A Dynamic Scheduling Model for Construction Enterprises

by

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To my parents, wife & children

LIST OF CONTENTS

ABSTRACT

The vast majority of researches in the scheduling context focused on finding optimal or near-optimal predictive schedules under different scheduling problem characteristics. In the construction industry, predictive schedules are often produced in advance in order to direct construction operations and to support other planning activities. However, construction projects operate in dynamic environments subject to various real-time events, which usually disrupt the predictive optimal schedules, leading to schedules neither feasible nor optimal. Accordingly, the development of a dynamic scheduling model which can accommodate these real-time events would be of great importance for the successful implementation of construction scheduling systems.

This research sought to develop a dynamic scheduling based solution which can be practically used for real time analysis and scheduling of construction projects, in addition to resources optimization for construction enterprises. The literature reviews for scheduling, dynamic scheduling, and optimization showed that despite the numerous researches presented and applications performed in the dynamic scheduling field within manufacturing and other industries, there was dearth in dynamic scheduling literature in relation to the construction industry. The research followed two main interacting research paths, a path related to the development of the practical solution, and another path related to the core model development.

The aim of the first path (or the proposed practical solution path) was to develop a computer-based dynamic scheduling framework which can be used in practical applications within the construction industry. Following the scheduling literature review, the construction project management community's opinions about the problem under study and the user requirements for the proposed solution were collected from 364 construction project management practitioners from 52 countries via a questionnaire survey and were used to form the basis for the functional specifications of a dynamic scheduling framework. The framework was in the form of a software tool and the process of its integration with current planning/scheduling practices with all core modelling which can support the integration of the dynamic scheduling processes to the current planning/scheduling process with minimal experience requirement from users about optimization.

The second research path, or the dynamic scheduling core model development path, started with the development of a mathematical model based on the

scheduling models in literature, with several extensions according to the practical considerations related to the construction industry, as investigated in the questionnaire survey. Scheduling problems are complex from operational research perspective; so, for the proposed solution to be functional in optimizing construction schedules, an optimization algorithm was developed to suit the problem's characteristics and to be used as part of the dynamic scheduling model's core. The developed algorithm contained few contributions to the scheduling context (such as schedule justification heuristics, and rectification to schedule generation schemes), as well as suggested modifications to the formulation and process of the adopted optimization technique (particle swarm optimization) leading to considerable improvement to this techniques outputs with respect to schedules quality.

After the completion of the model development path, the first research path was concluded by combining the gathered solution's functional specifications and the developed dynamic scheduling model into a software tool, which was developed to verify & validate the proposed model's functionalities and the overall solution's practicality and scalability.

The verification process started with an extensive testing of the model's static functionality using several well recognized scheduling problem sets available in literature, and the results showed that the developed algorithm can be ranked as one of the best state-of-the-art algorithms for solving resource-constrained project scheduling problems. To verify the software tool and the dynamic features of the developed model (or the formulation of data transfers from one optimization stage to the next), a case study was implemented on a construction entity in the Arabian Gulf area, having a mega project under construction, with all aspects to resemble an enterprise structure. The case study results showed that the proposed solution reasonably performed under large scale practical application (where all optimization targets were met in reasonable time) for all designed schedule preparation processes (baseline, progress updates, look-ahead schedules, and what-if schedules).

Finally, to confirm and validate the effectiveness and practicality of the proposed solution, the solution's framework and the verification results were presented to field experts, and their opinions were collected through validation forms. The feedbacks received were very positive, where field experts/practitioners confirmed that the proposed solution achieved the main functionalities as designed in the solution's framework, and performed efficiently under the complexity of the applied case study.

ACKNOWLEDGEMENT

LIST OF CHAPTERS

LIST OF APPENDICES

LIST OF FIGURES

LIST OF TABLES

Chapter 1: Introduction

1.1. Summary of the research problem

Most of the research studies dealing with scheduling have primarily been focused on finding optimal or near-optimal predictive schedules for simple or complex scheduling models with respect to various changes in the problem characteristics. Such predictive schedules are often produced in advance in order to direct construction operations and to support other planning activities. Unfortunately, most construction projects operate in dynamic environments subject to various real-time events, which may lead that predictive optimal schedule becoming neither feasible nor optimal. Therefore, dynamic scheduling is of great importance for the successful implementation of real-world construction scheduling systems.

In addition, the vast majority of research efforts in project scheduling are based on two main assumptions: initial availability of the complete schedule information before the analysis start, and a static deterministic environment within which the pre-computed schedule will be executed. However, in real world, project activities are subject to considerable uncertainty, which is gradually resolved during project execution *[Herroelen, 2005]*, and schedules are executed in an environment full of dynamic events which were neither initially anticipated nor fitting with the pre-optimized schedule.

Taking into consideration the uncertainty and the unavailability of some of the problem's data during the initial stage is called *Scheduling under Uncertainty*; several approaches were created to handle this issue starting from the original *PERT* method, up to very complex *Stochastic* approaches. In addition to uncertainty, unexpected real-time events affecting