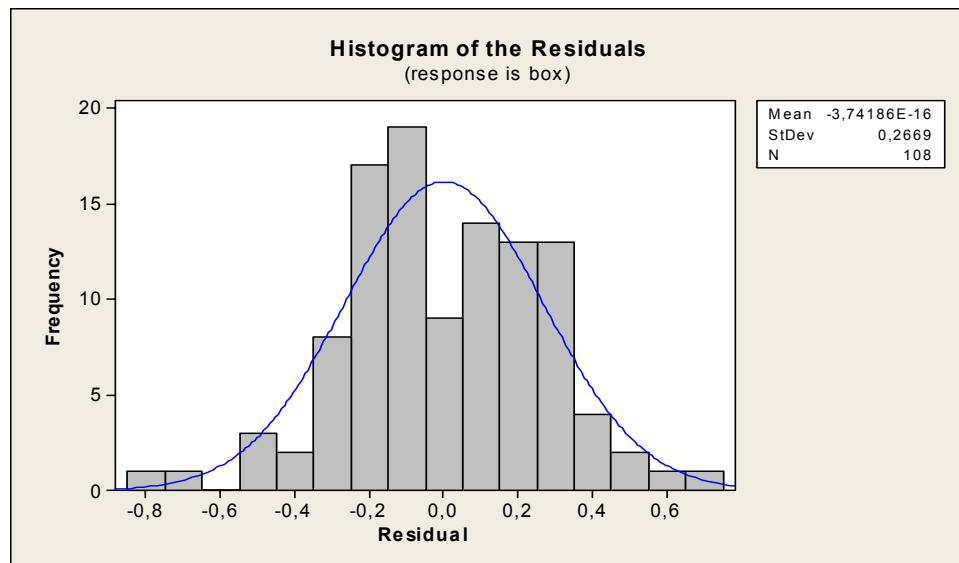
Figure A.6.2.2 Histogram of the Residuals of M1-Small-MS Model
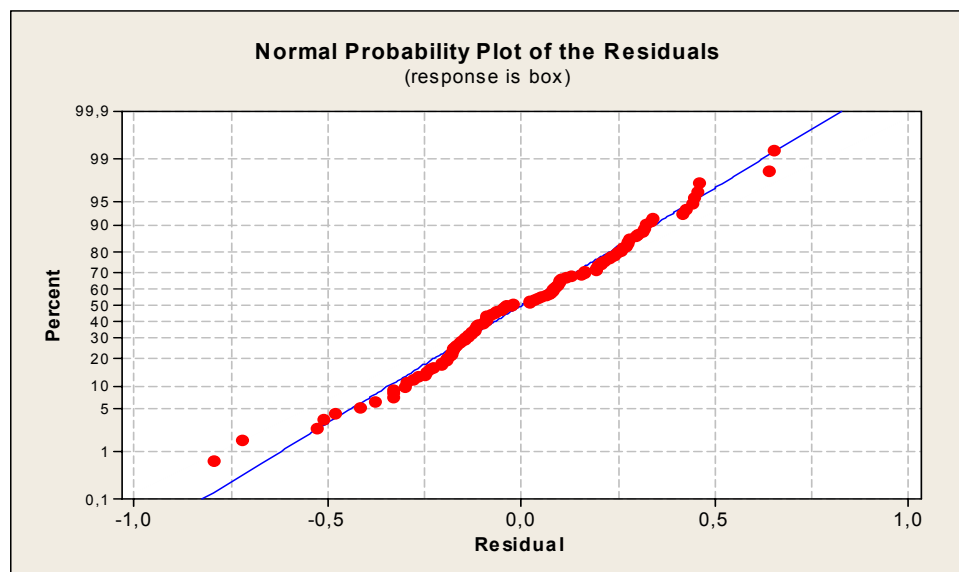
Figure A.6.2.3 Normal Probability Plot of the Residuals of M1-Small-MS Model

A.7 M2-Small-PV-1 Model

A.7.1 M2-Small-PV-1 Model Before Transformation
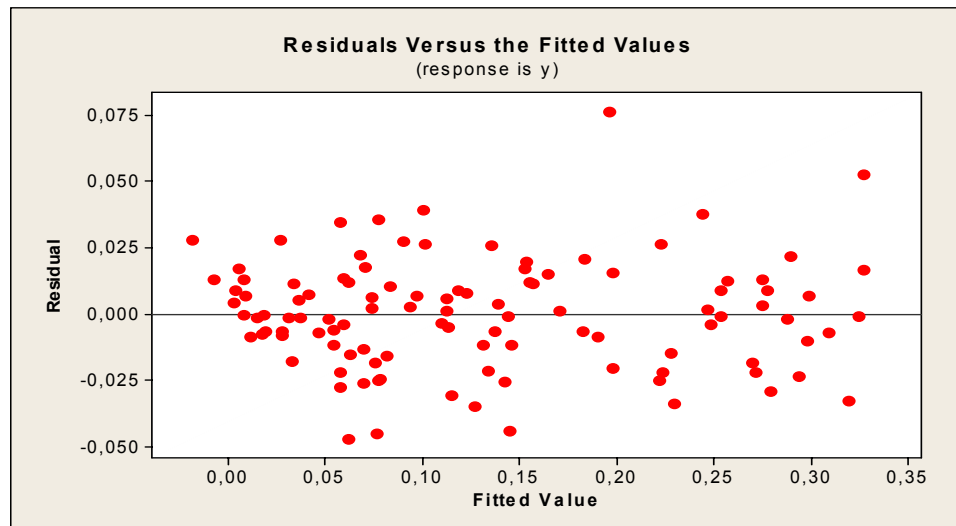
Figure A.7.1.1 Residual versus Fitted Values of M1-Small-PV-1 Model
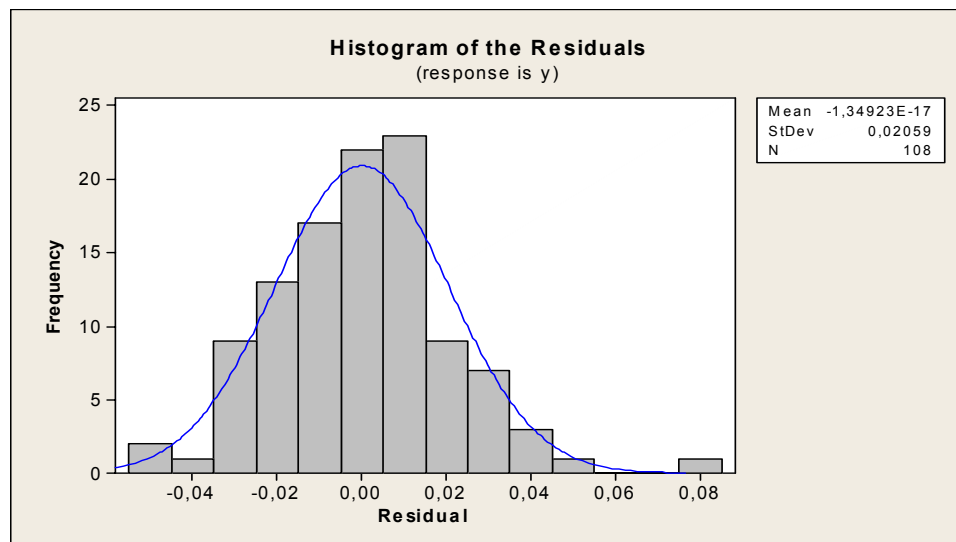
Figure A.7.1.2 Histogram of the Residuals of M1-Small-PV-1 Model
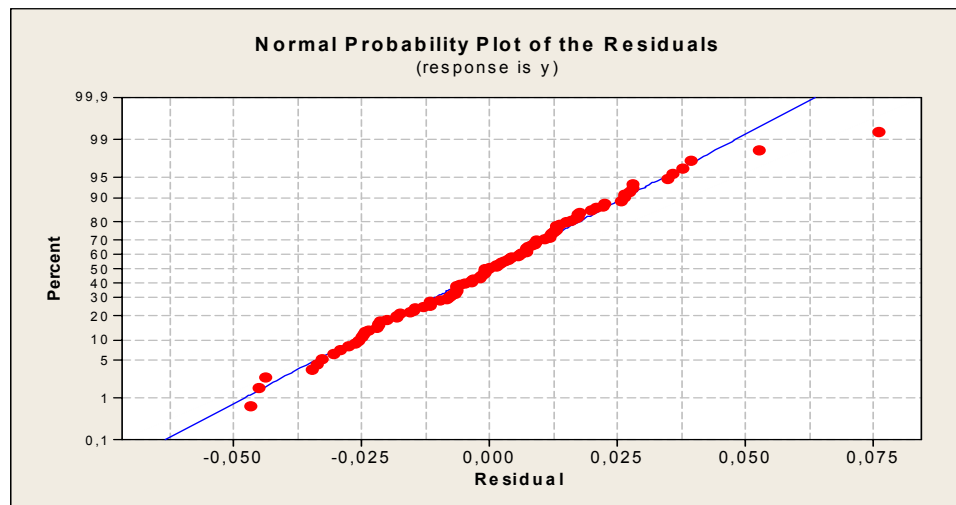
Figure A.7.1.3 Normal Probability Plot of the Residuals of M1-Small-PV-1 Model

A.7.2 M2-Small-PV-1 Model After Transformation
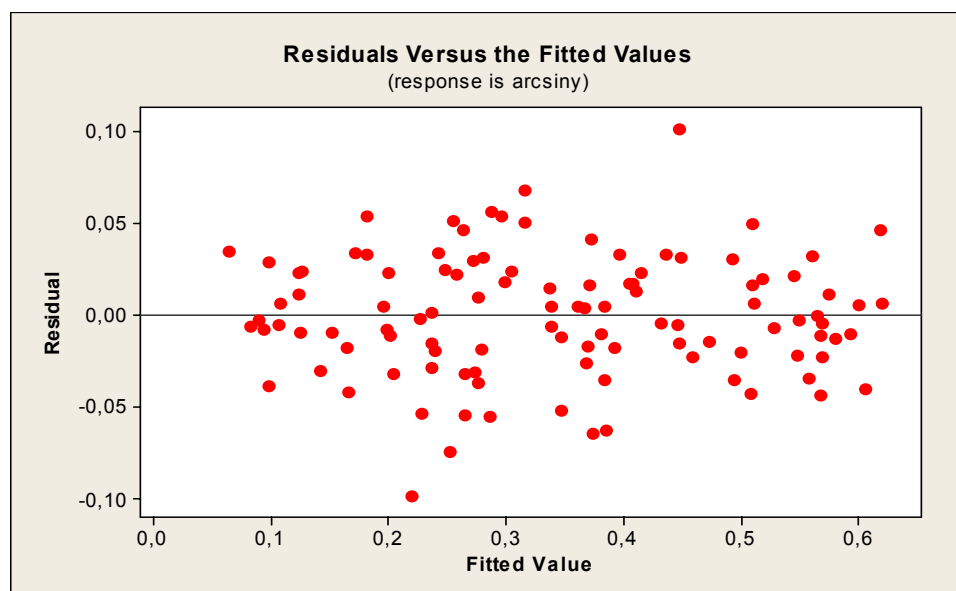
Figure A.7.2.1 Residual versus Fitted Values of M1-Small-PV-1 Model
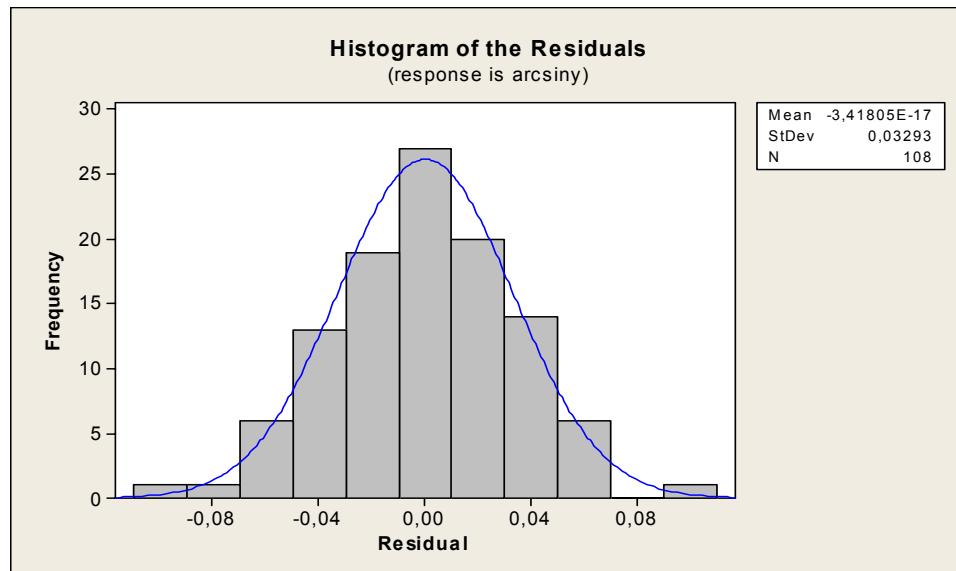
Figure A.7.2.2 Histogram of the Residuals of M1-Small-PV-1 Model
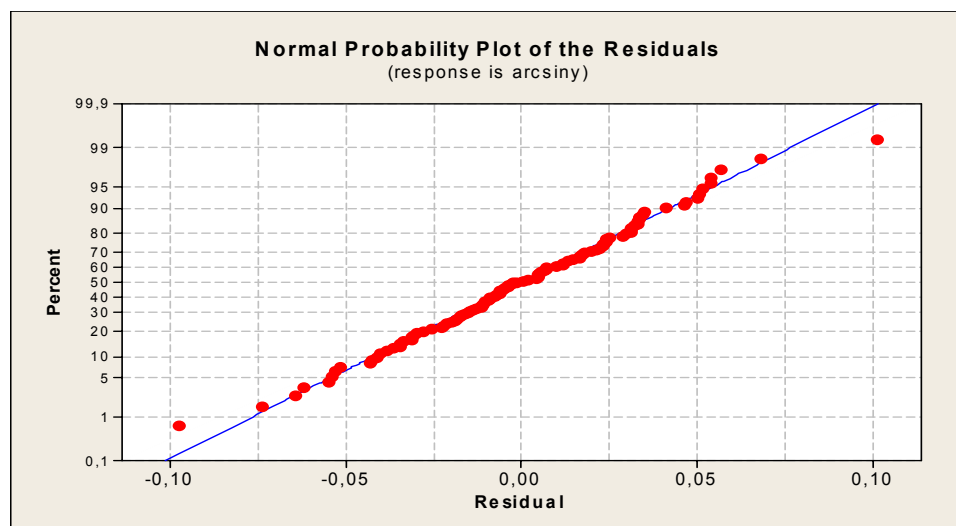
Figure A.7.2.3 Normal Probability Plot of the Residuals of M1-Small-PV-1 Model

A.8 M2-Small-PV-2 Model

A.8.1 M2-Small-PV-2 Model Before Transformation
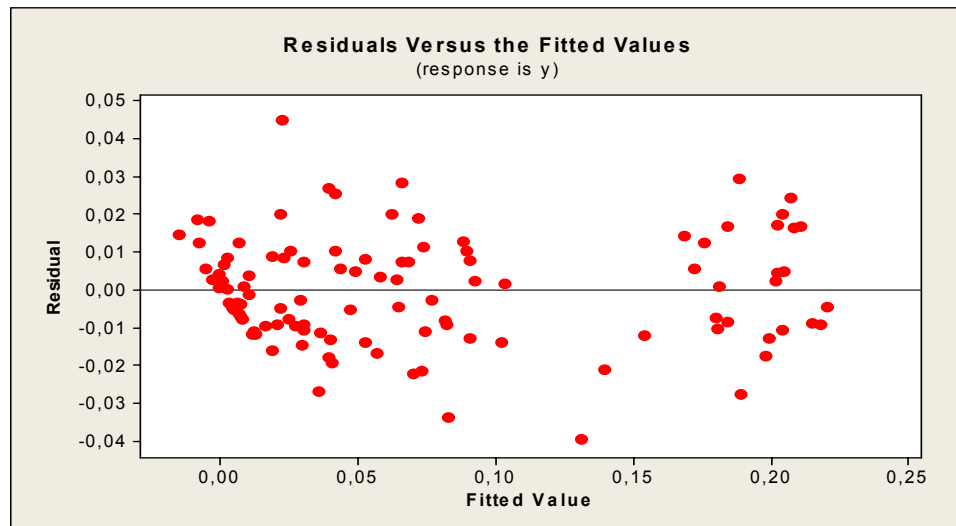
Figure A.8.1.1 Residual versus Fitted Values of M1-Small-PV-2 Model
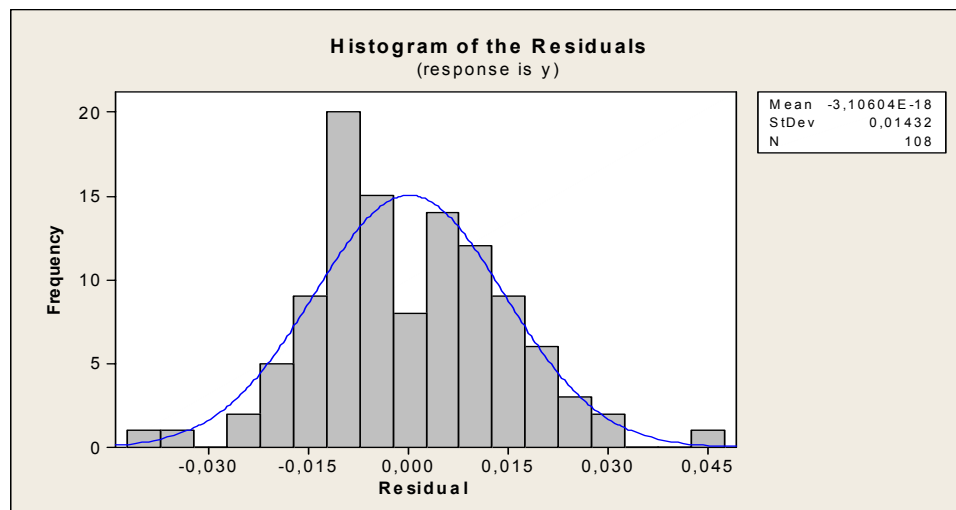
Figure A.8.1.2 Histogram of the Residuals of M1-Small-PV-2 Model
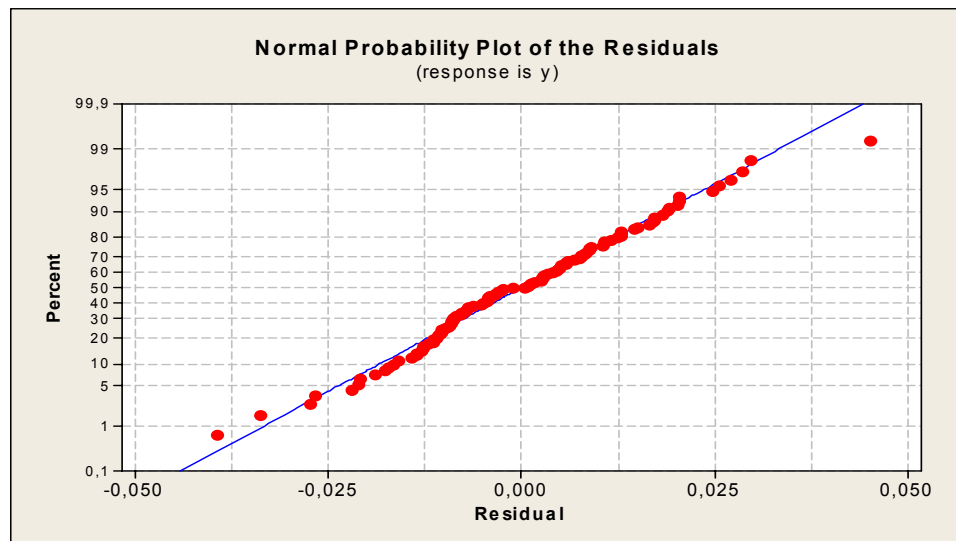
Figure A.8.1.3 Normal Probability Plot of the Residuals of M1-Small-PV-2 Model

A.8.2 M2-Small-PV-2 Model After Transformation
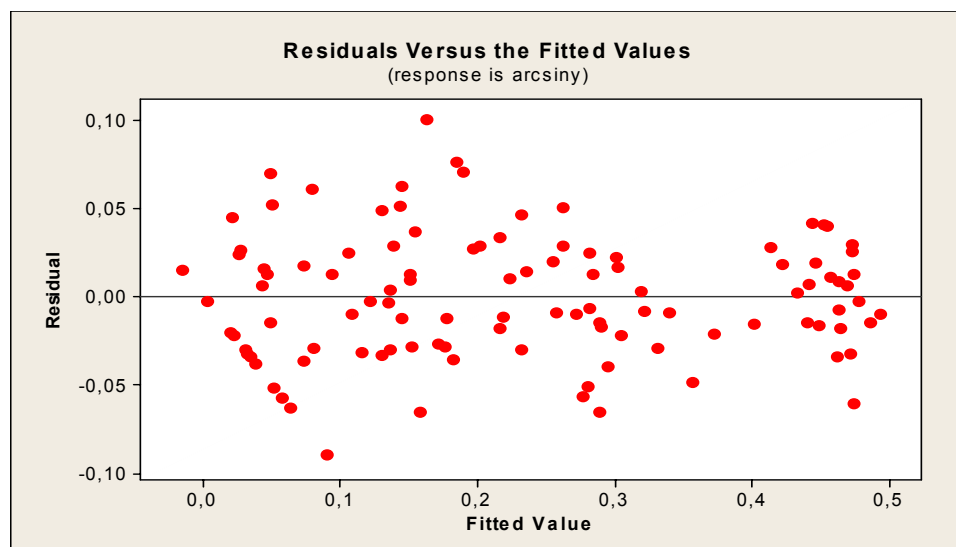
Figure A.8.2.1 Residual versus Fitted Values of M1-Small-PV-2 Model
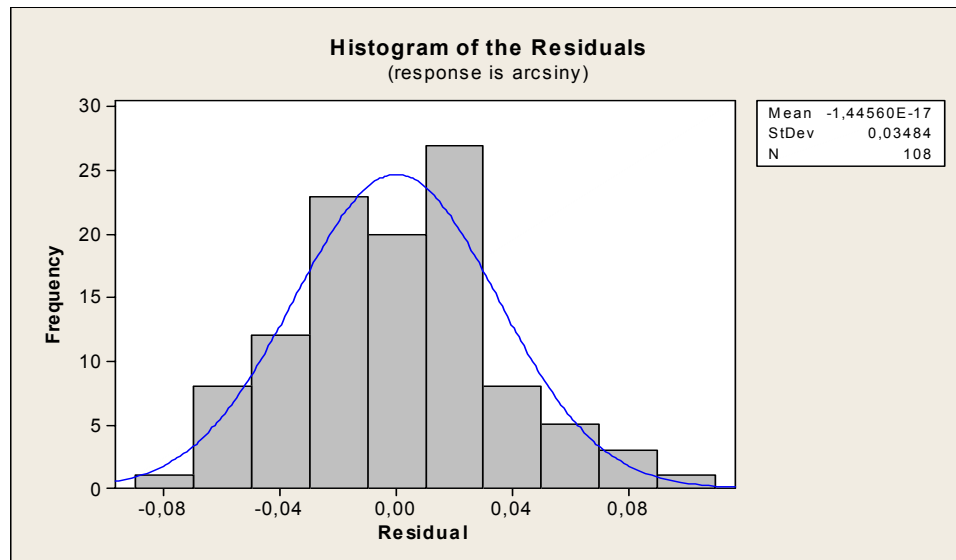
Figure A.8.2.2 Histogram of the Residuals of M1-Small-PV-2 Model
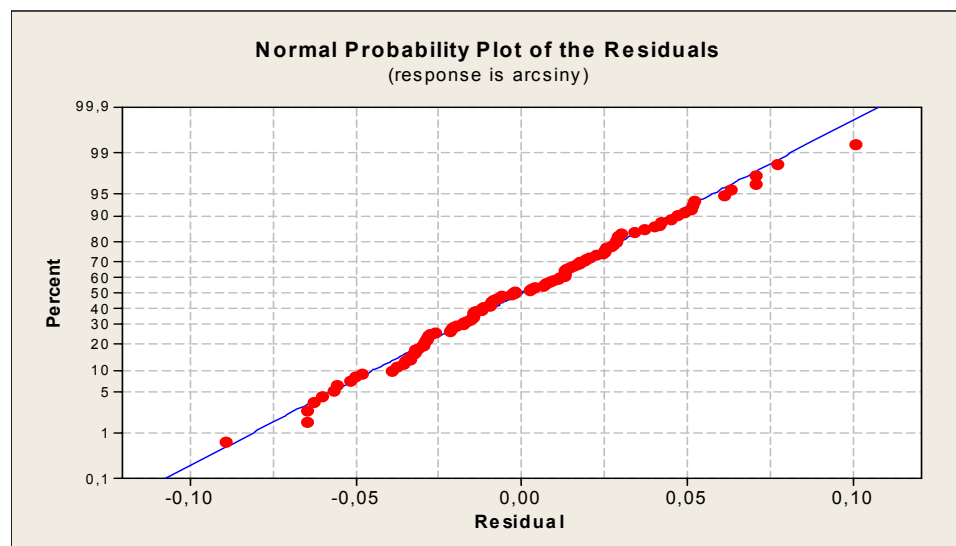
Figure A.8.2.3 Normal Probability Plot of the Residuals of M1-Small-PV-2 Model

A.9 M3-Large-Progs. Model
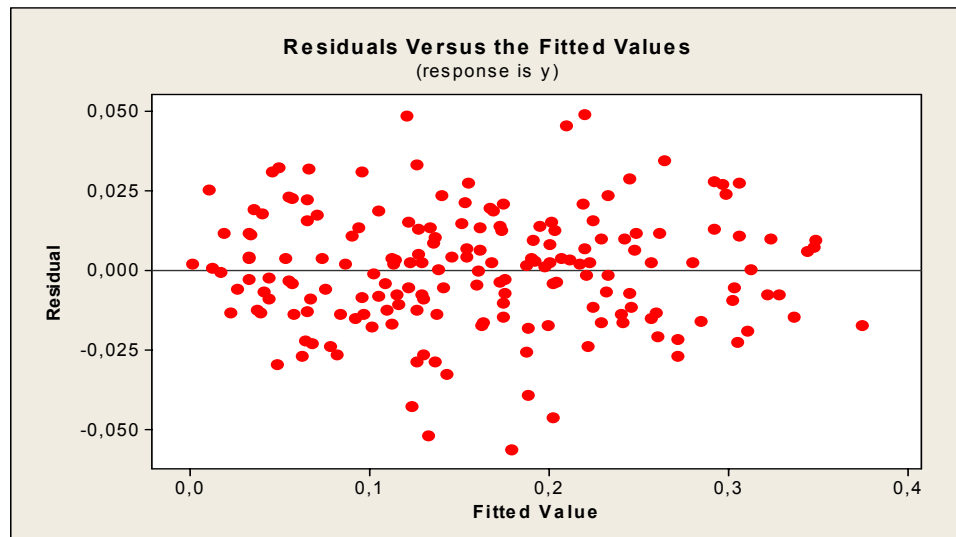
Figure A.9.1.1 Residual versus Fitted Values of M3-Large-Progs.
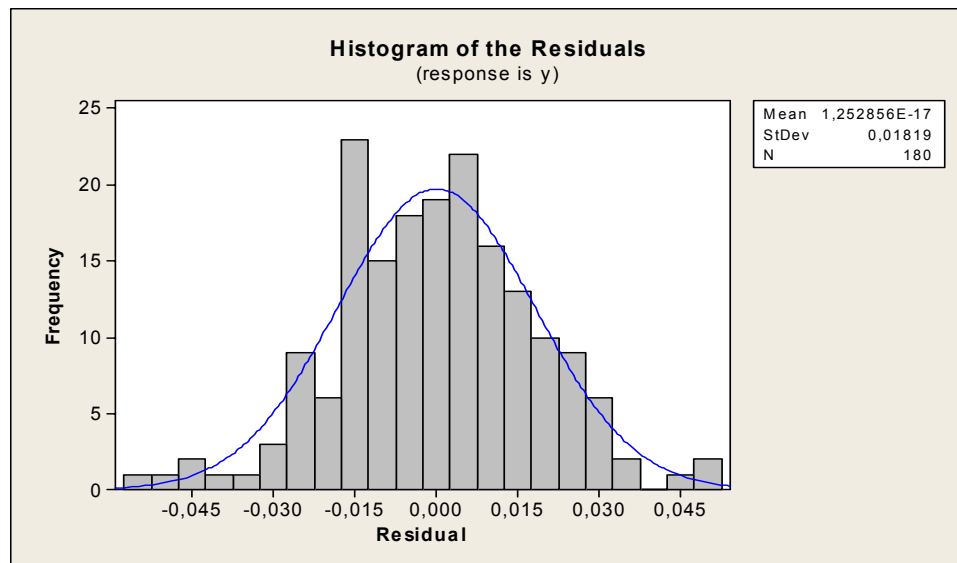
Model

Figure A.9.1.2 Histogram of the Residuals of M3-Large-Progs. Model
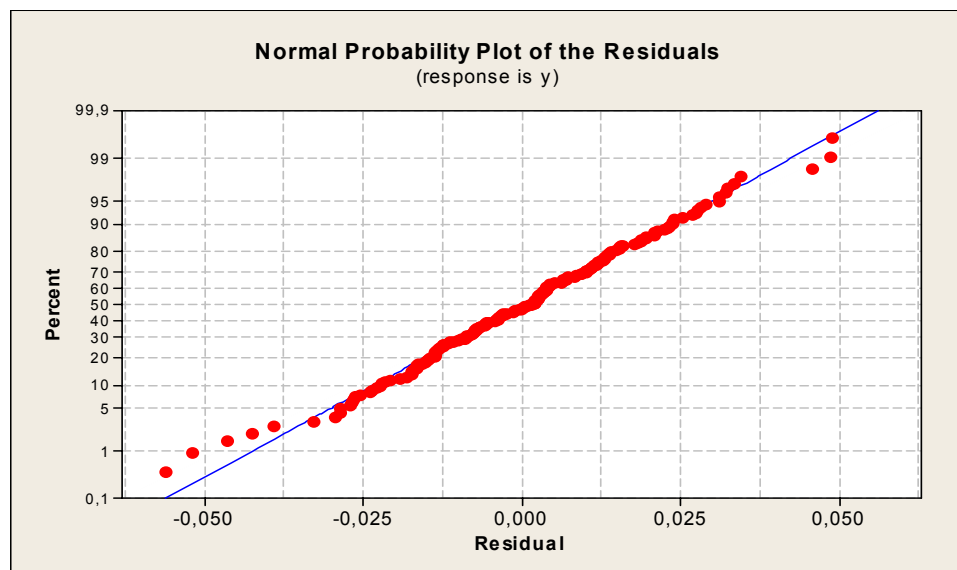
Figure A.9.1.3 Normal Probability Plot of the Residuals of M3-Large-
Progs. Model

A.10 M3-Large-MS Model

A.10.1 M3-Large-MS Model Before Transformation
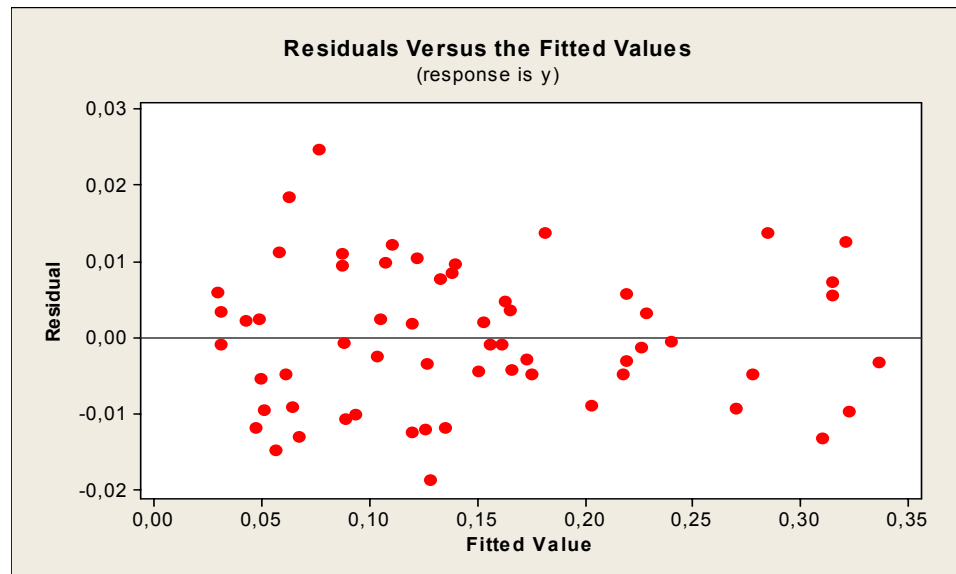
Figure A.10.1.1 Residual versus Fitted Values of M3-Large-MS Model
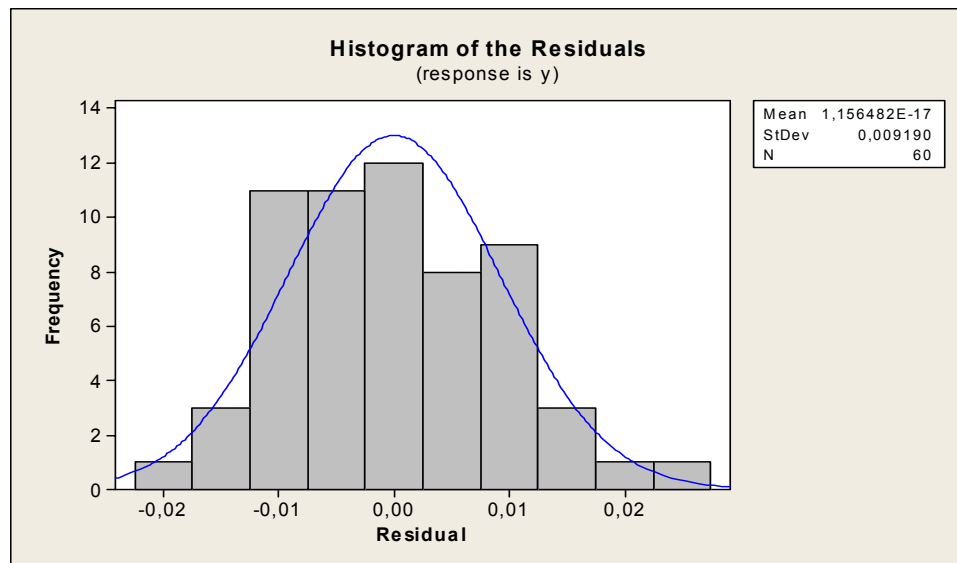
Figure A.10.1.2 Histogram of the Residuals of M3-Large-MS Model
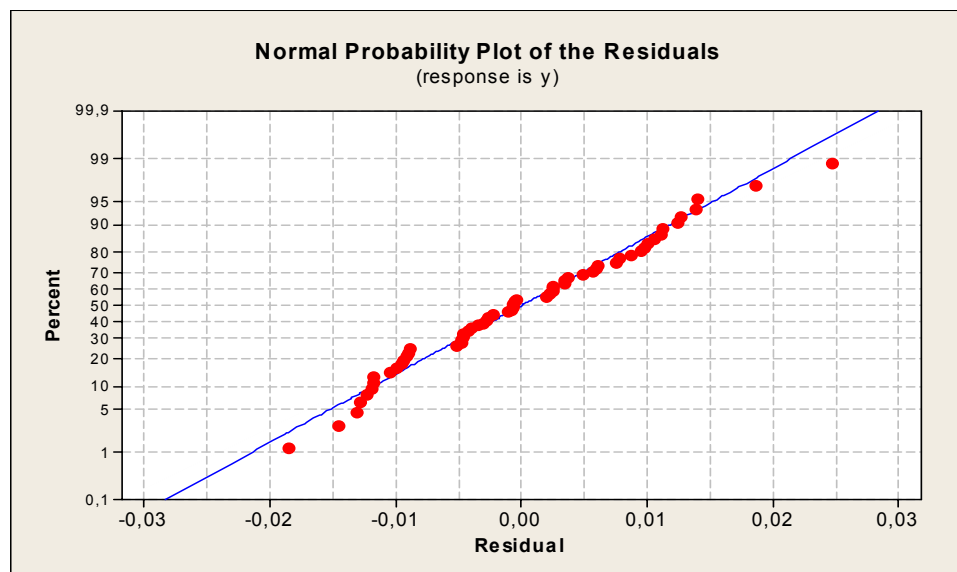
Figure A.10.1.3 Normal Probability Plot of the Residuals of M3-Large-
MS Model

A.10.2 M3-Large-MS Model After Transformation
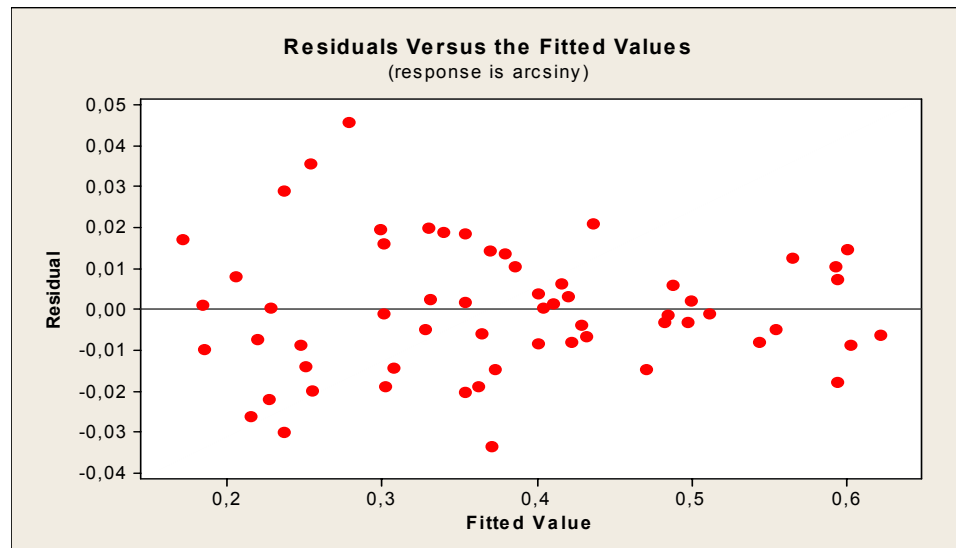
Figure A.10.2.1 Residual versus Fitted Values of M3-Large-MS Model
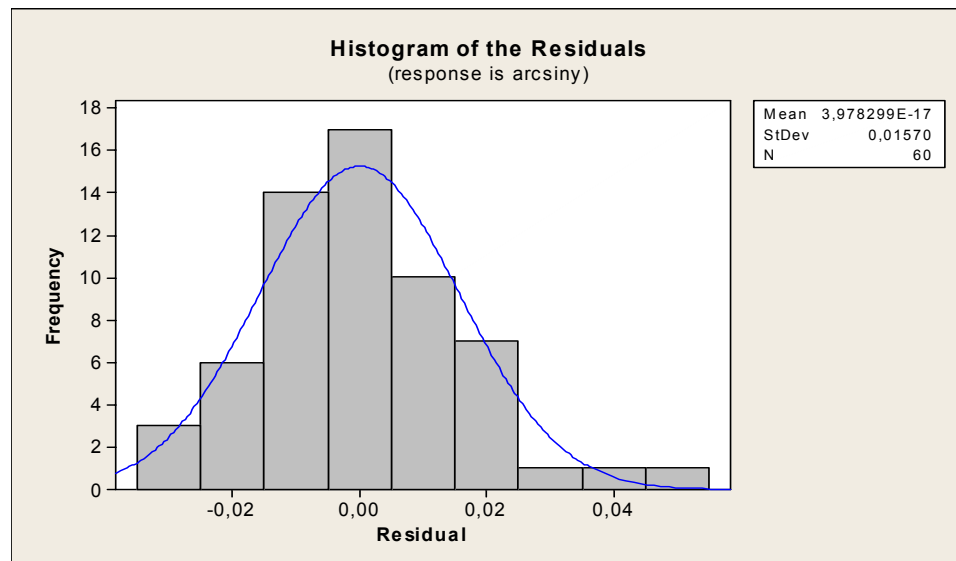
Figure A.10.2.2 Histogram of the Residuals of M3-Large-MS Model
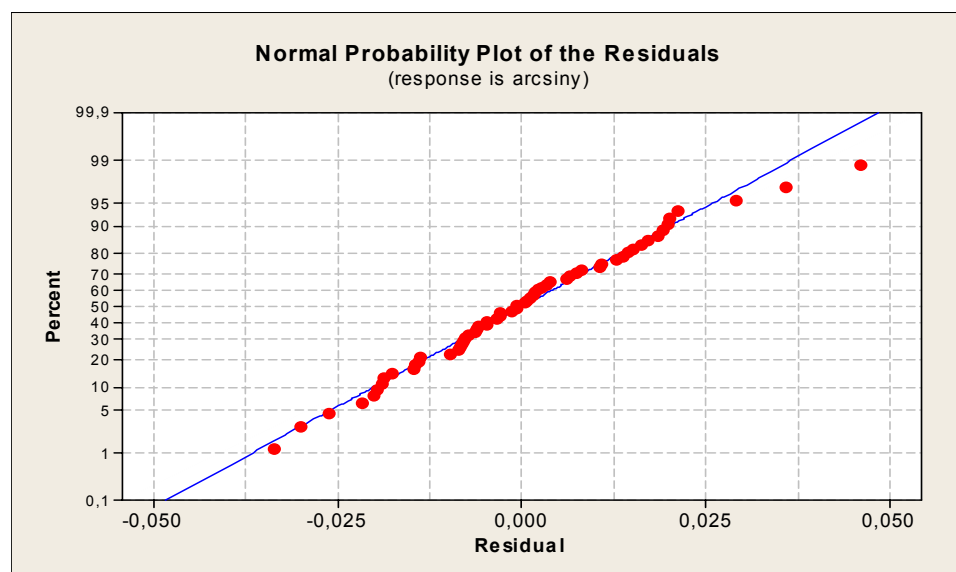
Figure A.10.2.3 Normal Probability Plot of the Residuals of M3-Large-MS Model

A.11 M3-Large-PV-1 Model

A.11.1 M3-Large-PV-1 Model Before Transformation
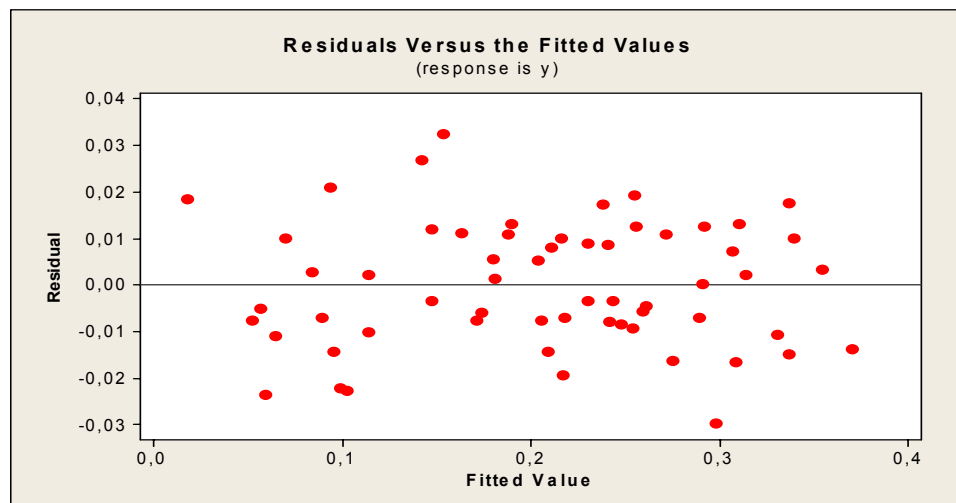
Figure A.11.1.1 Residual versus Fitted Values of M3-Large-PV-1
Model
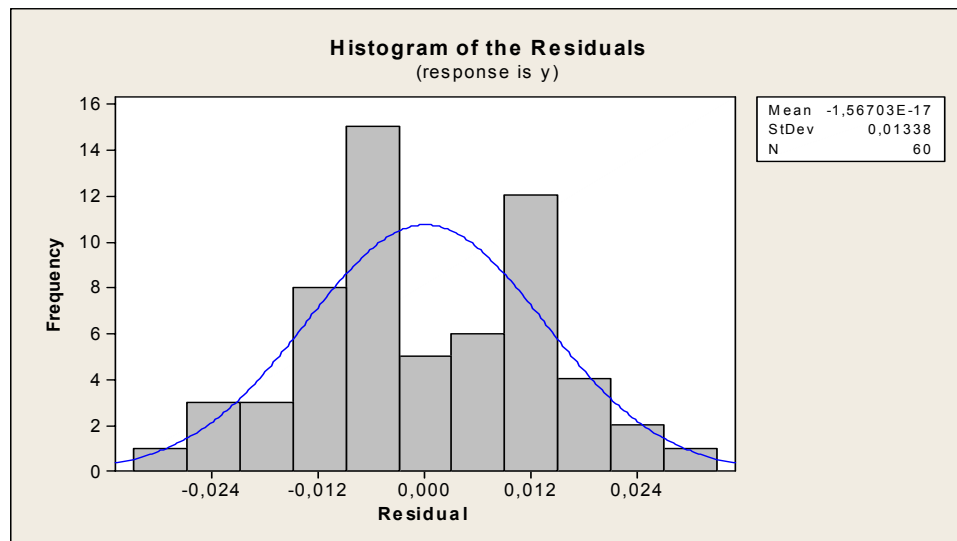
Figure A.11.1.2 Histogram of the Residuals of M3-Large-PV-1 Model
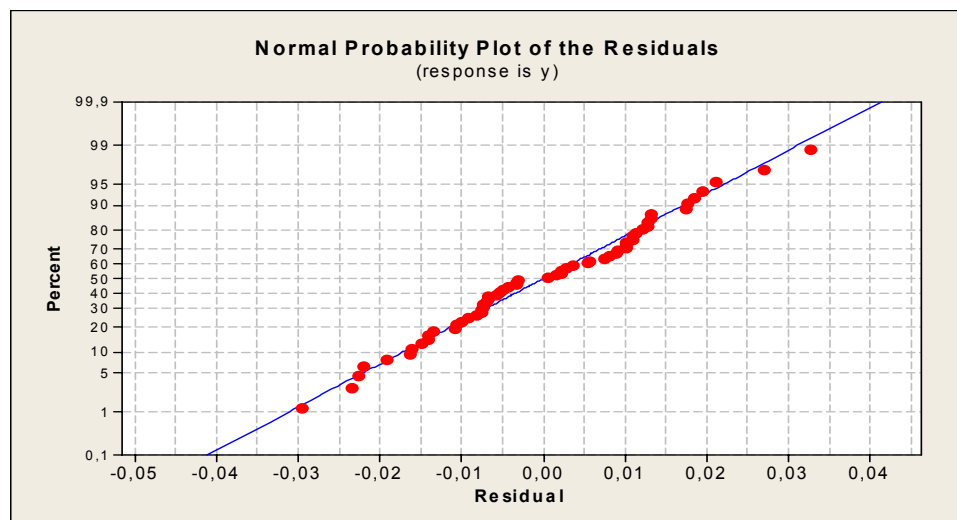
Figure A.11.1.3 Normal Probability Plot of the Residuals of M3-Large-

PV-1 Model

A.11.2 M3-Large-PV-1 Model After Transformation
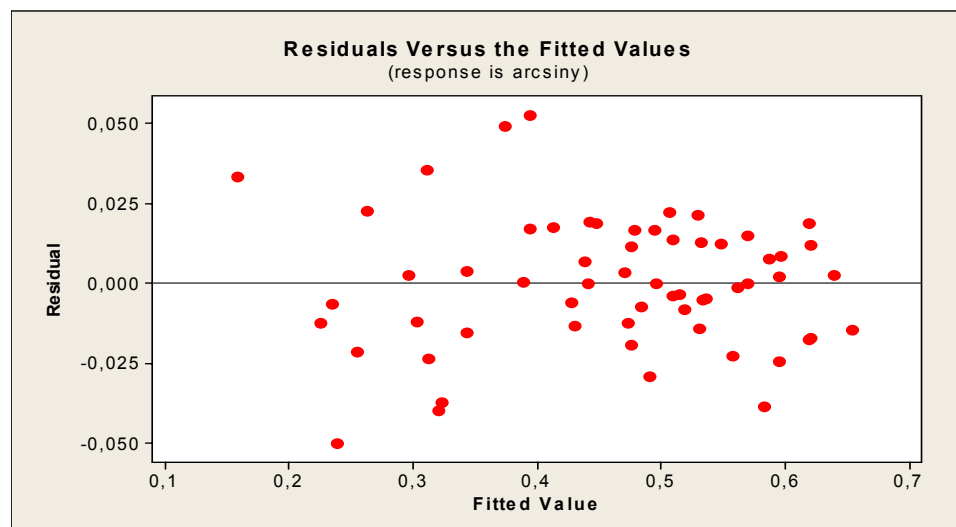
Figure A.11.2.1 Residual versus Fitted Values of M3-Large-PV-1
Model
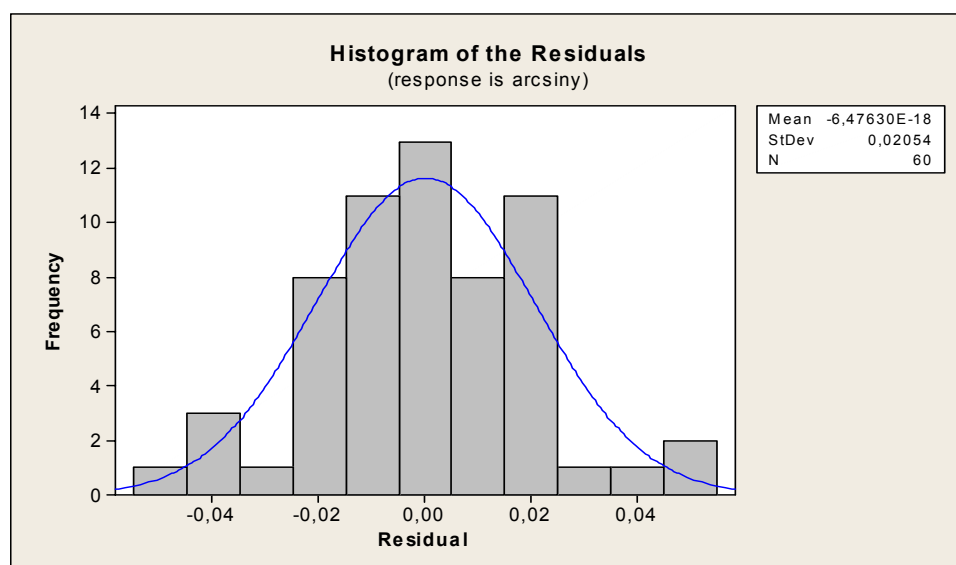
Figure A.11.2.2 Histogram of the Residuals of M3-Large-PV-1 Model
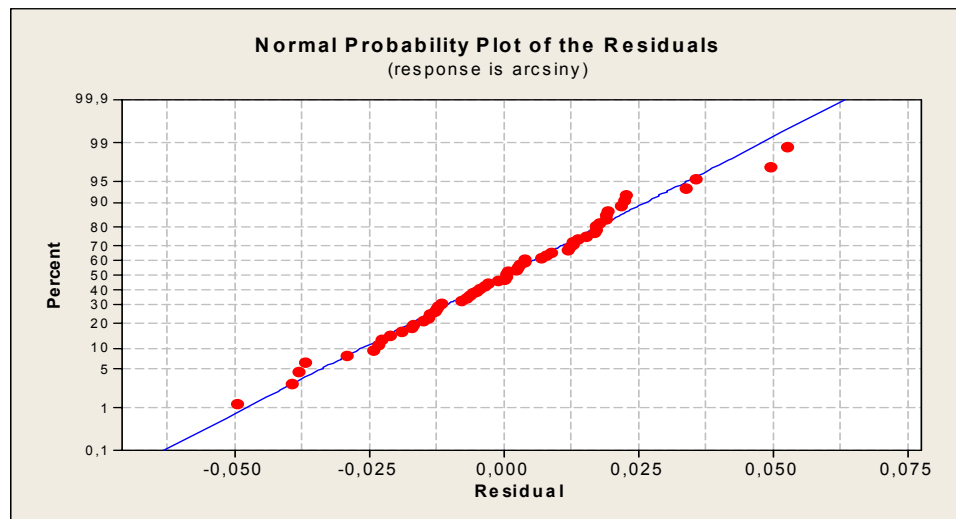
Figure A.11.2.3 Normal Probability Plot of the Residuals of M3-Large-PV-1 Model

A.12 M3-Large-PV-2 Model
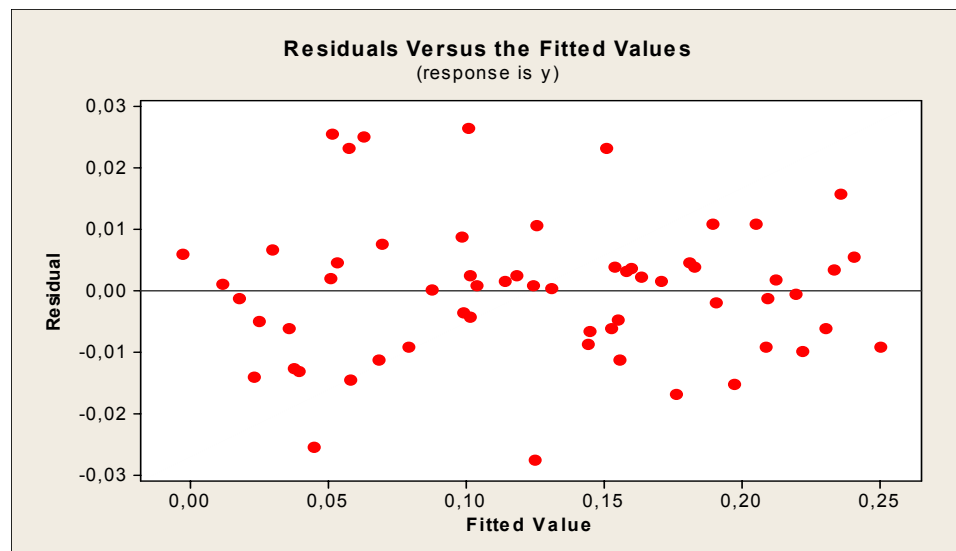
Figure A.12.1 Residual versus Fitted Values of M3-Large-PV-2 Model
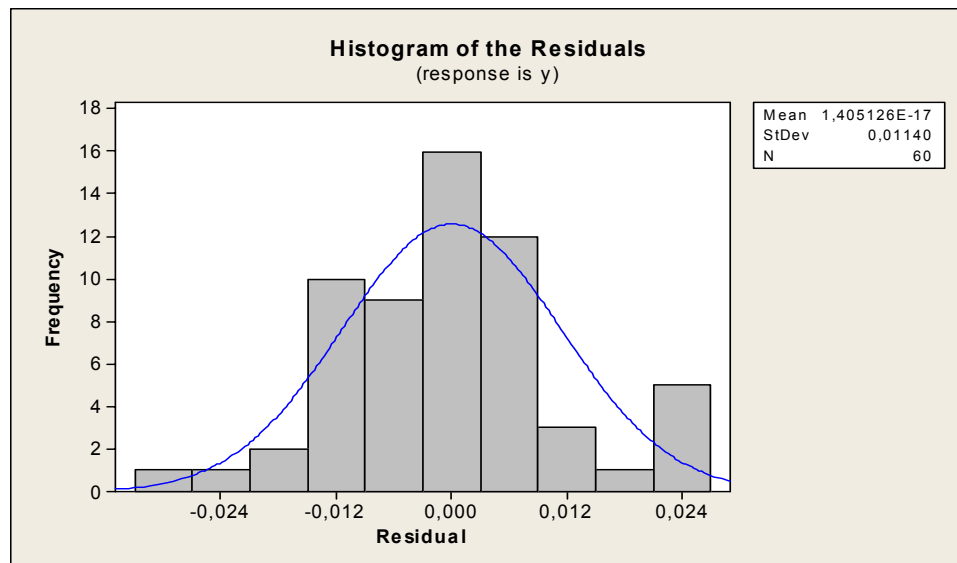
Figure A.12.2 Histogram of the Residuals of M3-Large-PV-2 Model
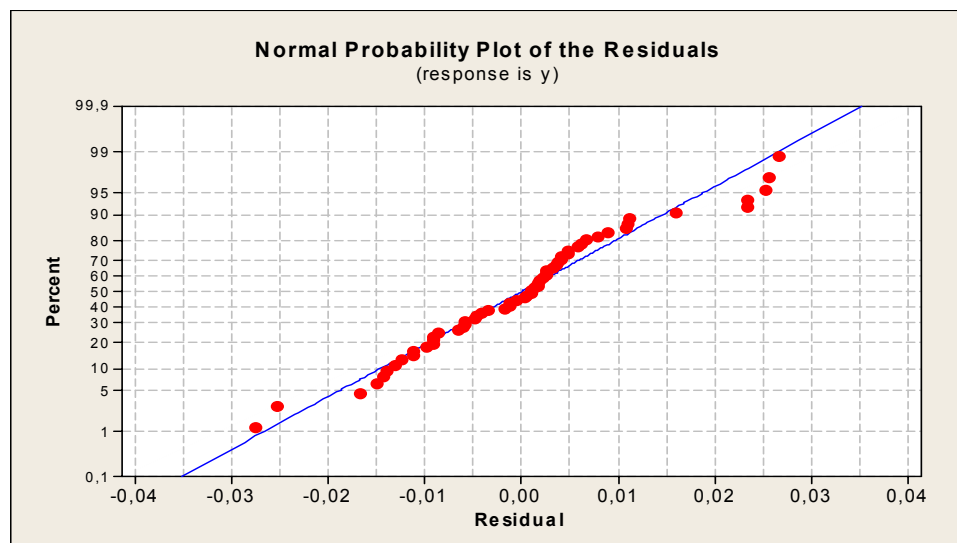
Figure A.12.3 Normal Probability Plot of the Residuals of M3-Large-
PV-2 Model

APPENDIX B

RESIDUAL VS FACTOR CHARTS

B.1 M1-All-Progs. Model Residuals Vs Factors

B.1.1 M1-All-Progs. Model Residuals Vs Factors Before Transformation
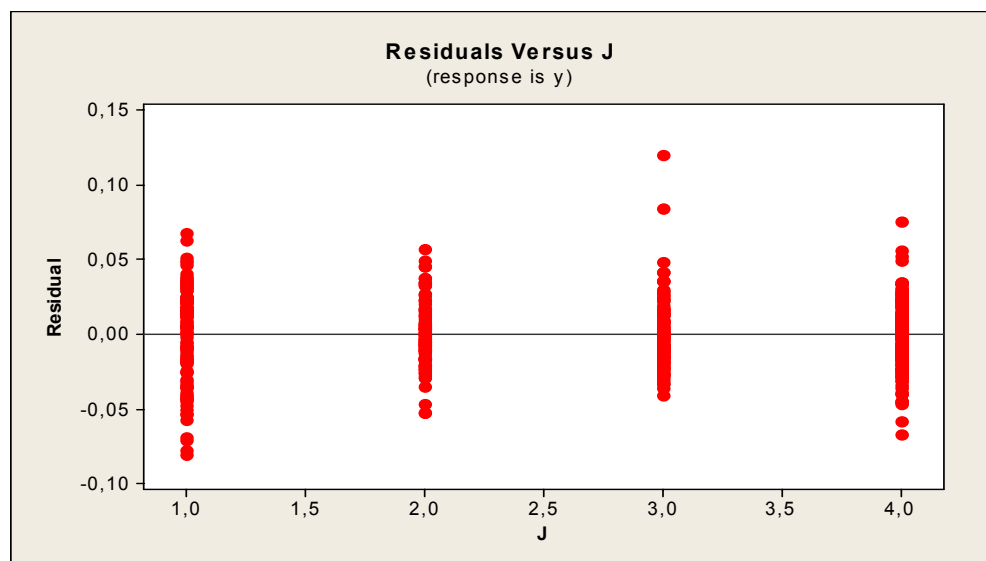
Figure B.1.1.1 Residuals versus *J* of M1-All-Progs. Model
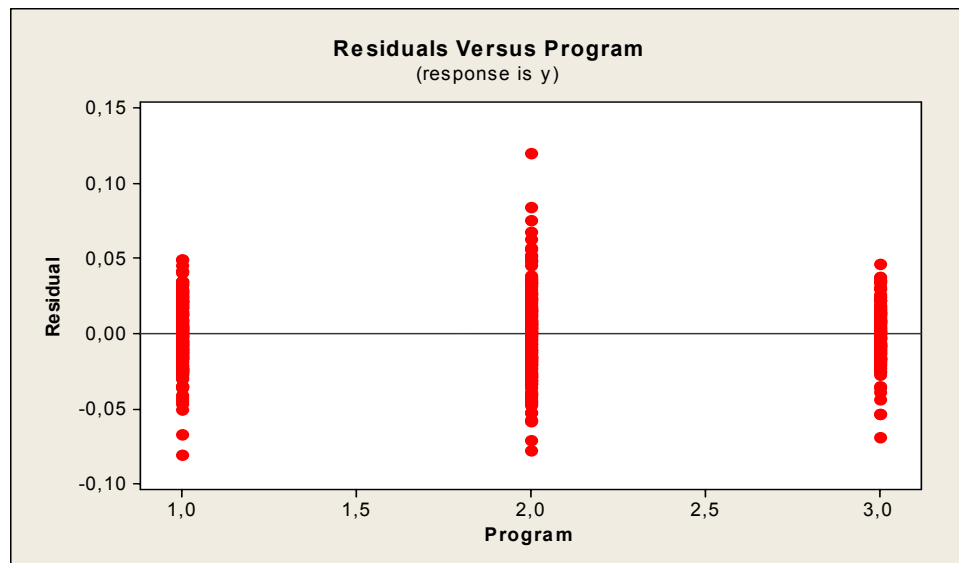
Figure B.1.1.2 Residuals versus *Program* of M1-All-Progs. Model
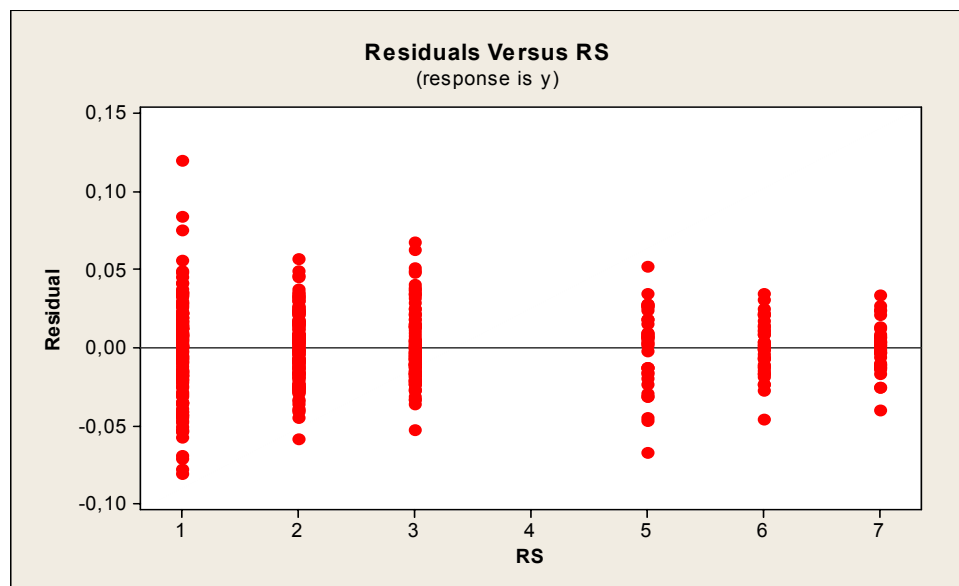
Figure B.1.1.3 Residuals versus *RS* of M1-All-Progs. Model

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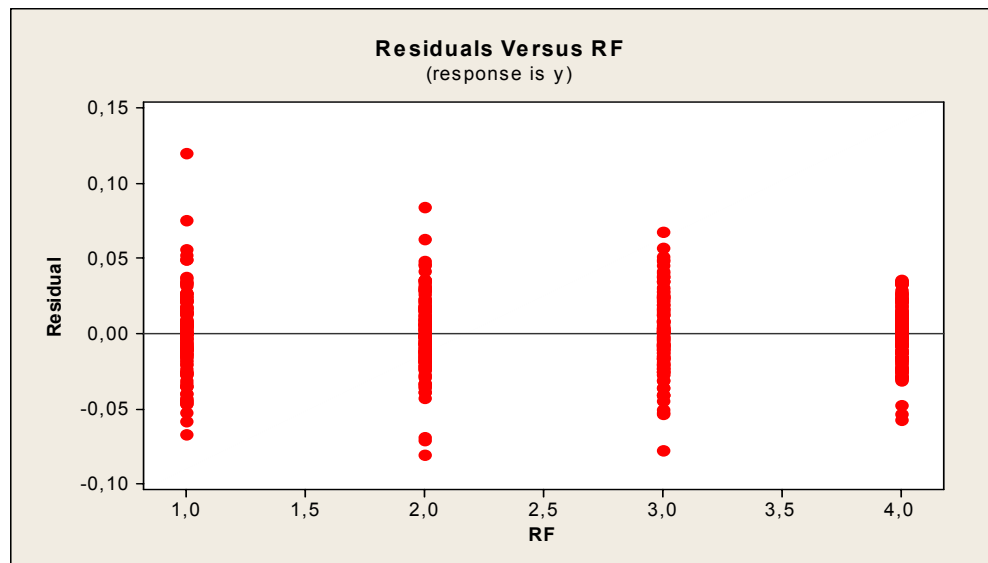
Figure B.1.1.4 Residuals versus *RF* of M1-All-Progs. Model
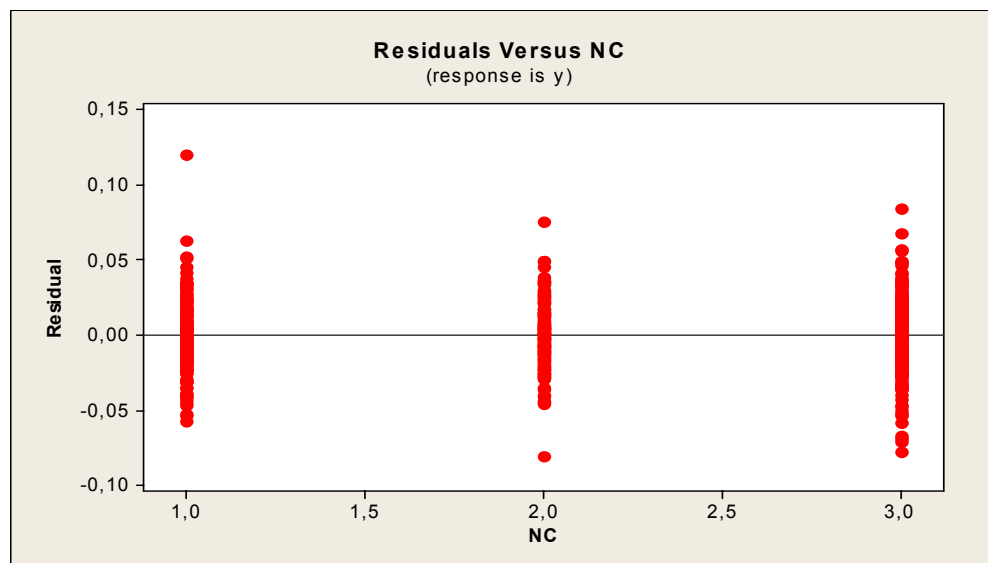
Figure B.1.1.5 Residuals versus *NC* of M1-All-Progs. Model

B.1.2 M1-All-Progs. Model Residuals Vs Factors After Transformation
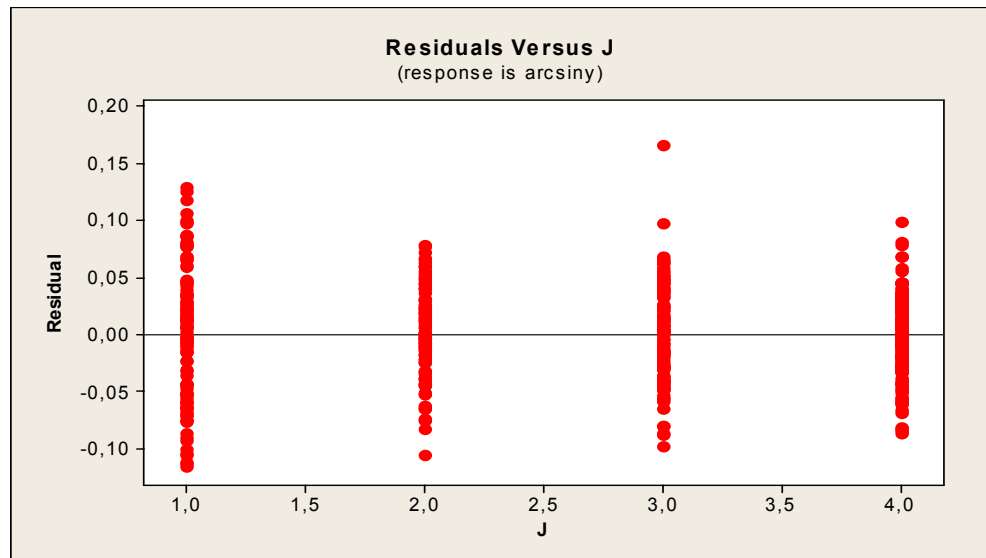
Figure B.1.2.1 Residuals versus *J* of M1-All-Progs. Model
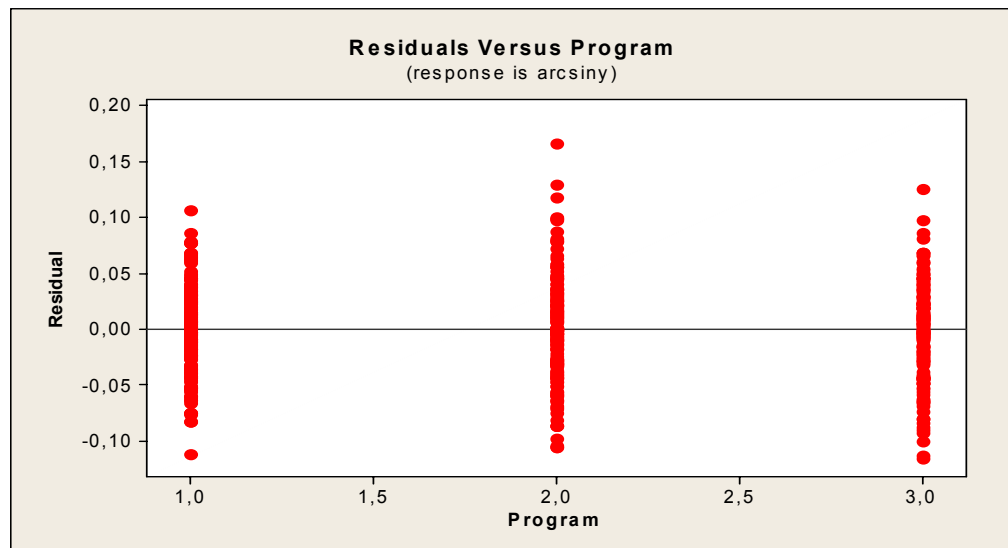
Figure B.1.2.2 Residuals versus *Program* of M1-All-Progs. Model
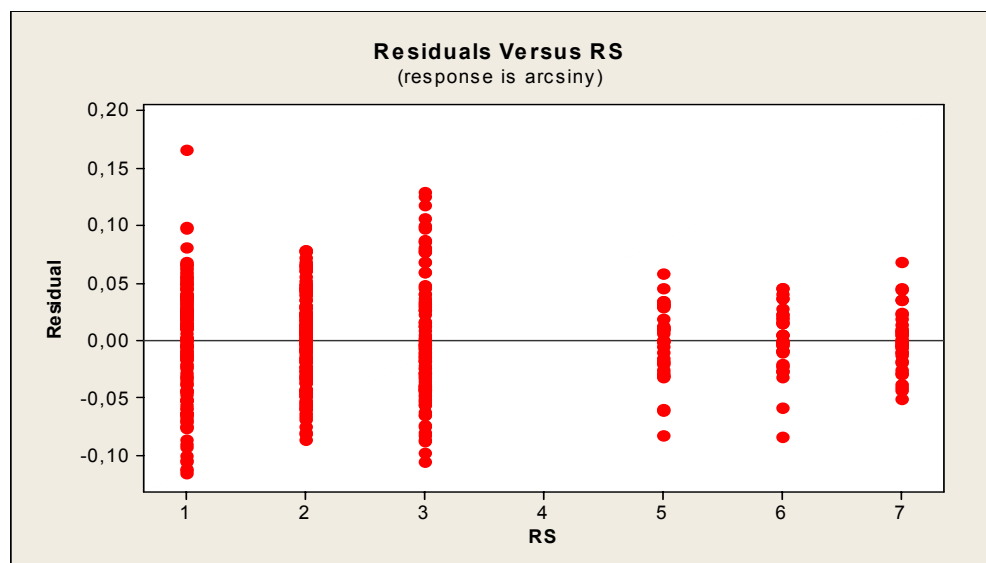
Figure B.1.2.3 Residuals versus *RS* of M1-All-Progs. Model
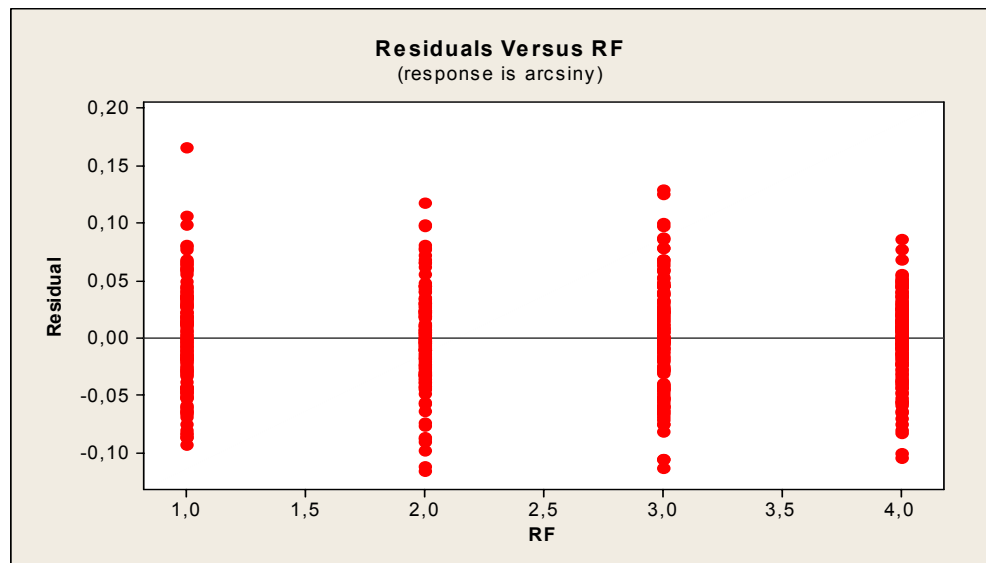
Figure B.1.2.4 Residuals versus *R̲F̲* of M1-All-Progs. Model
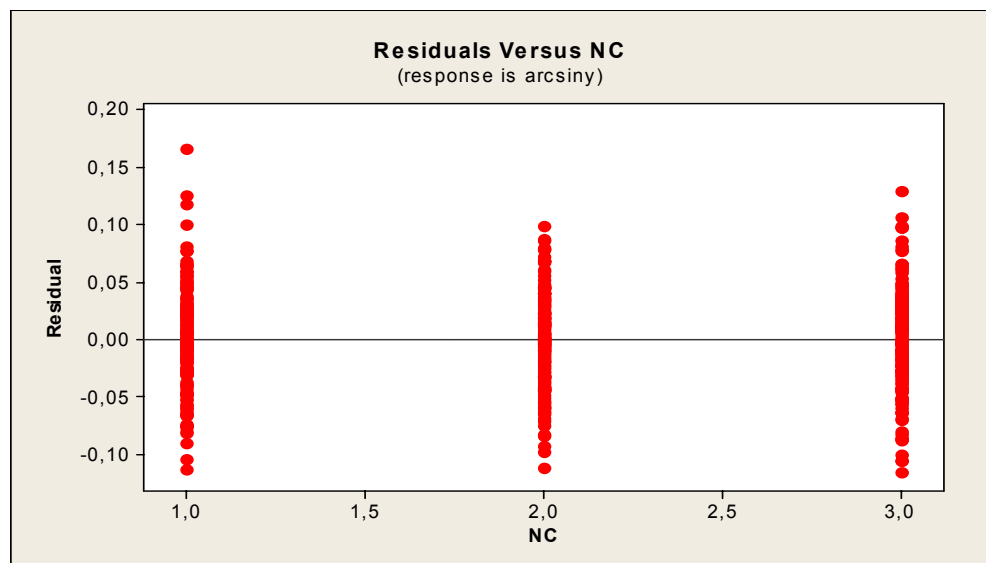
Figure B.1.2.5 Residuals versus *NC* of M1-All-Progs. Model

B.2 M1-All-MS Model Residuals Vs Factors

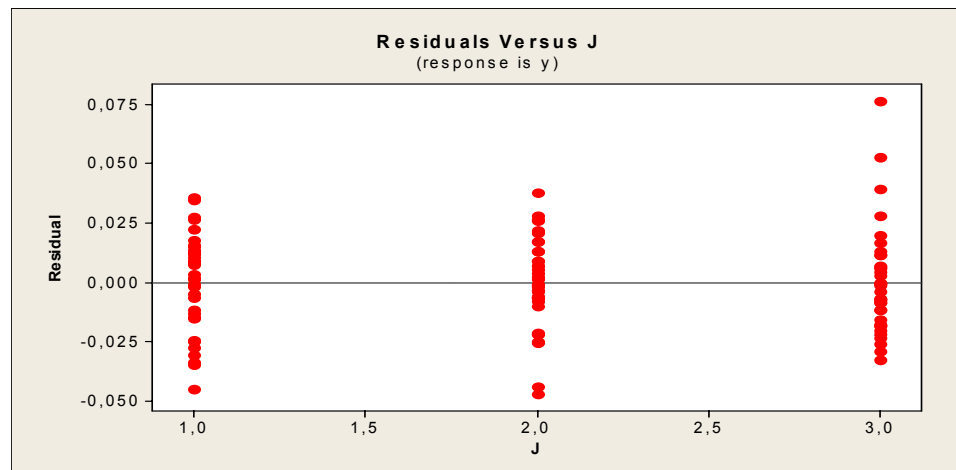### B.2.1 M1-All-MS Model Residuals Vs Factors Before Transformation
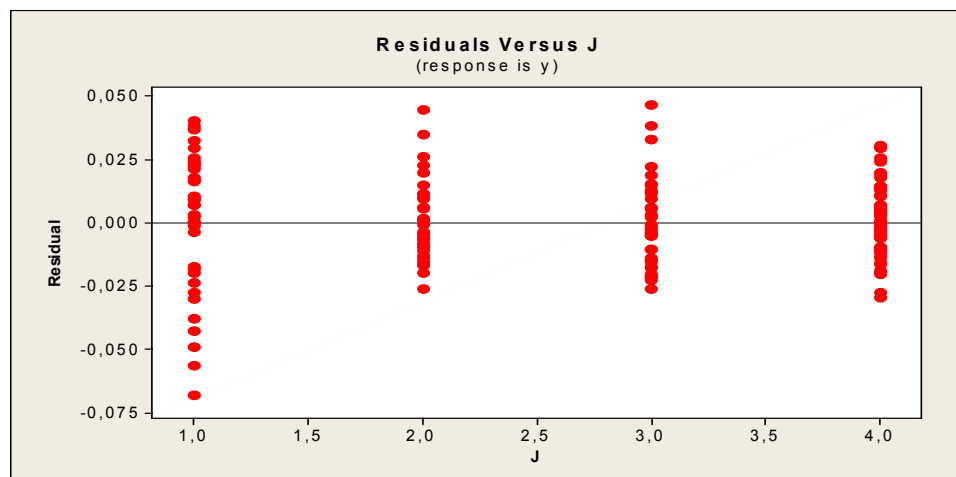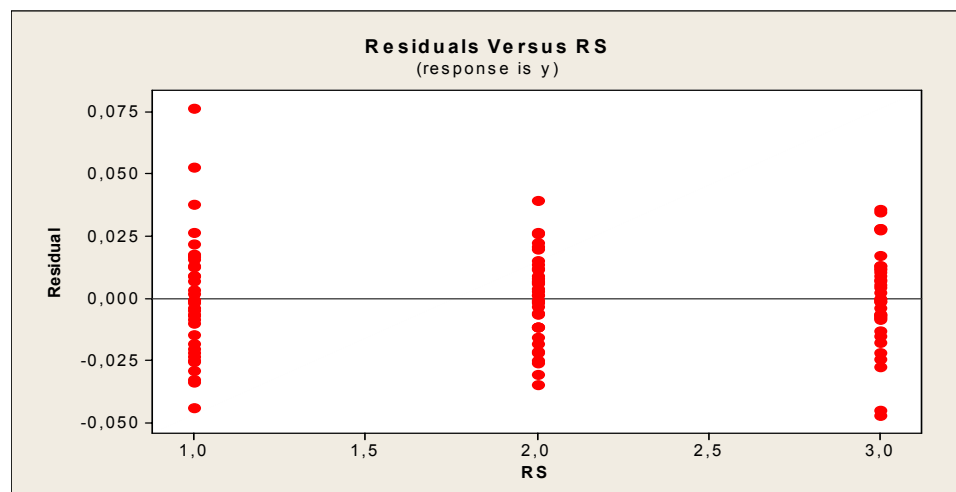

Figure B.2.1.1 Residuals versus *J* of M1-All-MS Model
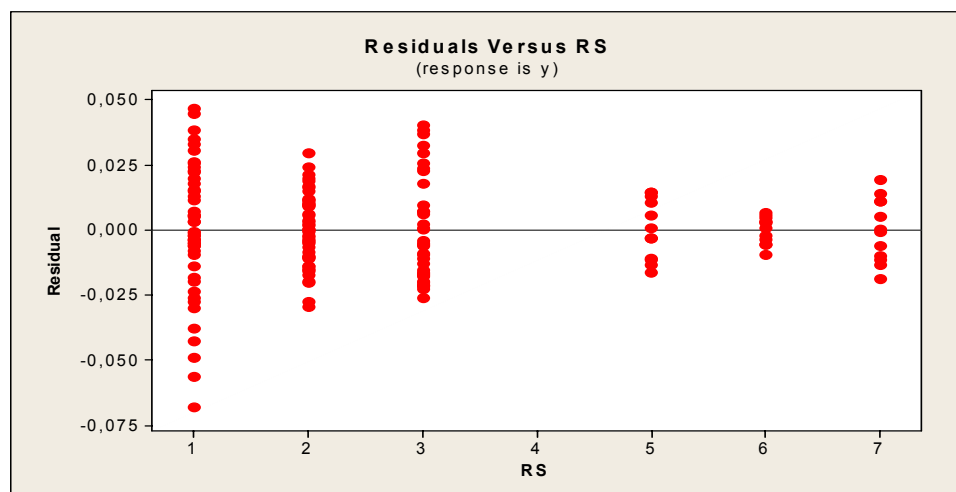

Figure B.2.1.2 Residuals versus *RS* of M1-All-MS Model
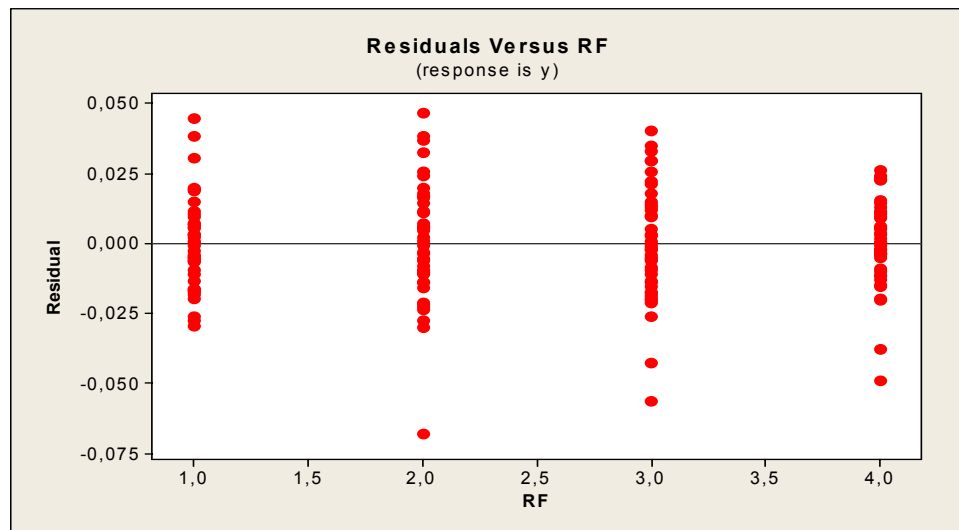
Figure B.2.1.3 Residuals versus *RF* of M1-All-MS Model
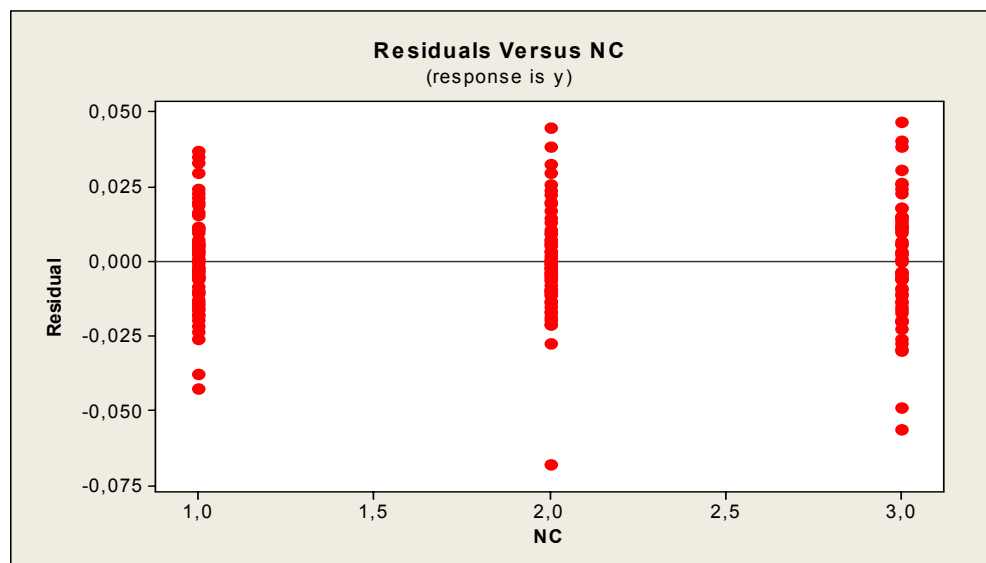
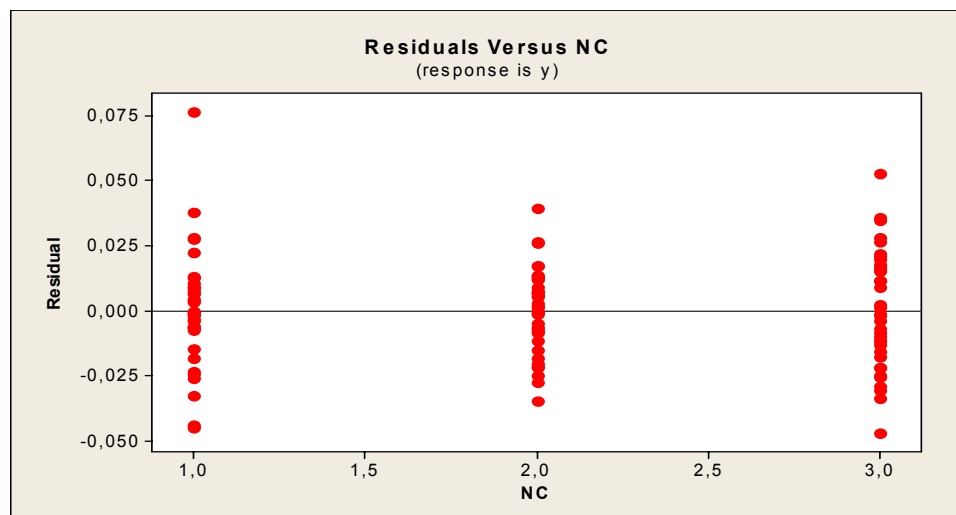Figure B.2.1.4 Residuals versus *NC* of M1-All-MS Model

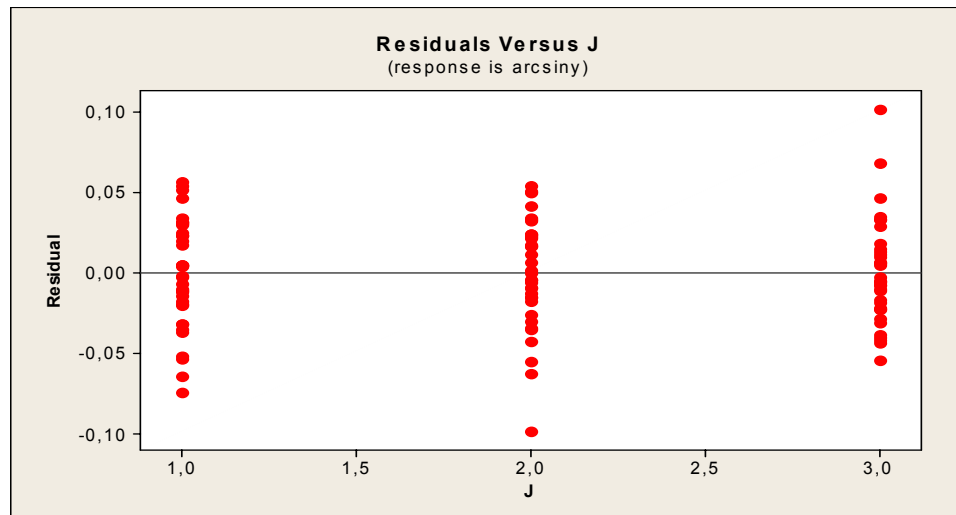## B.2.2 M1-All-MS Model Residuals Vs Factors After Transformation
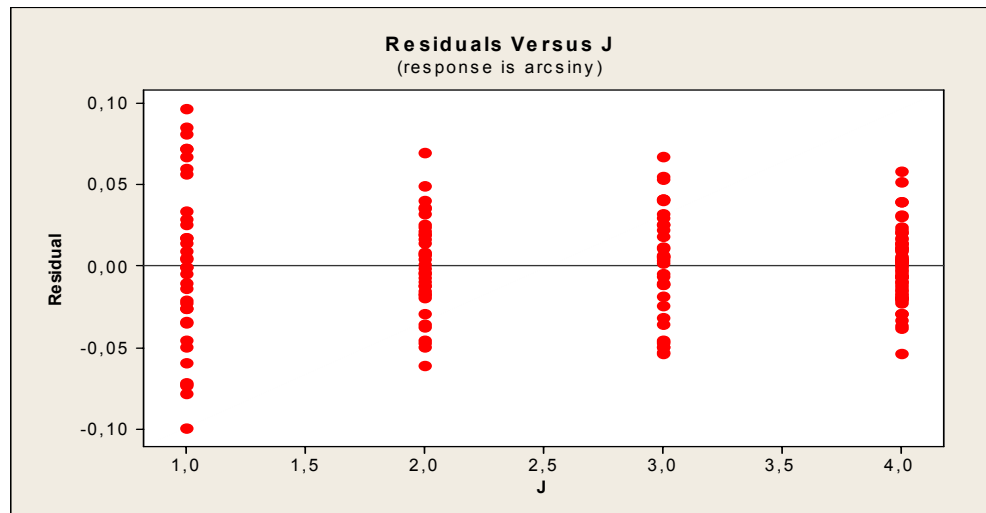
Figure B.2.2.1 Residuals versus *J* of M1-All-MS Model
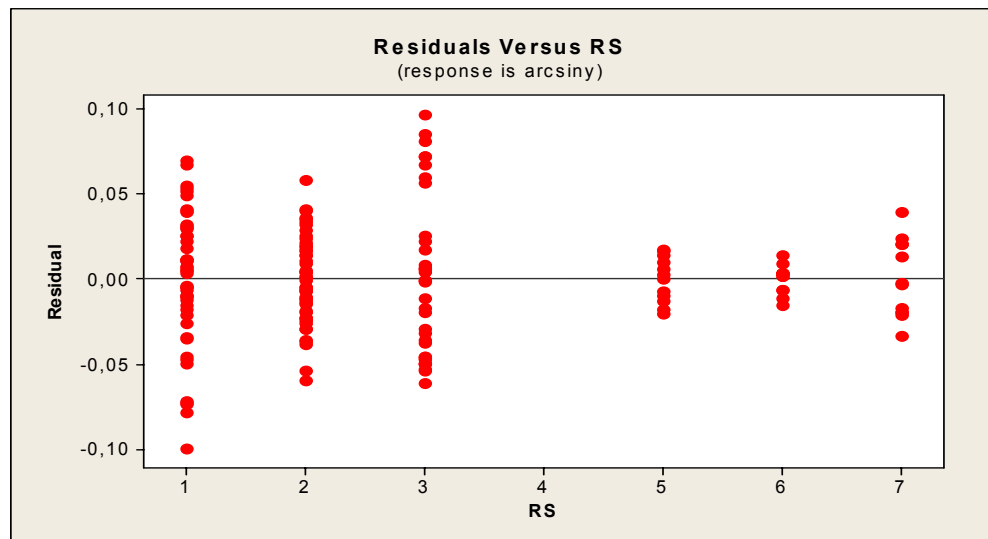
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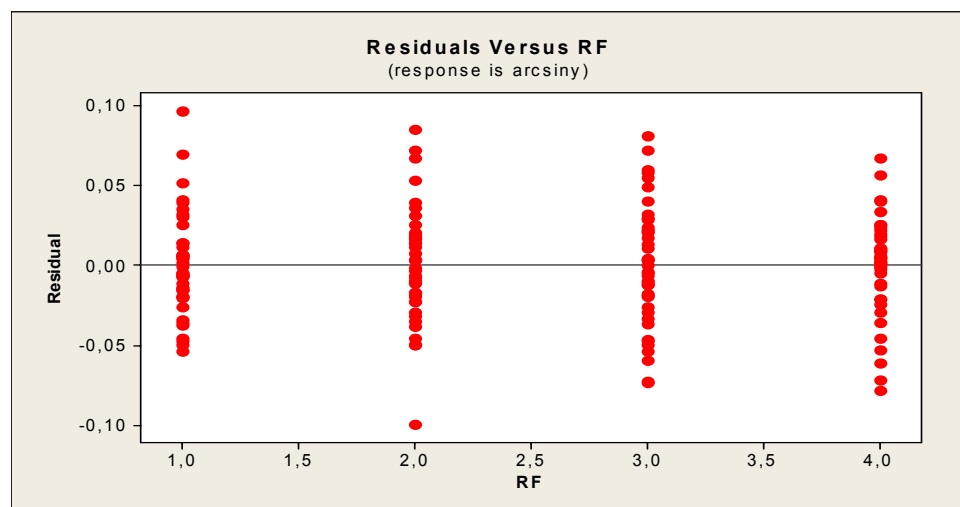
Figure B.2.2.3 Residuals versus *RF* of M1-All-MS Model

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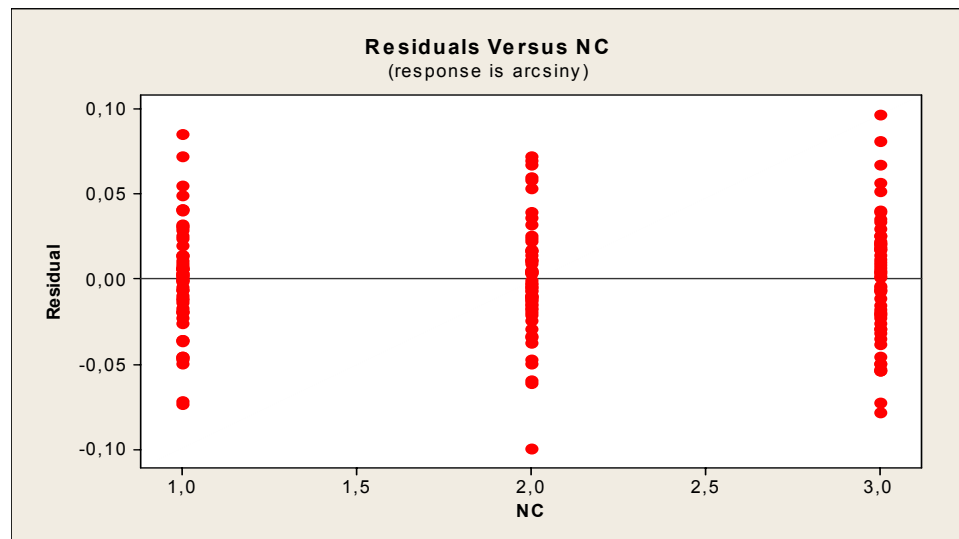
Figure B.2.2.4 Residuals versus *NC* of M1-All-MS Model

B.3 M1-All-PV-1 Model Residuals Vs Factors

B.3.1 M1-All-PV-1 Model Residuals Vs Factors Before Transformation
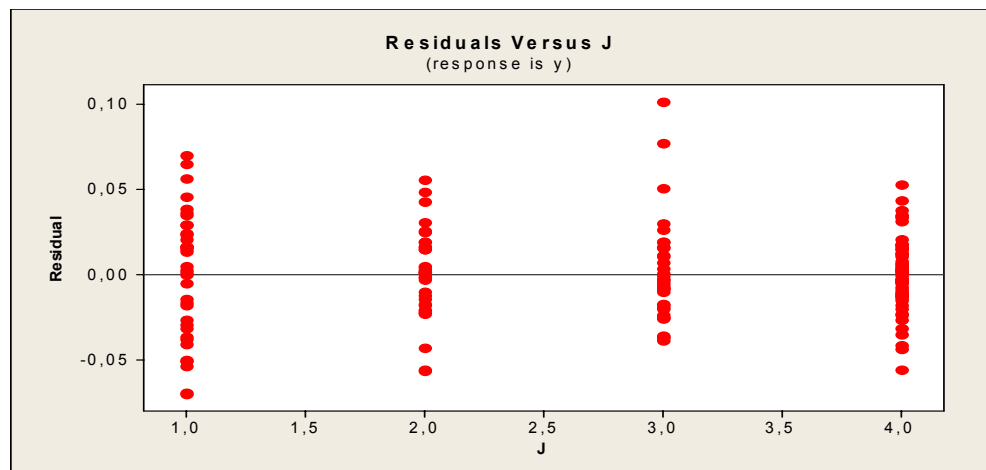
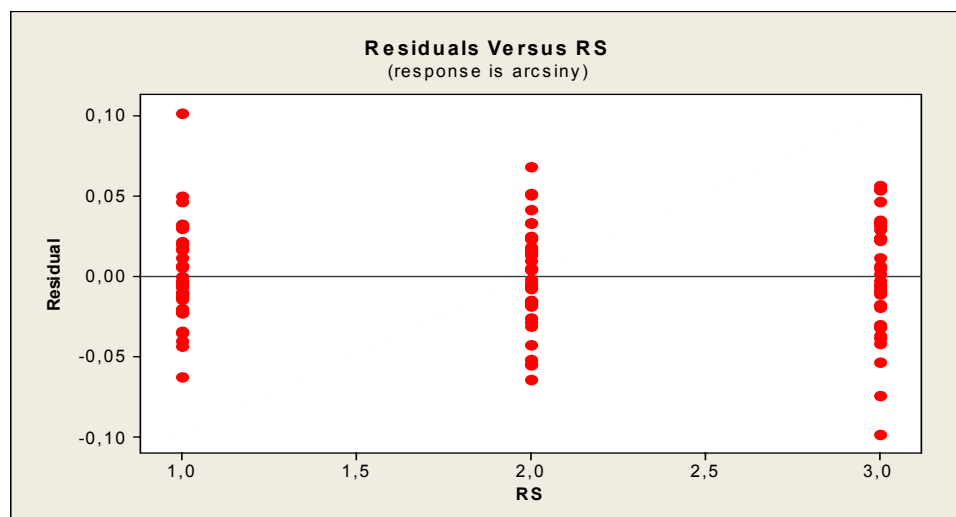Figure B.3.1.1 Residuals versus *J* of M1-All-PV-1 Model
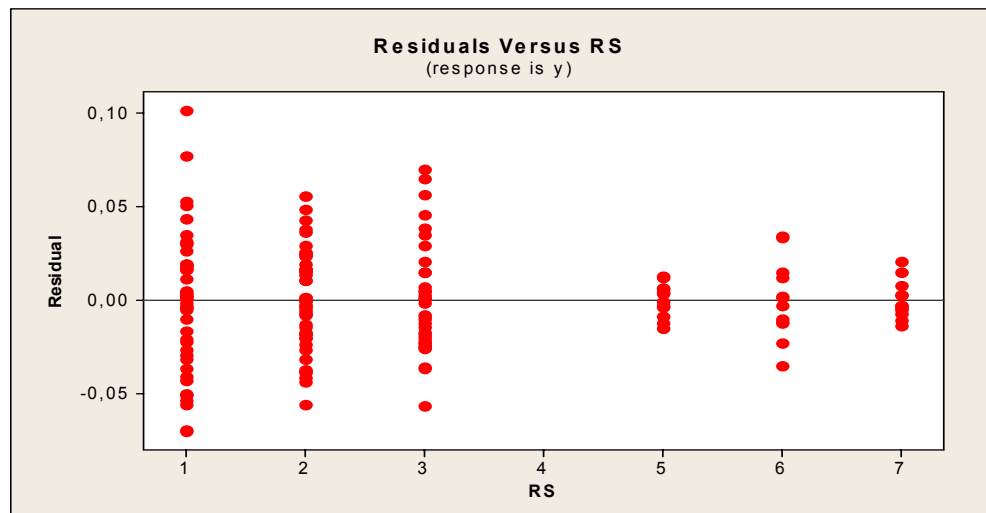
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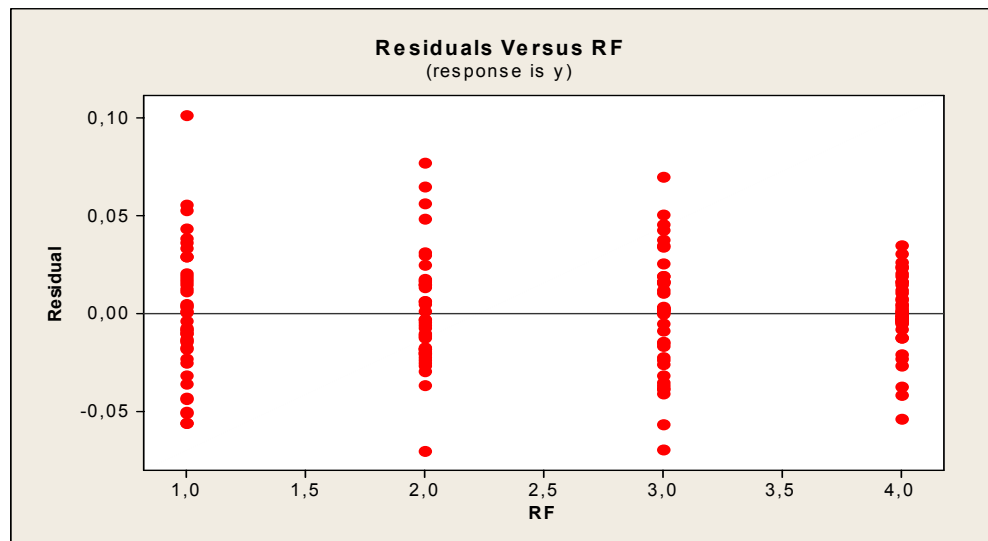
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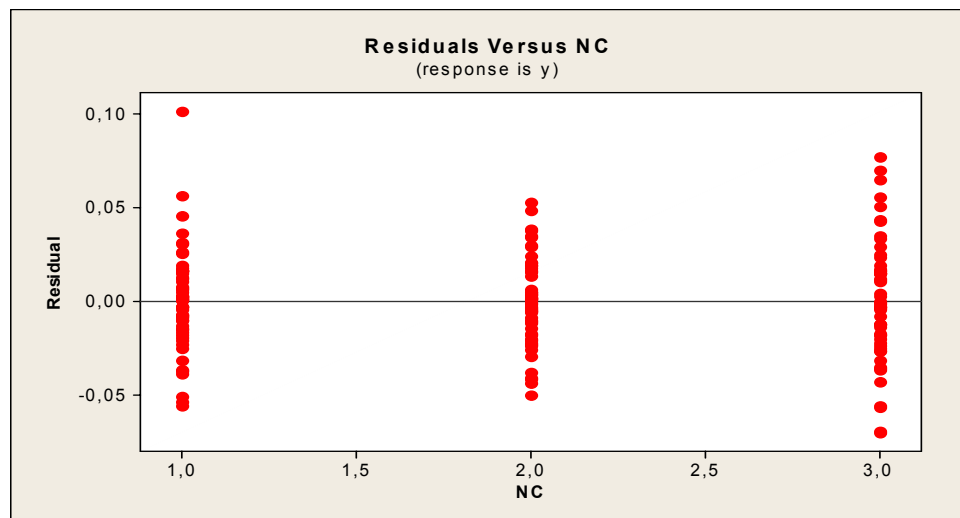
Figure B.3.1.4 Residuals versus *NC* of M1-All-PV-1 Model

B.3.2 M1-All-PV-1 Model Residuals Vs Factors After Transformation
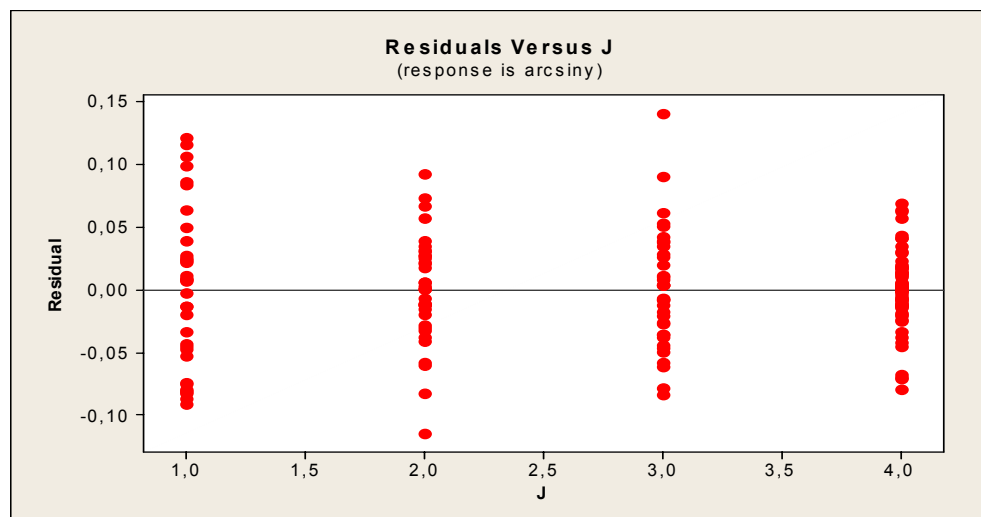
Figure B.3.2.1 Residuals versus *J* of M1-All-PV-1 Model
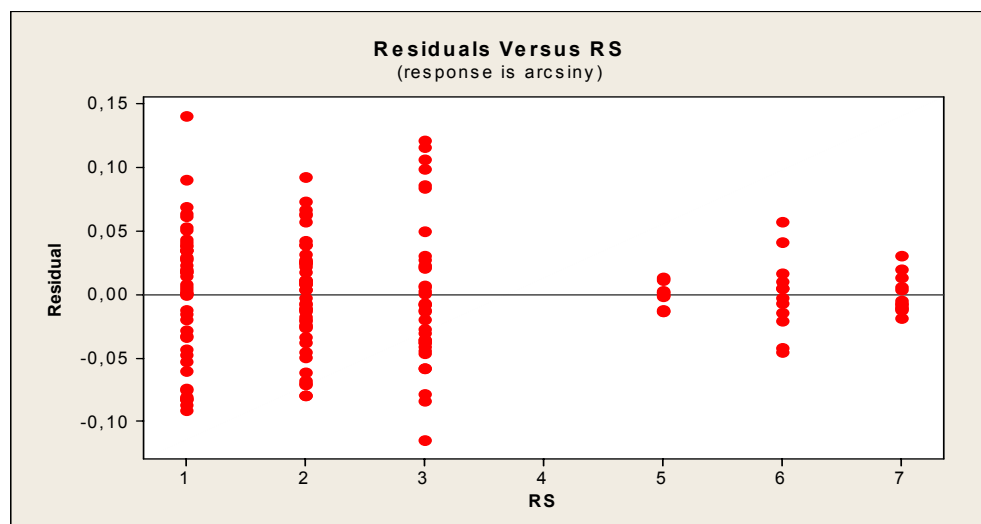
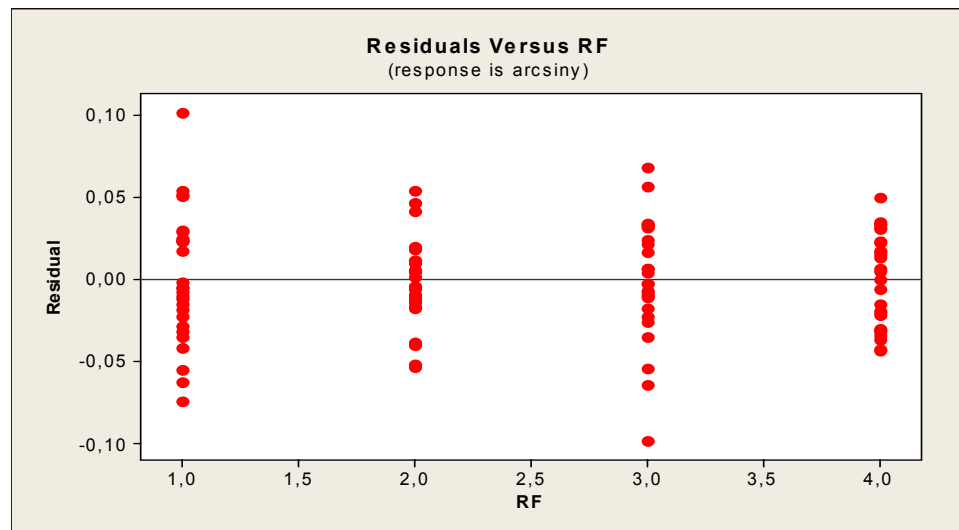Figure B.3.2.2 Residuals versus *RS* of M1-All-PV-1 Model
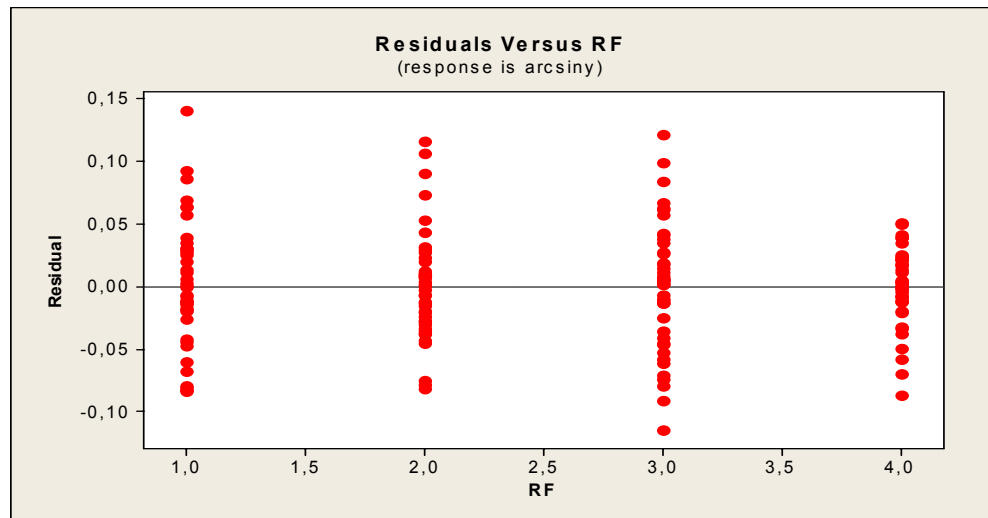
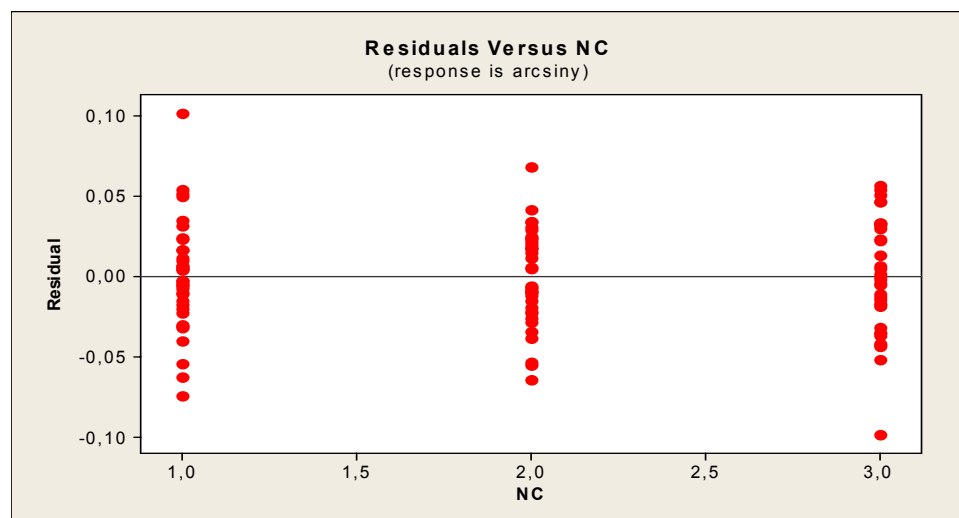Figure B.3.2.3 Residuals versus *RF* of M1-All-PV-1 Model
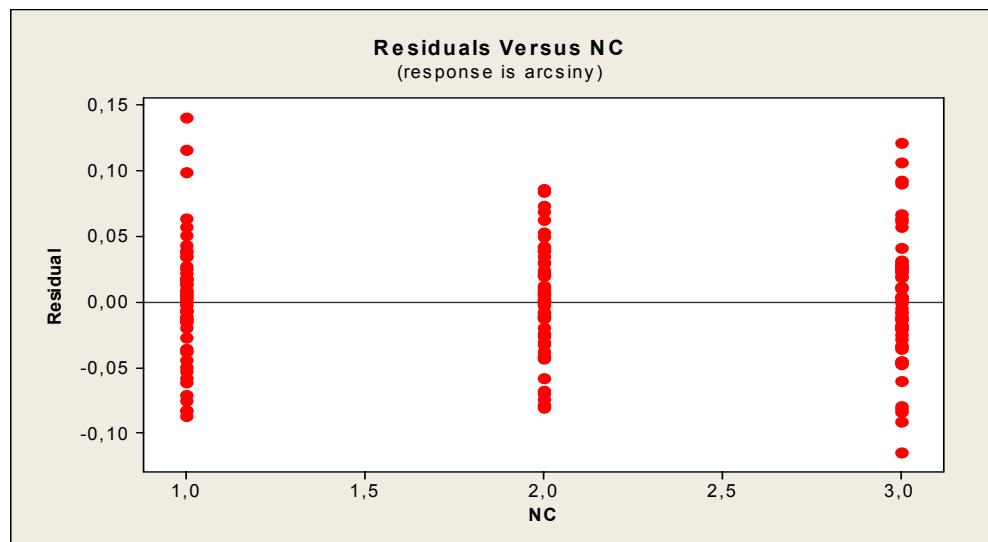
Figure B.3.2.4 Residuals versus *NC* of M1-All-PV-1 Model

B.4 M1-All-PV-2 Model Residuals Vs Factors

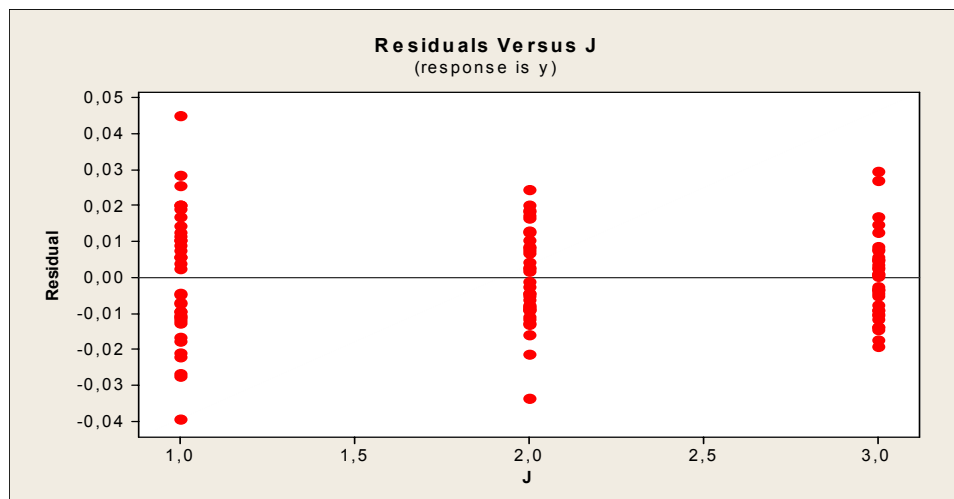### B.4.1 M1-All-PV-2 Model Residuals Vs Factors Before Transformation
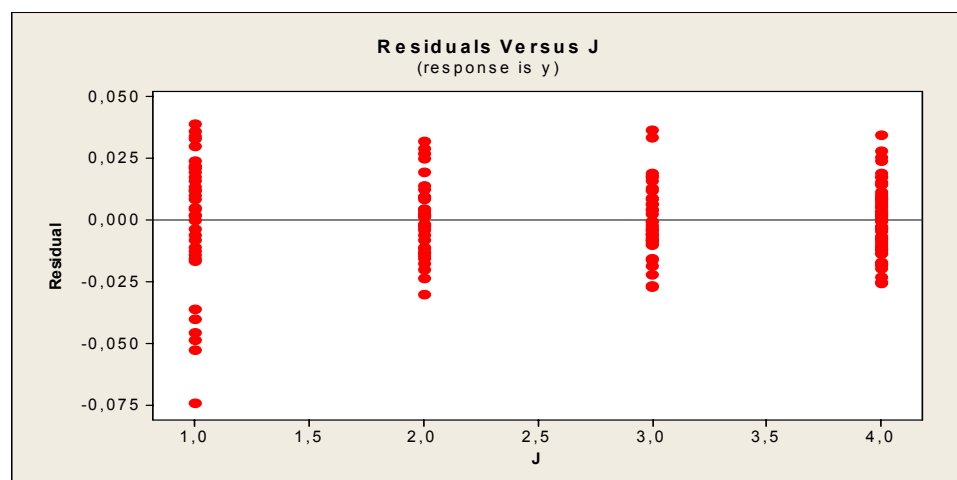
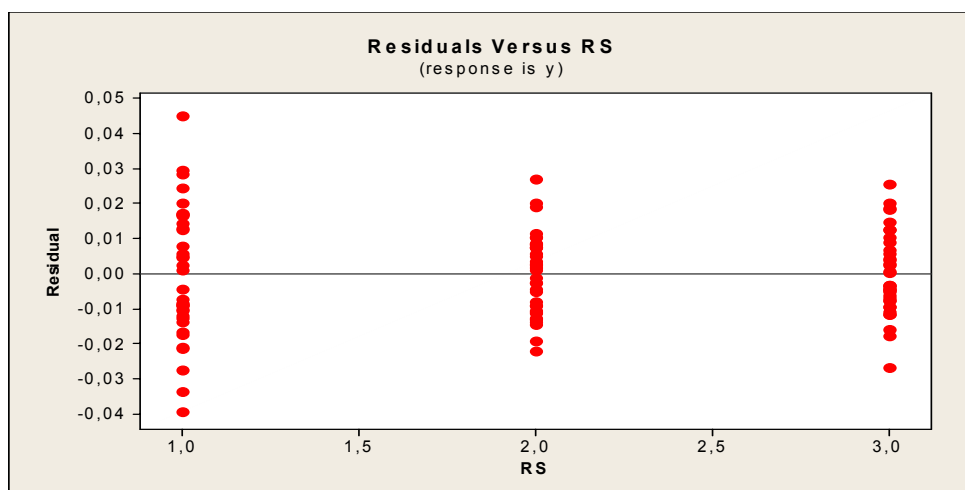Figure B.4.1.1 Residuals versus *J* of M1-All-PV-2 Model
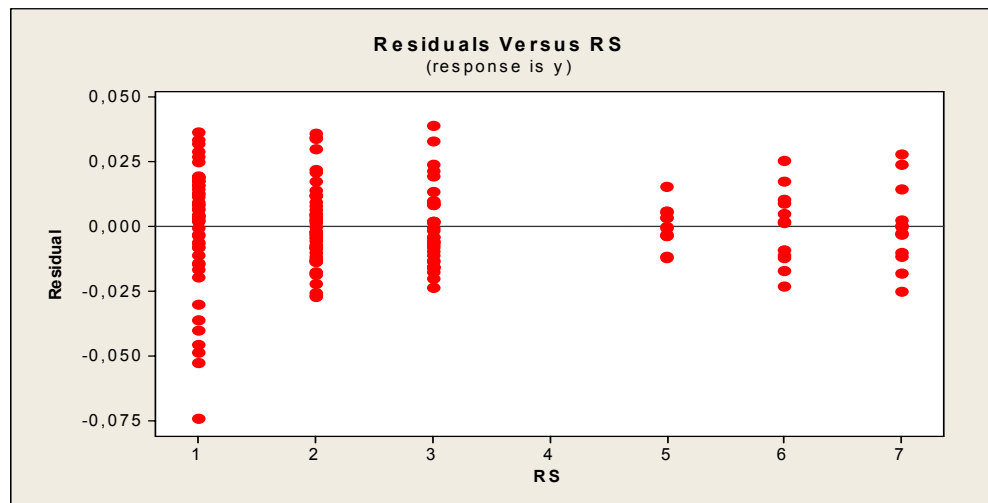
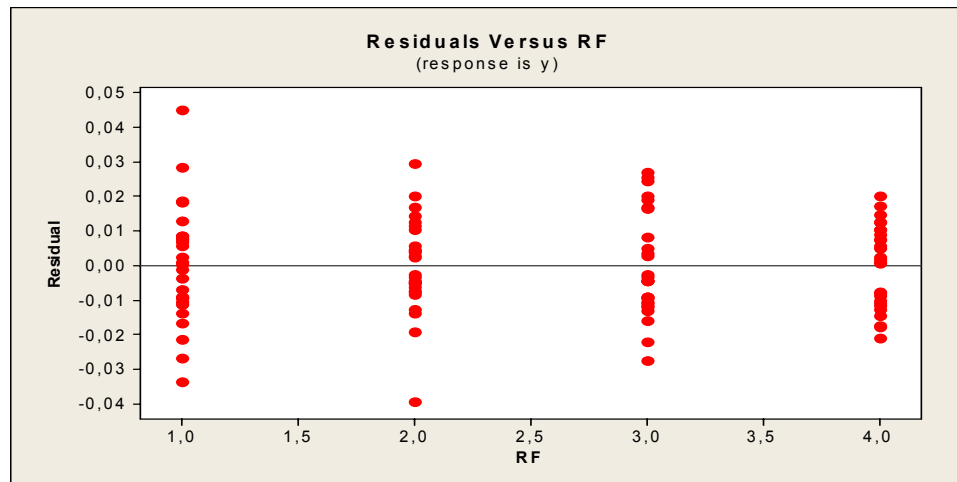Figure B.4.1.2 Residuals versus *RS* of M1-All-PV-2 Model
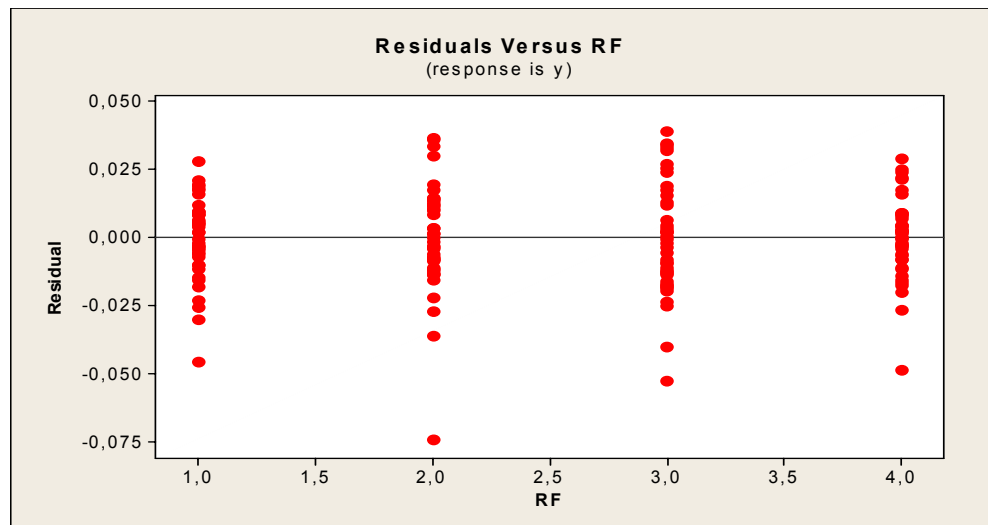
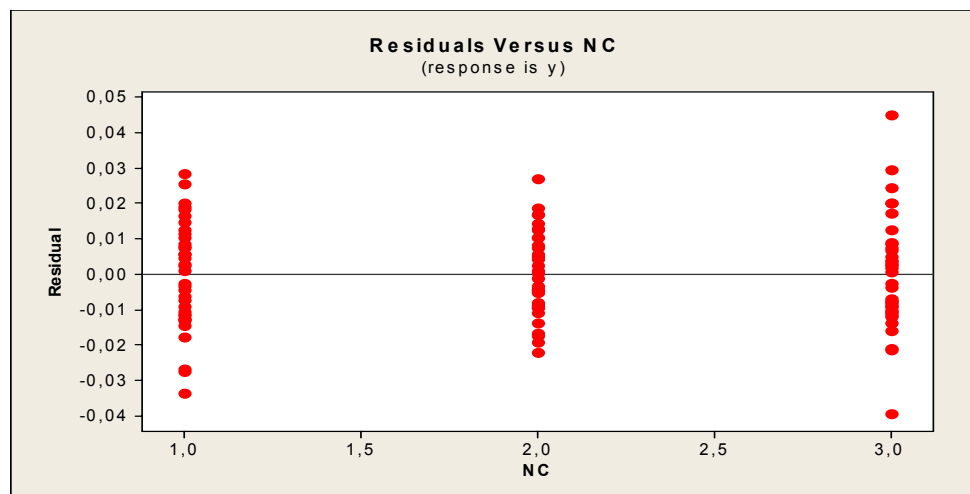Figure B.4.1.3 Residuals versus *RF* of M1-All-PV-2 Model
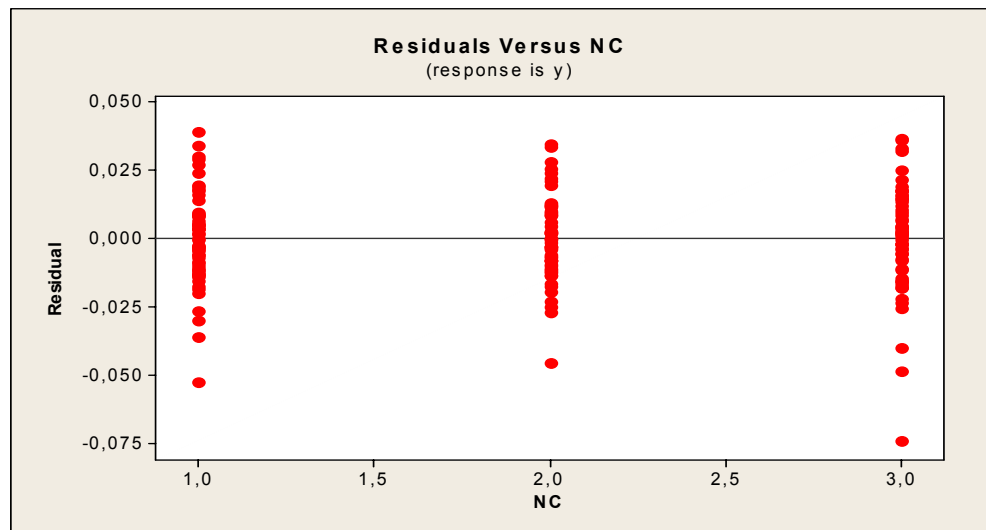
Figure B.4.1.4 Residuals versus *NC* of M1-All-PV-2 Model

B.4.2 M1-All-PV-2 Model Residuals Vs Factors After Transformation
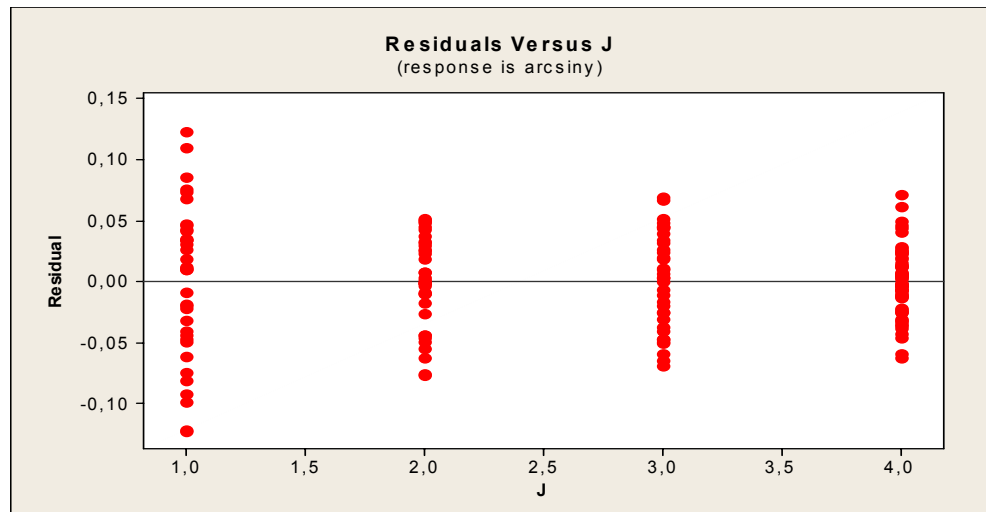
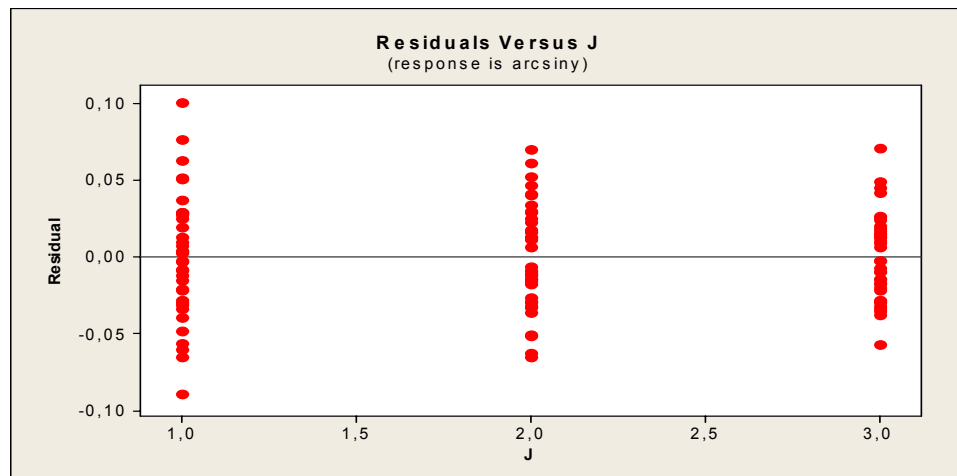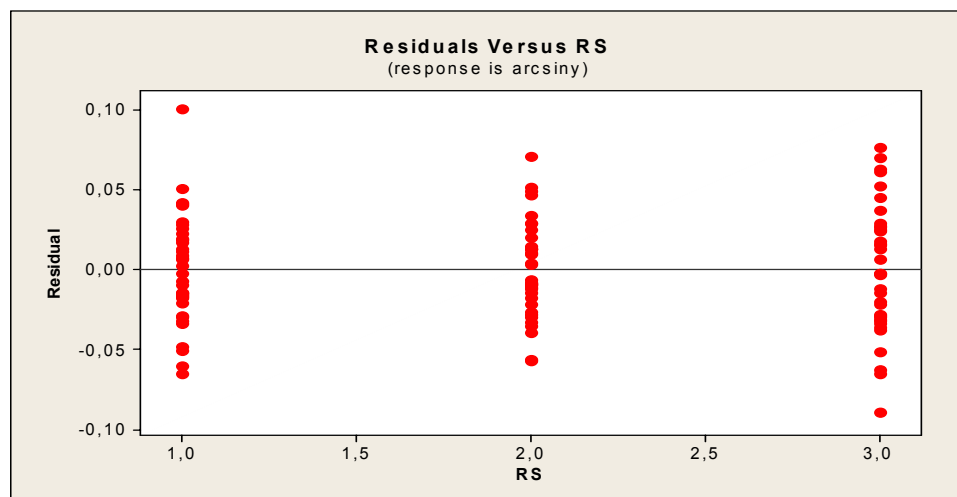

Figure B.4.2.1 Residuals versus *J* of M1-All-PV-2 Model

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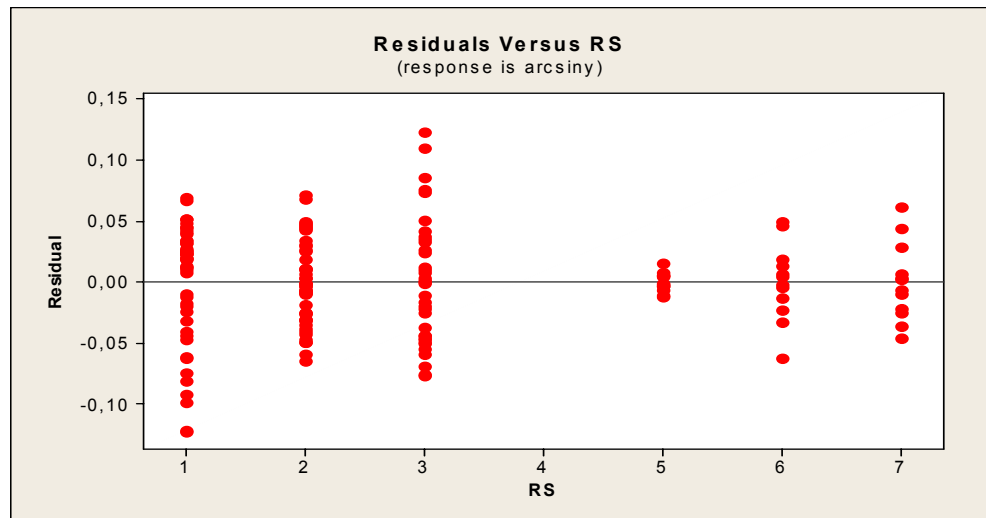
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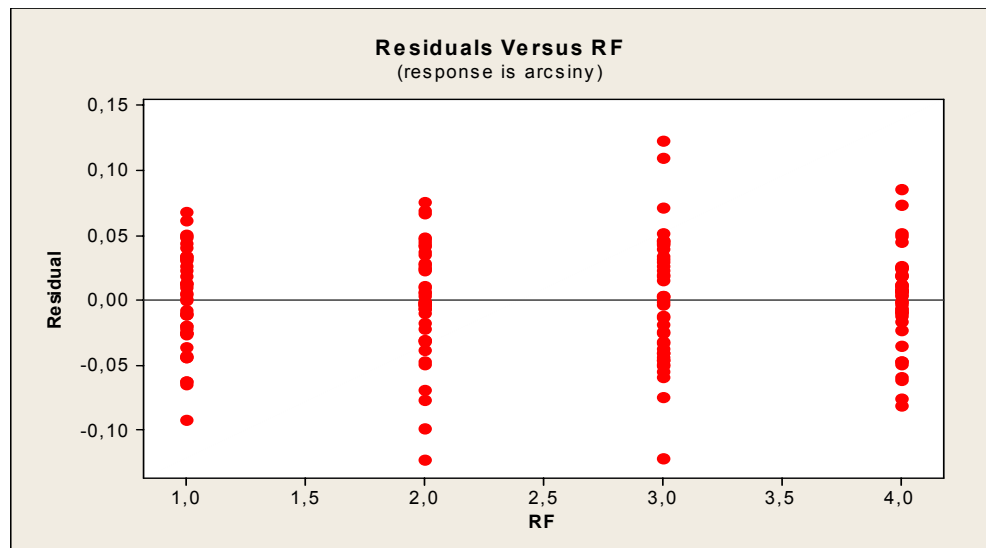
Figure B.4.2.3 Residuals versus *RF* of M1-All-PV-2 Model

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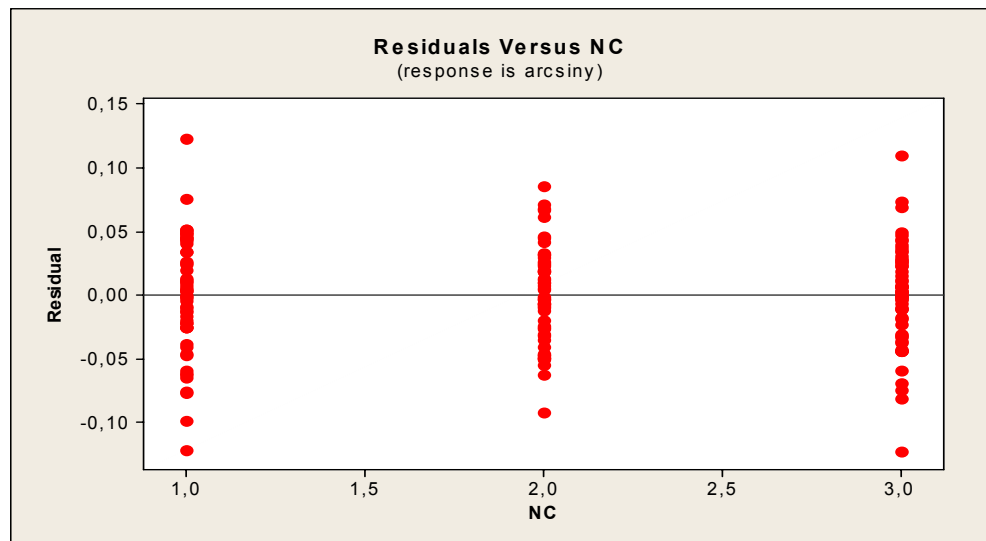
Figure B.4.2.4 Residuals versus *NC* of M1-All-PV-2 Model

B.5 M2-Small-Progs. Model Residuals Vs Factors

B.5.1 M2-Small-Progs. Model Residuals Vs Factors Before Transformation
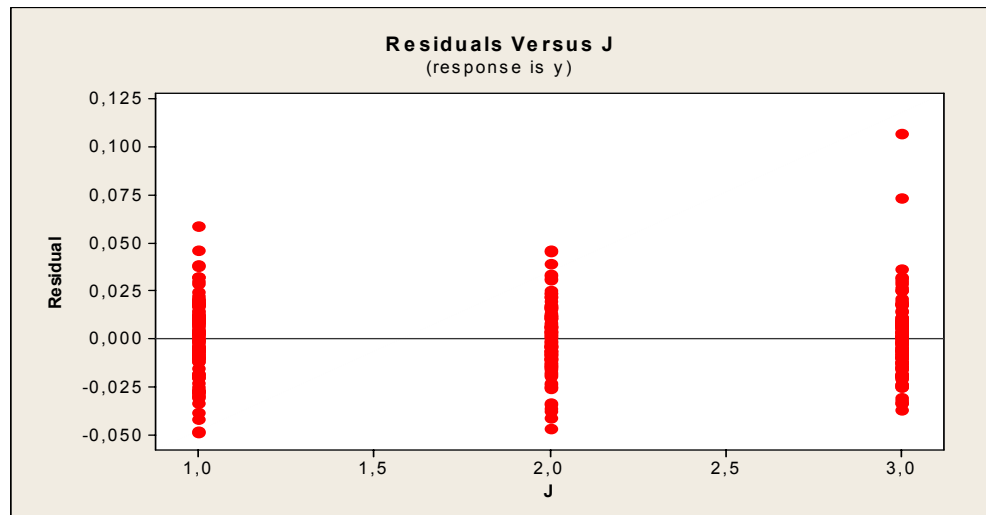
Figure B.5.1.1 Residuals versus *J* of M1-Small-Progs. Model
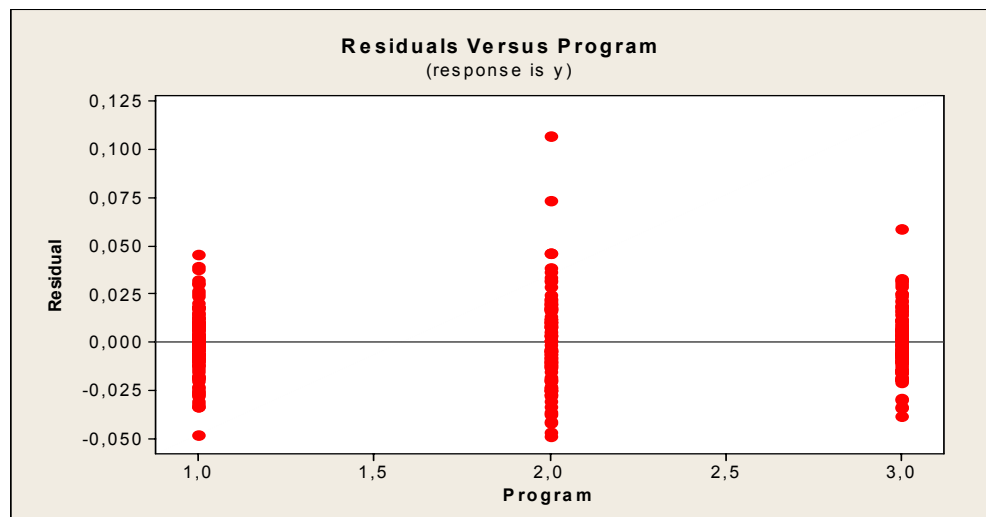
Figure B.5.1.2 Residuals versus *Program* of M1-Small-Progs. Model
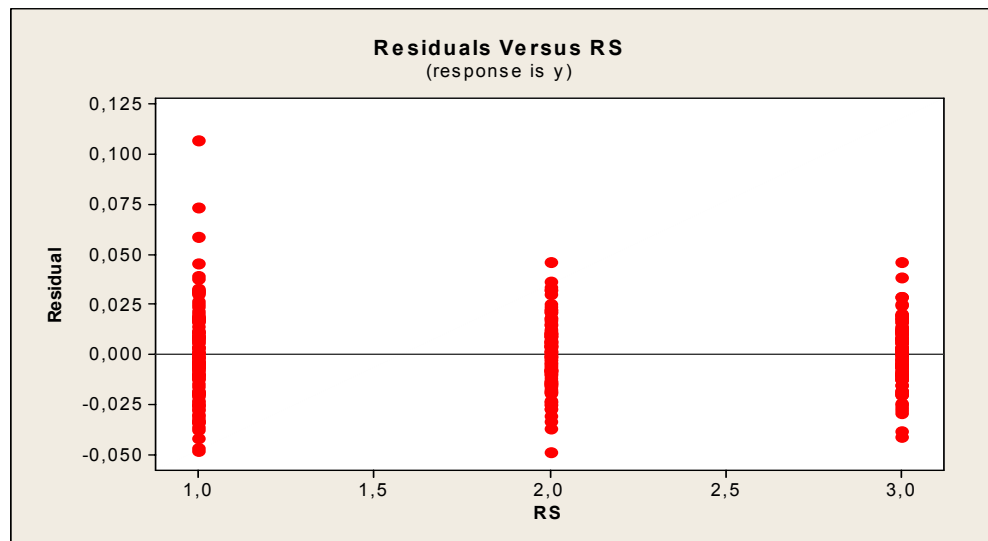
Figure B.5.1.3 Residuals versus *RS* of M1-Small-Progs. Model
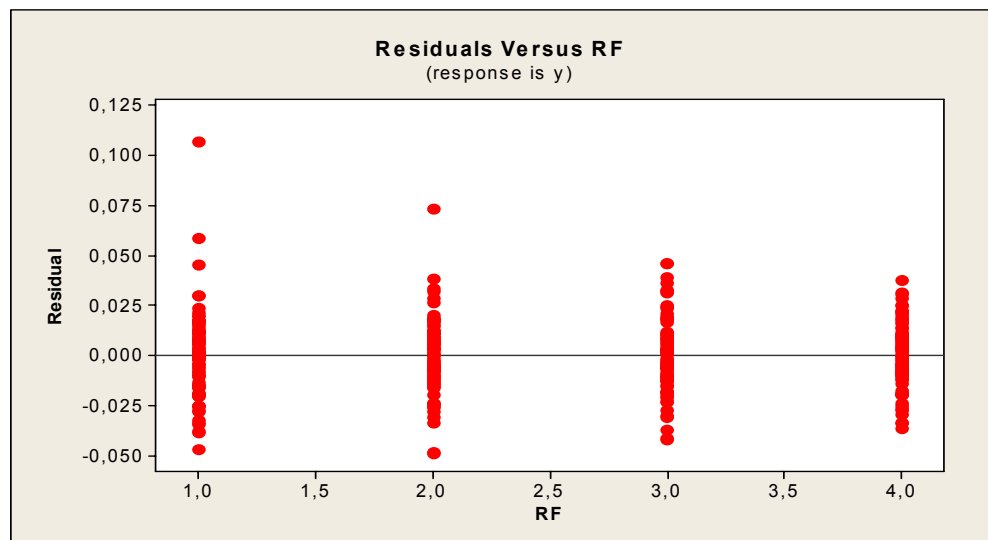
Figure B.5.1.4 Residuals versus *RF* of M1-Small-Progs. Model

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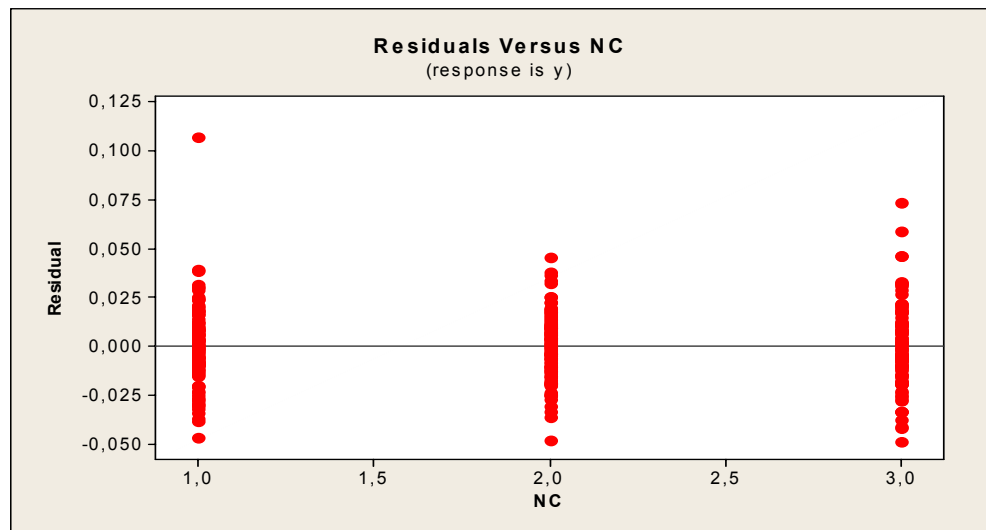
Figure B.5.1.5 Residuals versus *NC* of M1-Small-Progs. Model

B.5.2 M2-Small-Progs. Model Residuals Vs Factors After Transformation
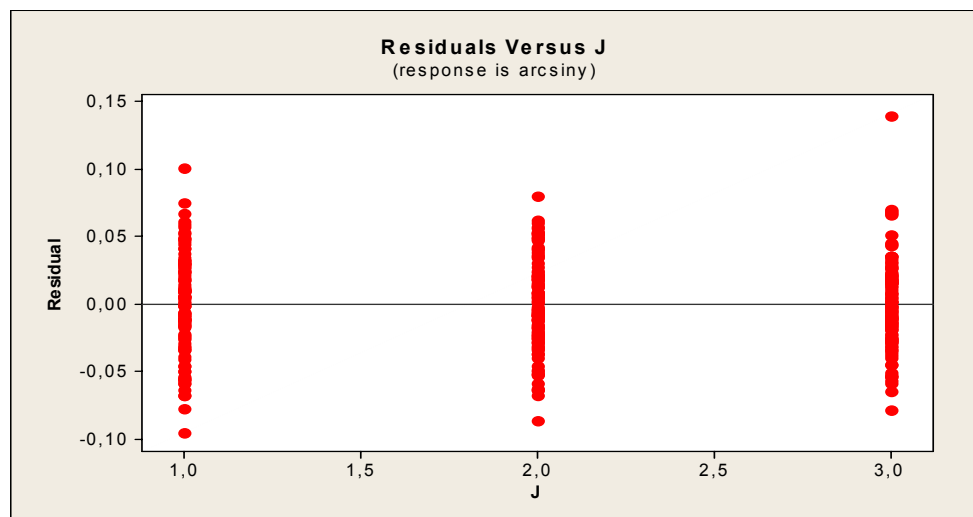
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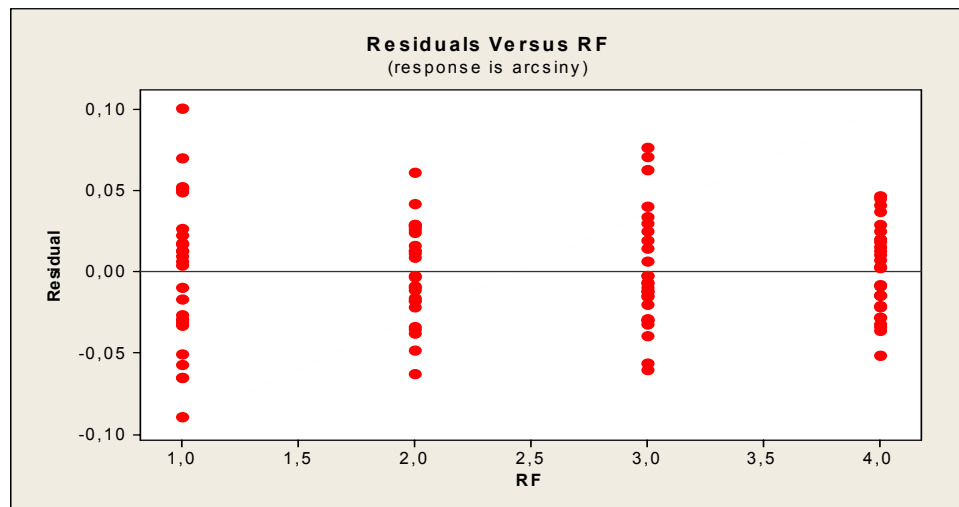
138
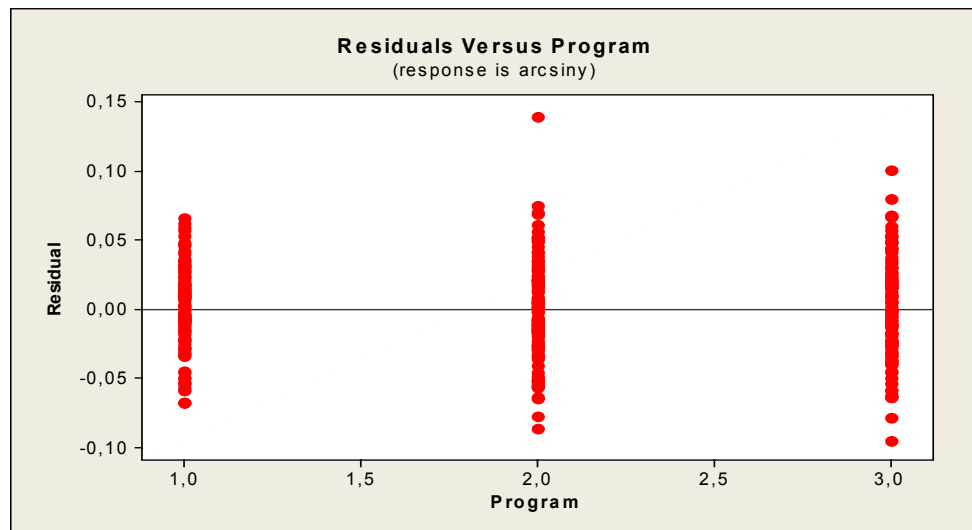
Figure B.5.2.2 Residuals versus *Program* of M1-Small-Progs. Model
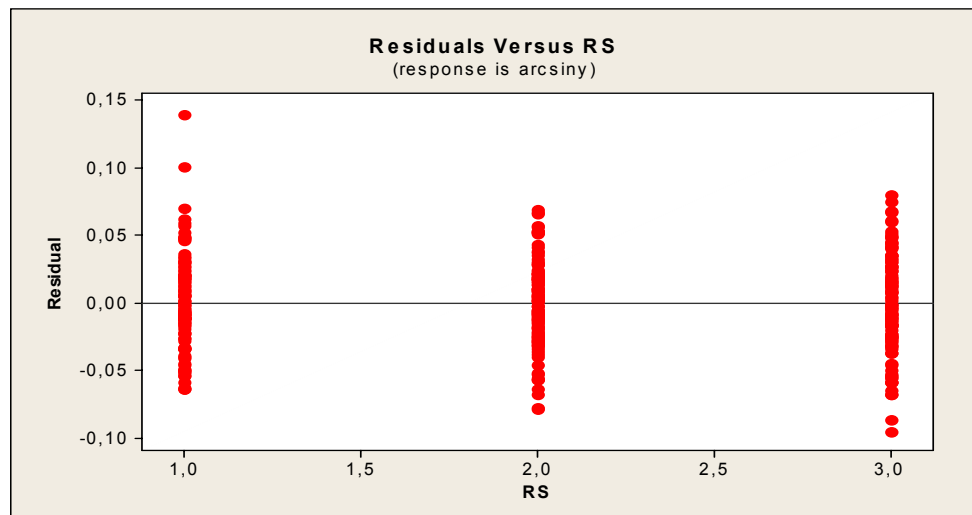
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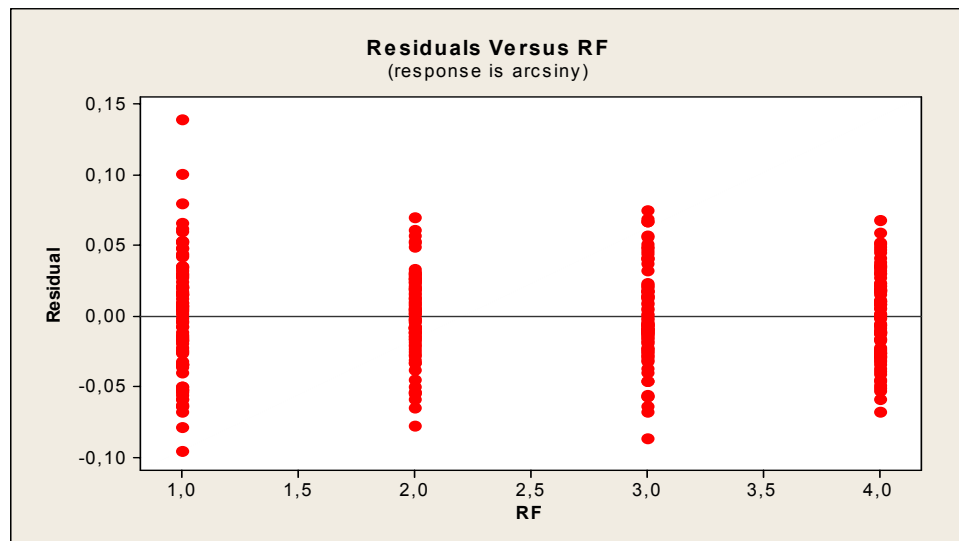
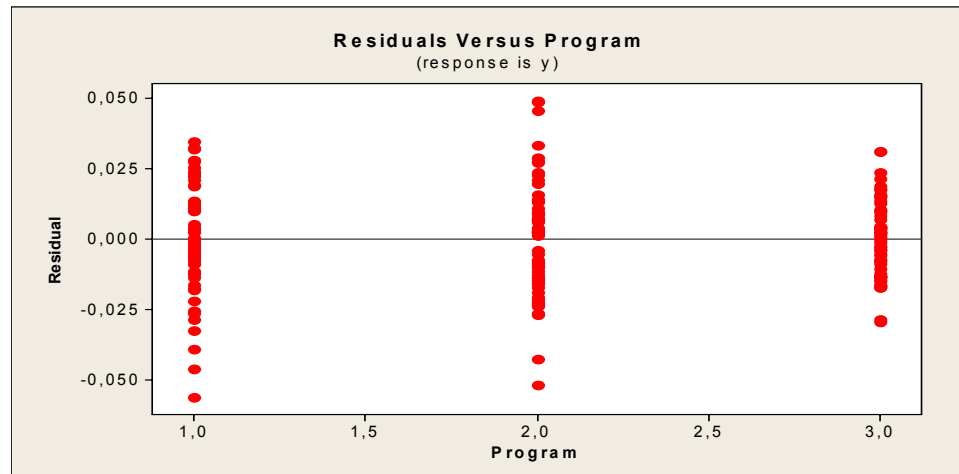Figure B.5.2.4 Residuals versus *RF* of M1-Small-Progs. Model
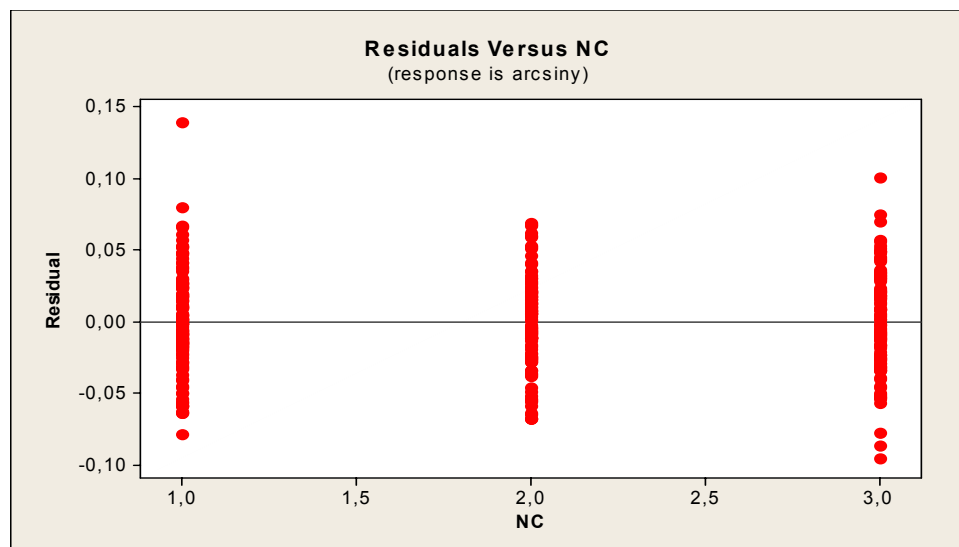
Figure B.5.2.5 Residuals versus *NC* of M1-Small-Progs. Model

B.6 M2-Small-MS Model Residuals Vs Factors

B.6.1 M2-Small-MS Model Residuals Vs Factors Before Transformation
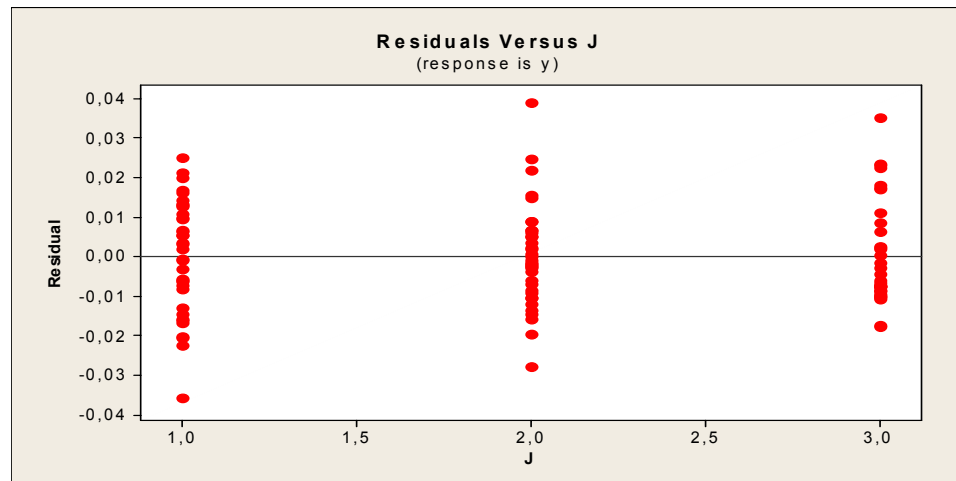
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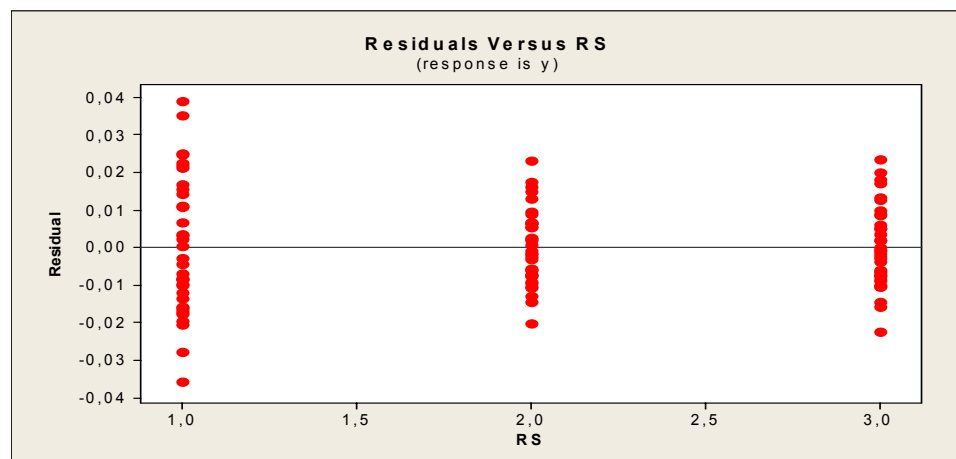
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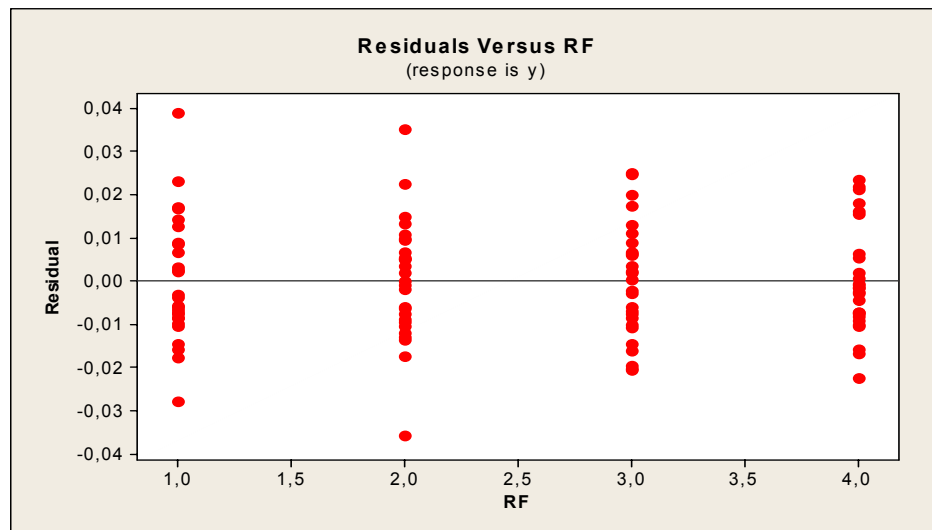
Figure B.6.1.3 Residuals versus *RF* of M1-Small-MS Model
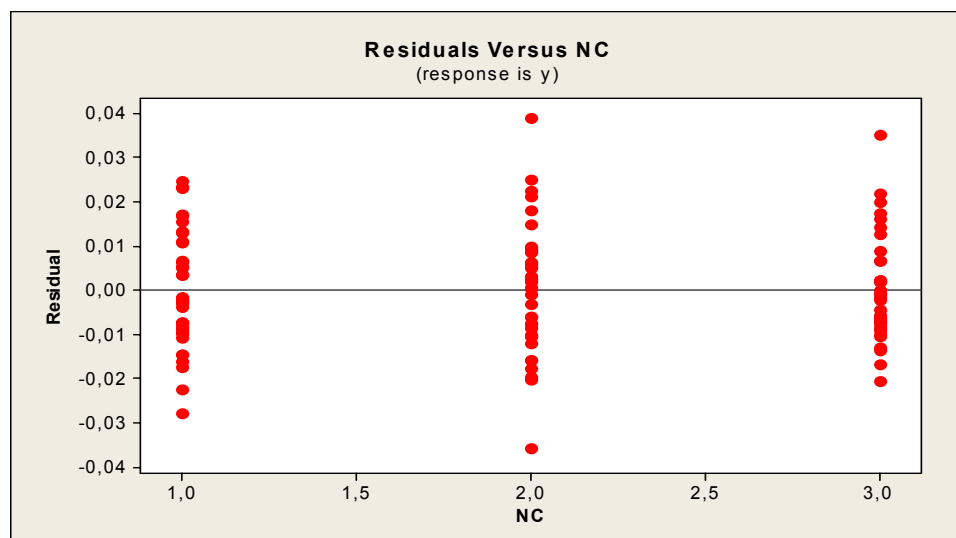
Figure B.6.1.4 Residuals versus *NC* of M1-Small-MS Model

B.6.2 M2-Small-MS Model Residuals Vs Factors After Transformation
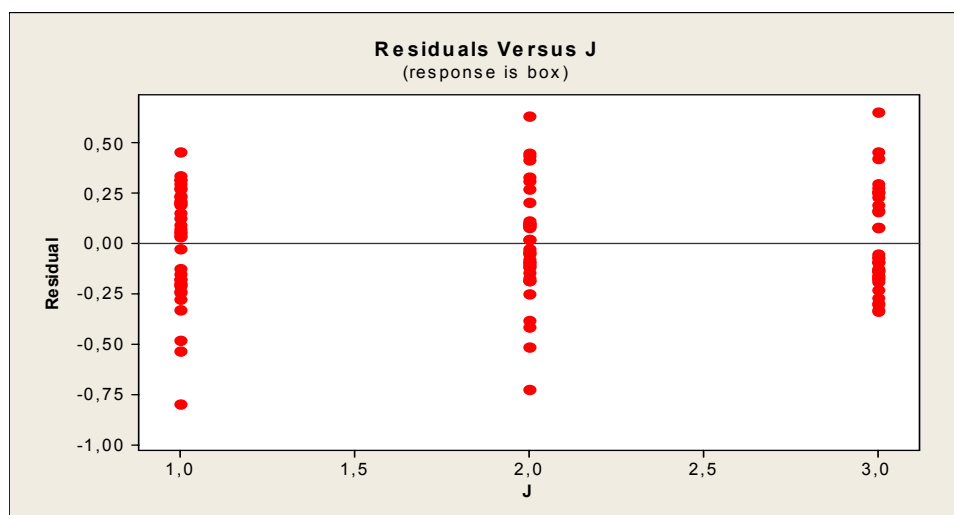
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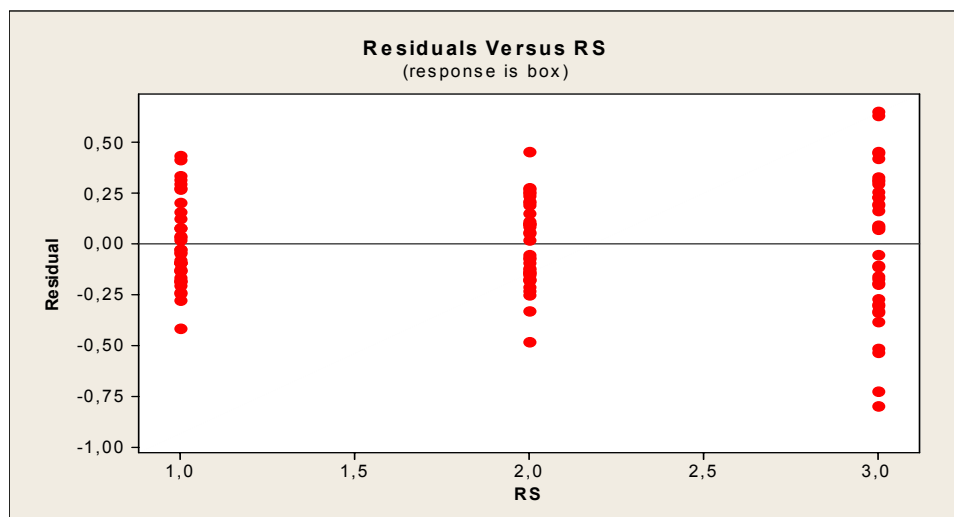
Figure B.6.2.2 Residuals versus *RS* of M1-Small-MS Model
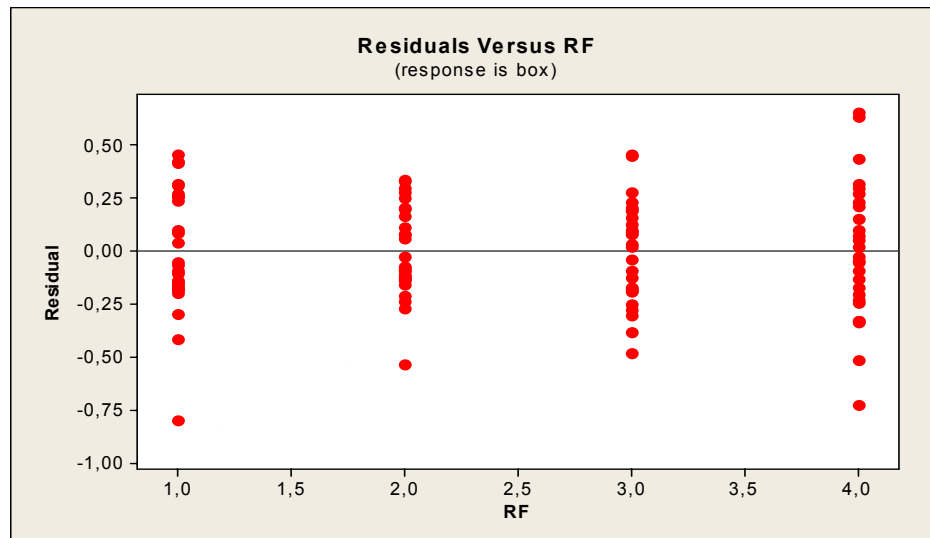
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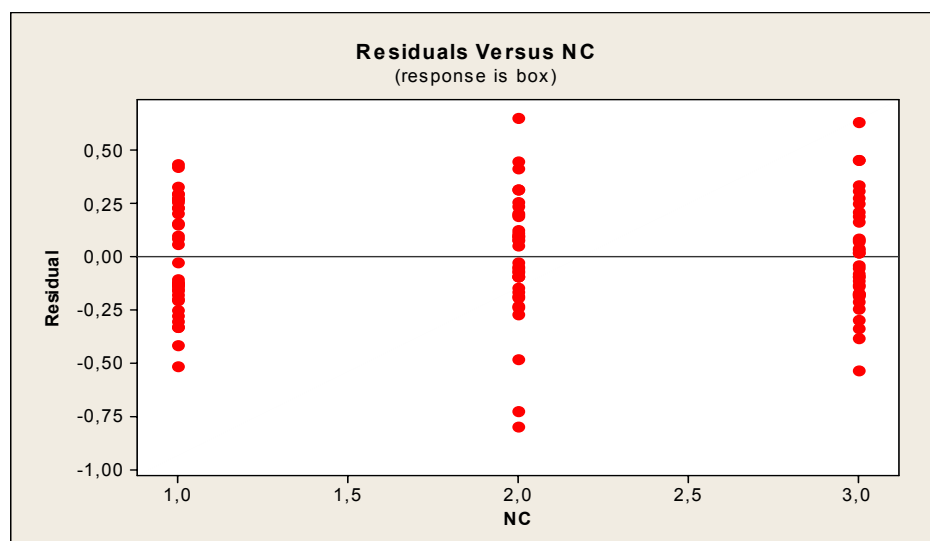
Figure B.6.2.4 Residuals versus *NC* of M1-Small-MS Model

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B.7 M2-Small-PV-1 Model Residuals Vs Factors

B.7.1 M2-Small-PV-1 Model Residuals Vs Factors Before Transformation

Figure B.7.1.1 Residuals versus *J* of M1-Small-PV-1 Model

Figure B.7.1.2 Residuals versus *RS* of M1-Small-PV-1 Model
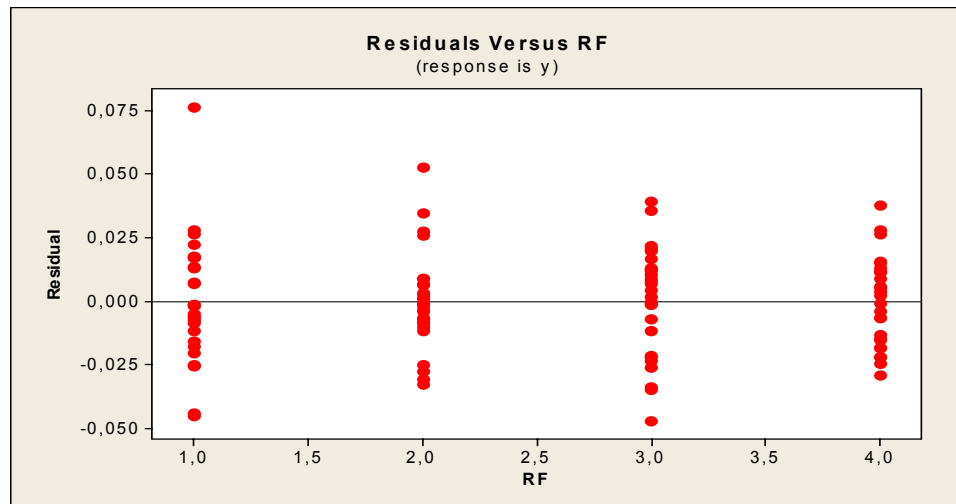
Figure B.7.1.3 Residuals versus *RF* of M1-Small-PV-1 Model

Figure B.7.1.4 Residuals versus *NC* of M1-Small-PV-1 Model

B.7.2 M2-Small-PV-1 Model Residuals Vs Factors After Transformation

Figure B.7.2.1 Residuals versus *J* of M1-Small-PV-1 Model

Figure B.7.2.2 Residuals versus *RS* of M1-Small-PV-1 Model

Figure B.7.2.3 Residuals versus *RF* of M1-Small-PV-1 Model

Figure B.7.2.4 Residuals versus *NC* of M1-Small-PV-1 Model

B.8 M2-Small-PV-2 Model Residuals Vs Factors

B.8.1 M2-Small-PV-2 Model Residuals Vs Factors Before Transformation

Figure B.8.1.1 Residuals versus *J* of M1-Small-PV-2 Model

Figure B.8.1.2 Residuals versus *RS* of M1-Small-PV-2 Model

Figure B.8.1.3 Residuals versus *RF* of M1-Small-PV-2 Model

Figure B.8.1.4 Residuals versus *NC* of M1-Small-PV-2 Model

B.8.2 M2-Small-PV-2 Model Residuals Vs Factors After Transformation

Figure B.8.2.1 Residuals versus *J* of M1-Small-PV-2 Model


Figure B.8.2.2 Residuals versus *RS* of M1-Small-PV-2 Model

Figure B.8.2.3 Residuals versus *RF* of M1-Small-PV-2 Model
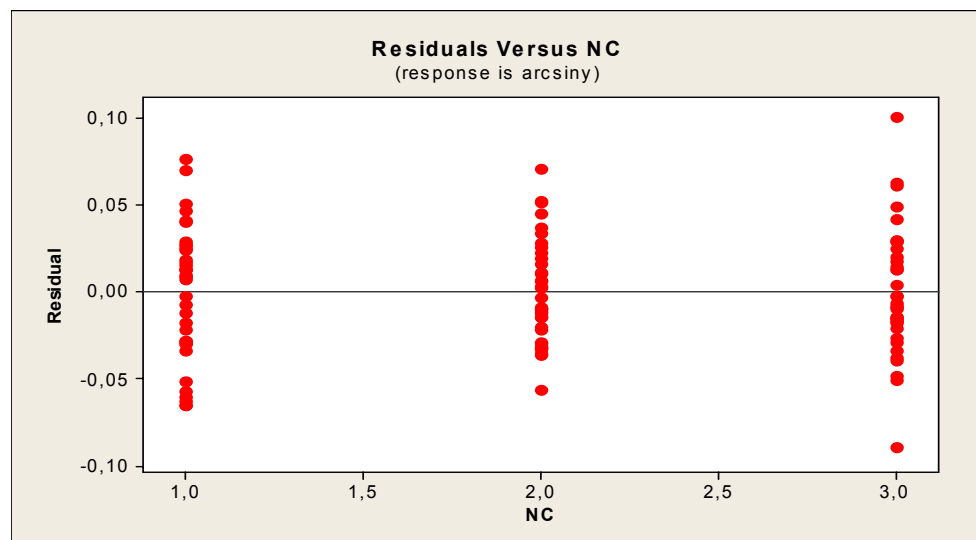
Figure B.8.2.4 Residuals versus *NC* of M1-Small-PV-2 Model

B.9 M3-Large-Progs. Model Residuals Vs Factors

Figure B.9.1. Residuals versus *Program* of M3-Large-Progs. Model
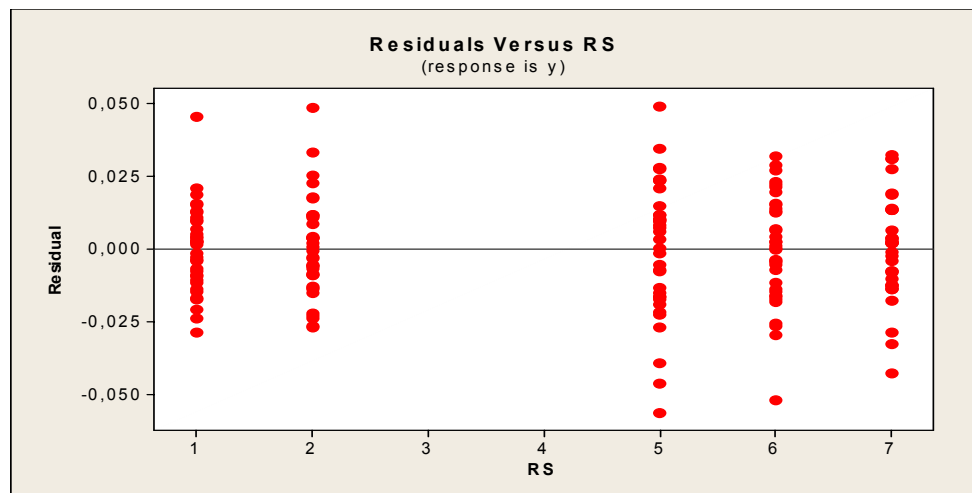
Figure B.9.2 Residuals versus *RS* of M3-Large-Progs. Model
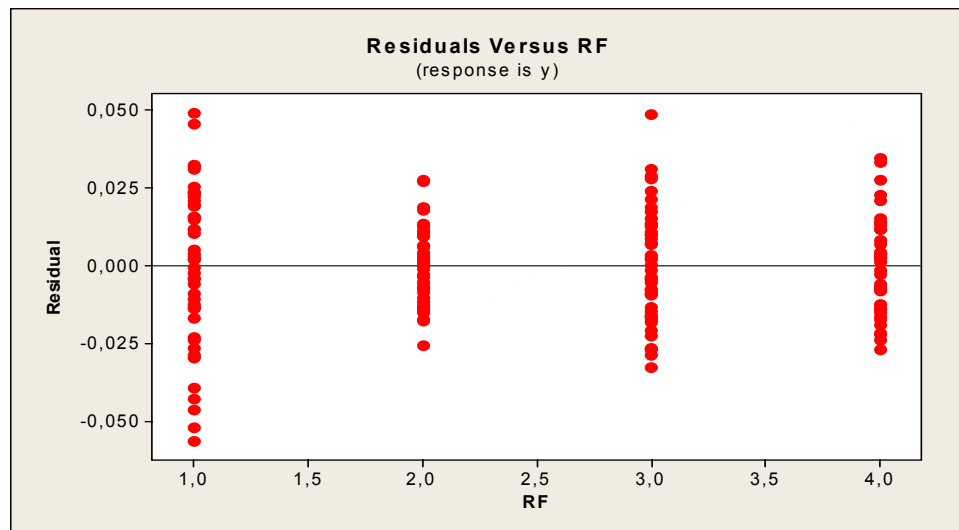
Figure B.9.3 Residuals versus *RF* of M3-Large-Progs. Model
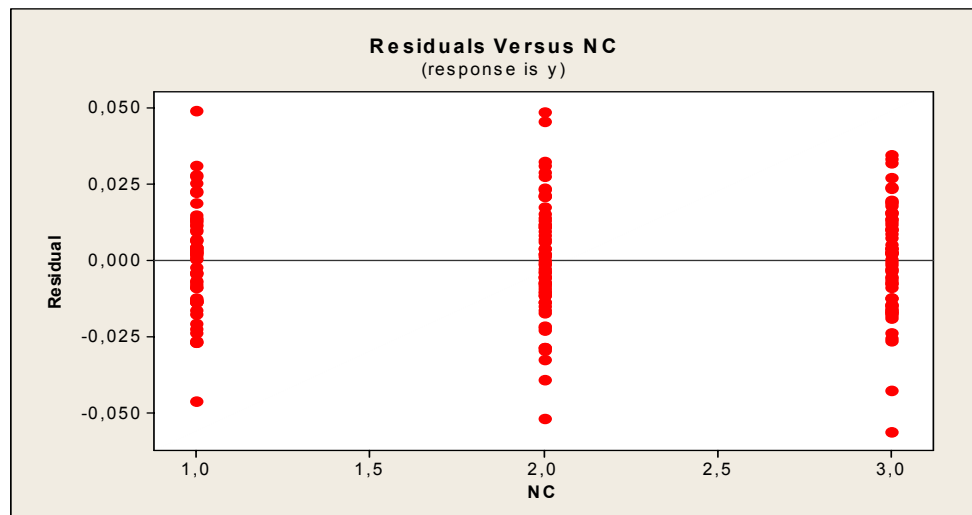
Figure B.9.4 Residuals versus *NC* of M3-Large-Progs. Model

B.10 M3-Large-MS Model Residuals Vs Factors

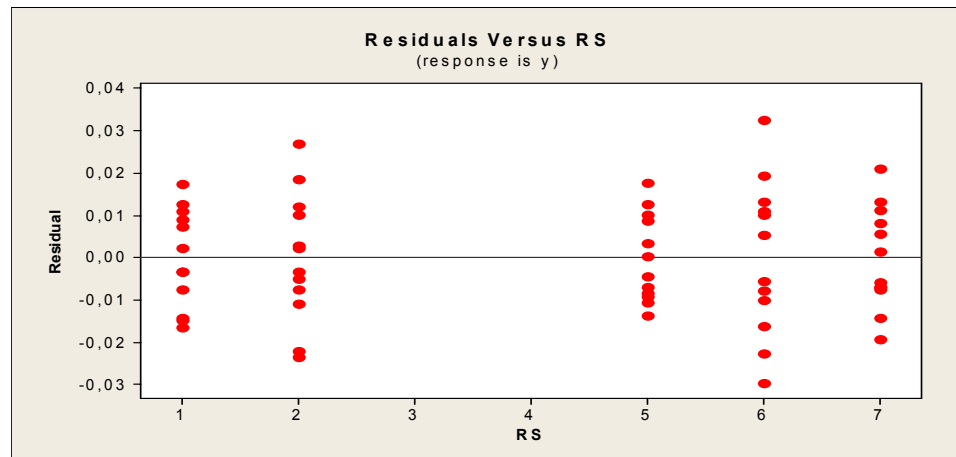### B.10.1 M3-Large-MS Model Residuals Vs Factors Before Transformation
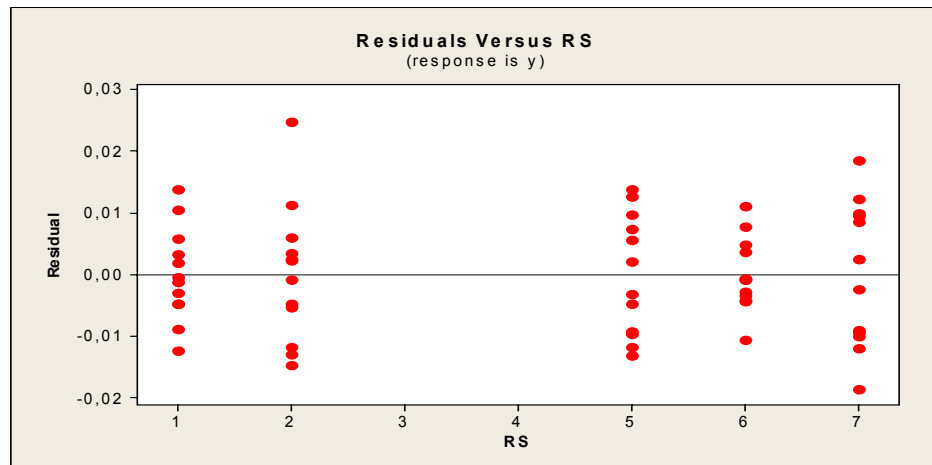
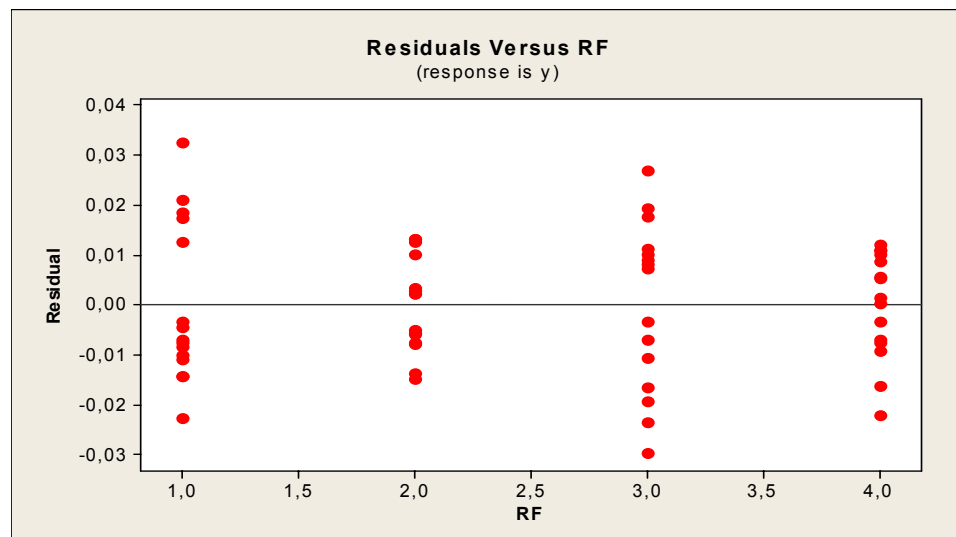Figure B.10.1.1 Residuals versus *RS* of M3-Large-MS Model
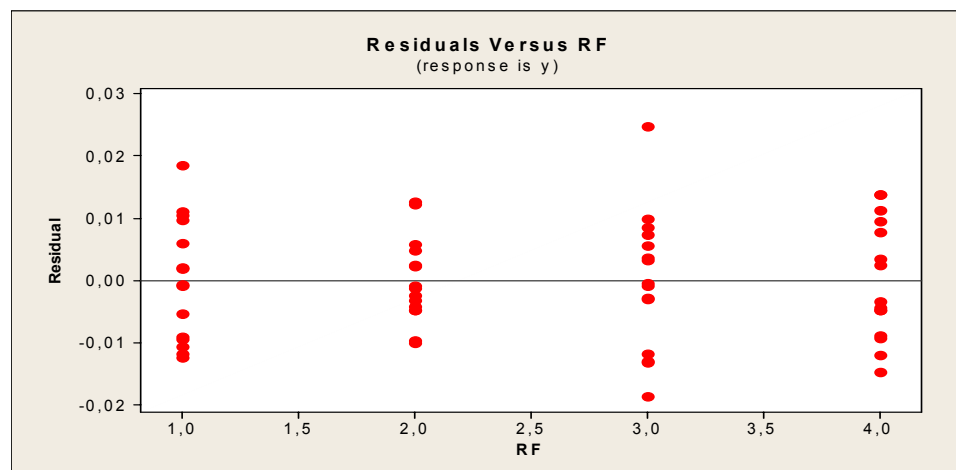
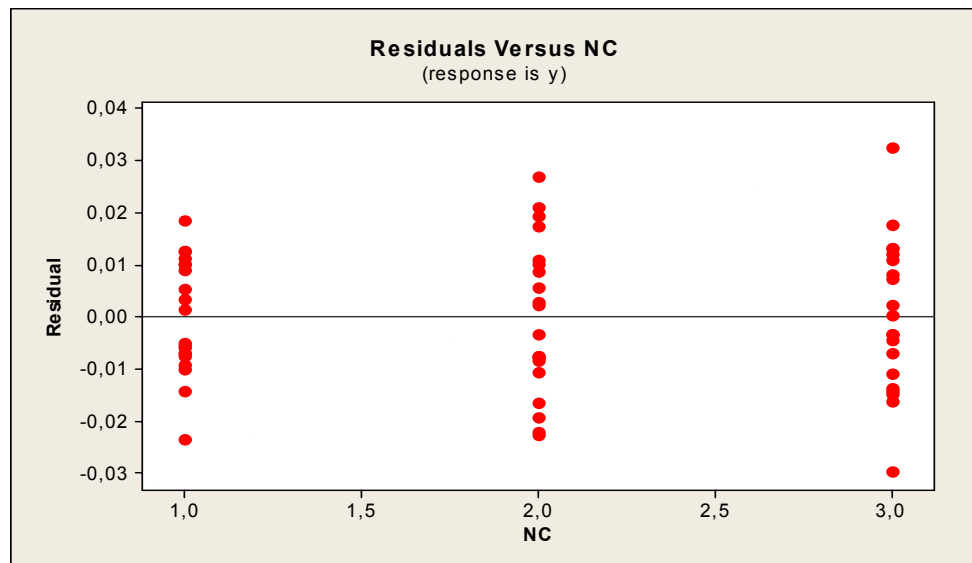Figure B.10.1.2 Residuals versus *RF* of M3-Large-MS Model
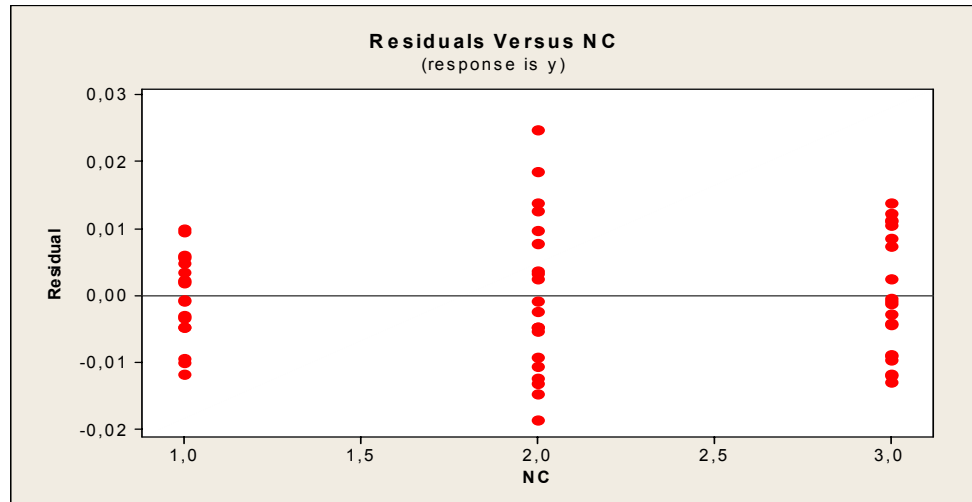
Figure B.10.1.3 Residuals versus *NC* of M3-Large-MS Model

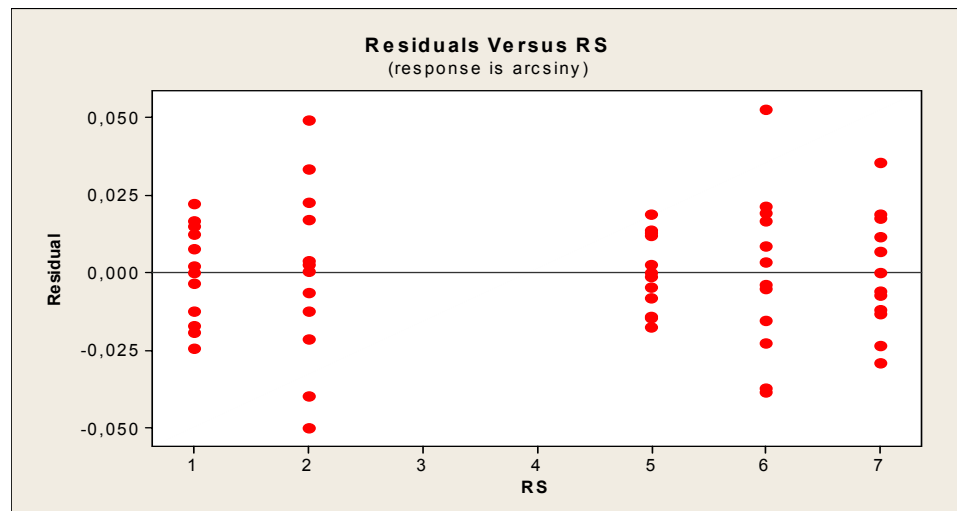## B.10.2 M3-Large-MS Model Residuals Vs Factors After Transformation
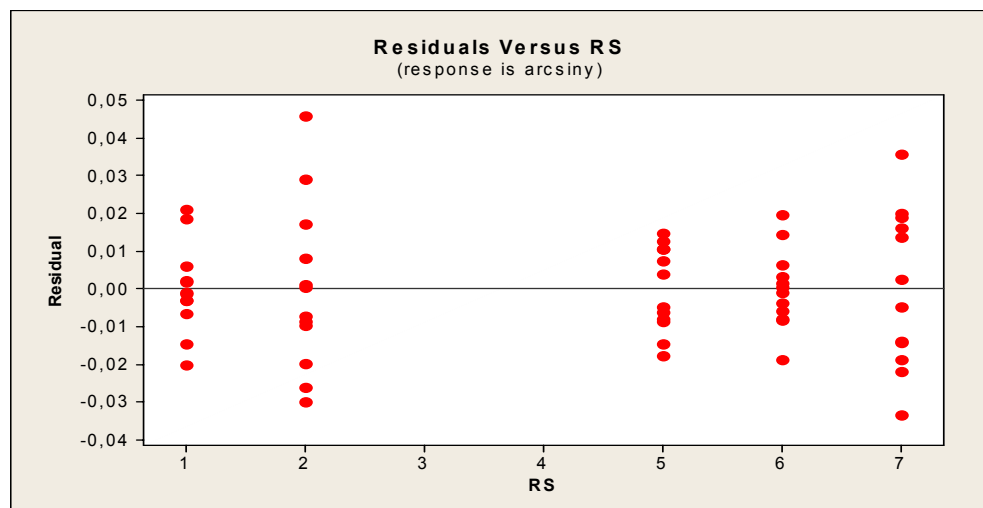
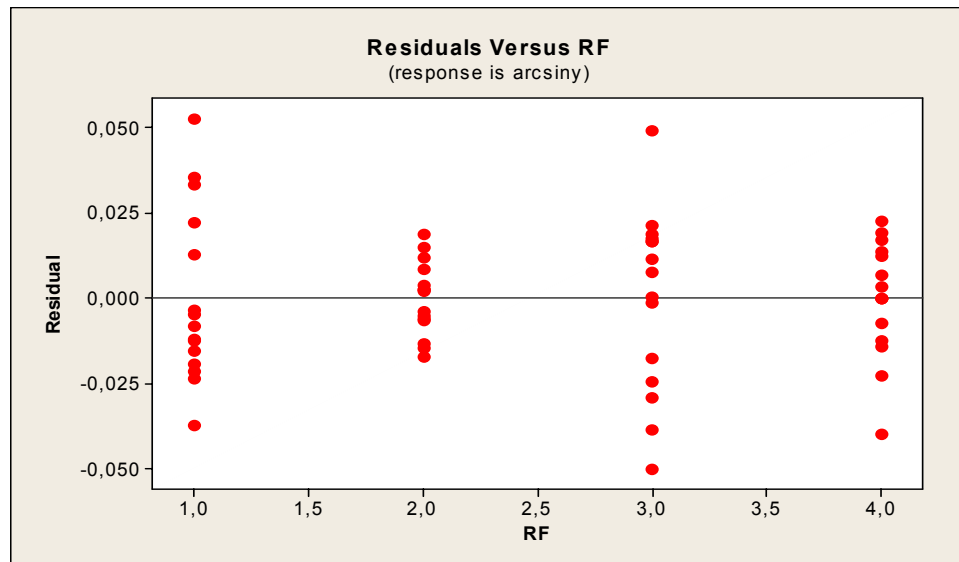Figure B.10.2.1 Residuals versus *RS* of M3-Large-MS Model
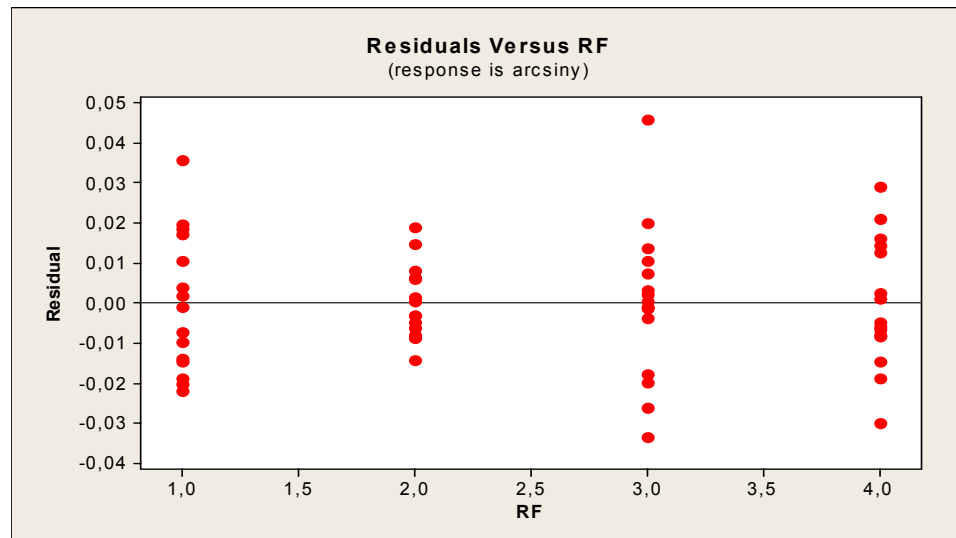
Figure B.10.2.2 Residuals versus *RF* of M3-Large-MS Model
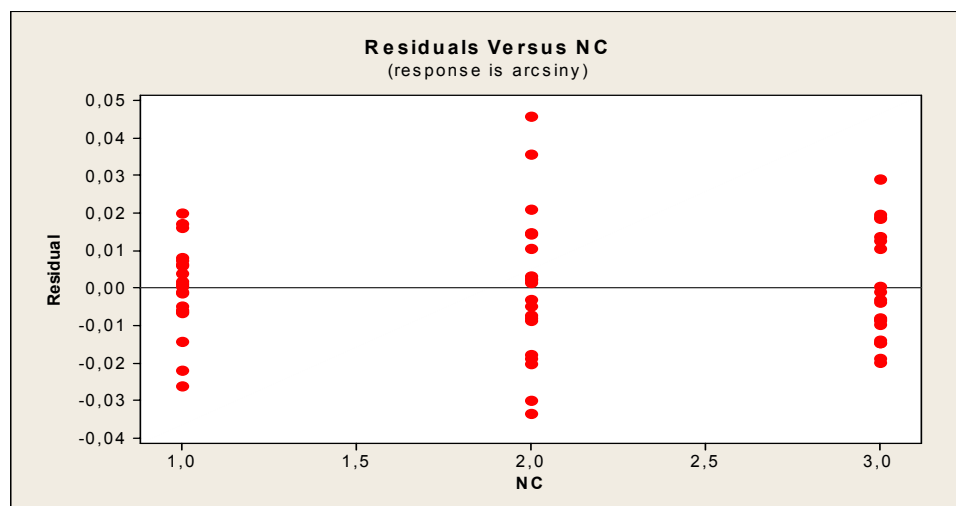
Figure B.10.2.3 Residuals versus *NC* of M3-Large-MS Model

B.11 M3-Large-PV-1 Model Residuals Vs Factors

B.11.1 M3-Large-PV-1 Model Residuals Vs Factors Before Transformation

Figure B.11.1.1 Residuals versus *RS* of M3-Large-PV-1 Model

Figure B.11.1.2 Residuals versus *RF* of M3-Large-PV-1 Model

Figure B.11.1.3 Residuals versus *NC* of M3-Large-PV-1 Model

B.11.2 M3-Large-PV-1 Model Residuals Vs Factors After Transformation

Figure B.11.2.1 Residuals versus *RS* of M3-Large-PV-1 Model

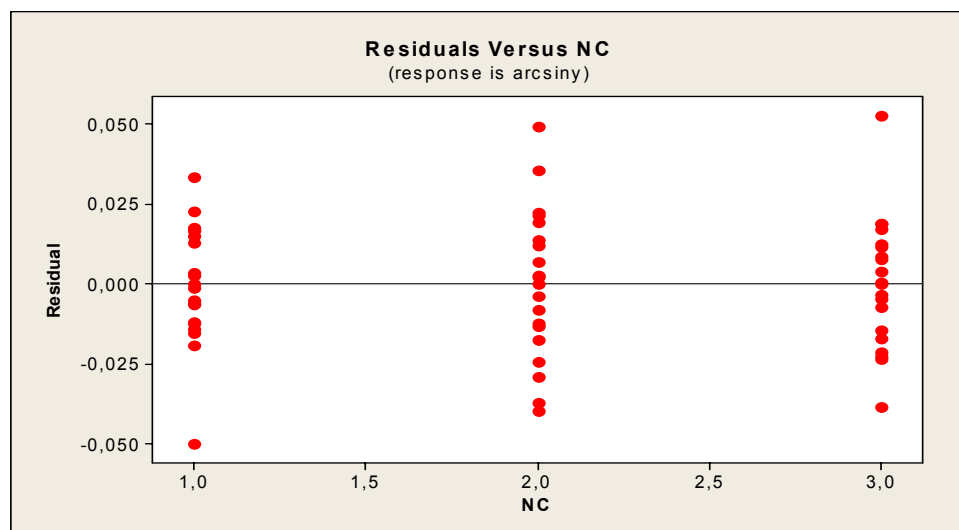Figure B.11.2.2 Residuals versus *RF* of M3-Large-PV-1 Model

Figure B.11.2.3 Residuals versus *NC* of M3-Large-PV-1 Model

B.12 M3-Large-PV-2 Model Residuals Vs Factors
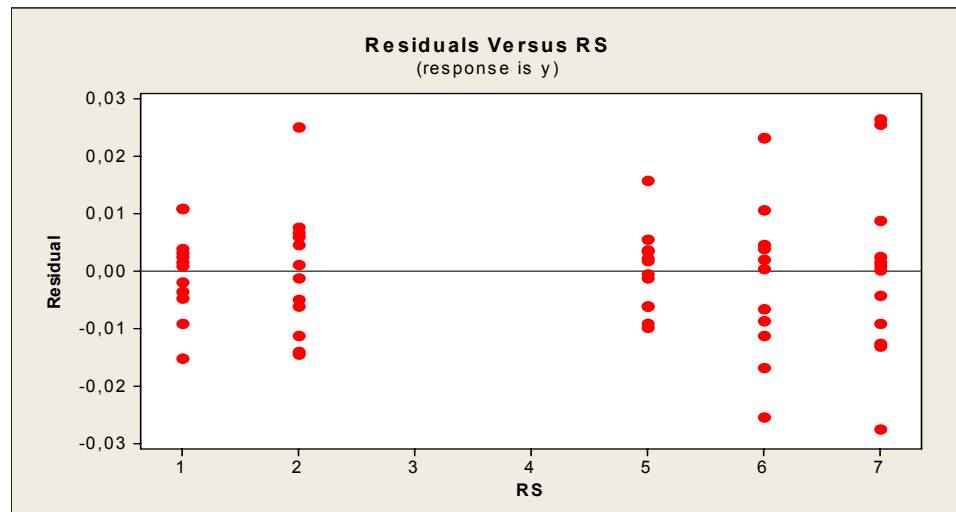

Figure B.12.1 Residuals versus *RS* of M3-Large-PV-2 Model
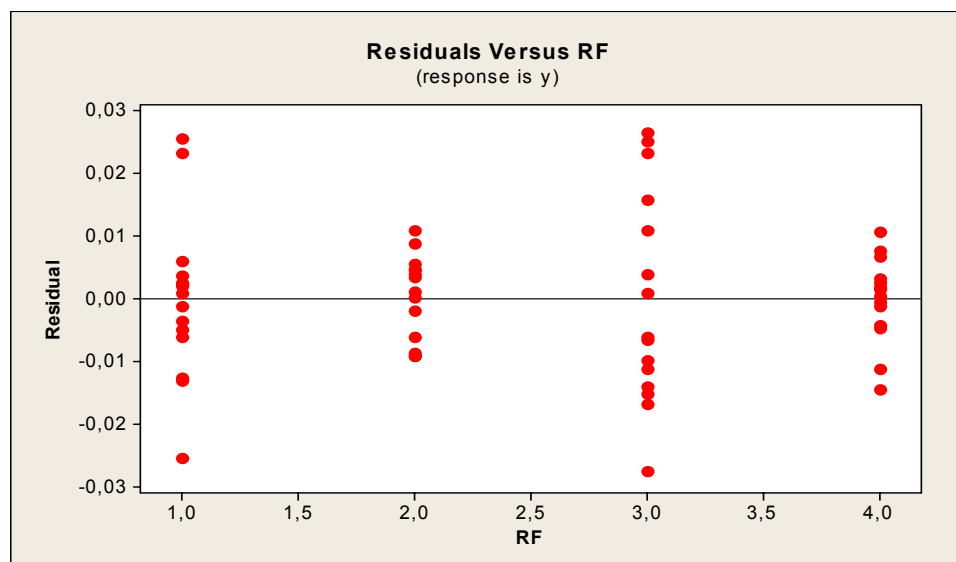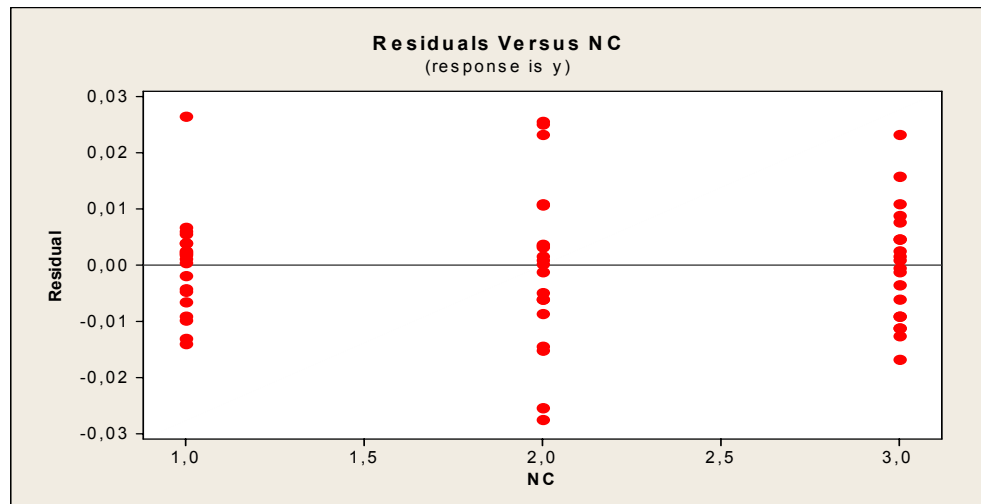

Figure B.12.2 Residuals versus *RF* of M3-Large-PV-2 Model

Figure B.12.3 Residuals versus *NC* of M3-Large-PV-2 Model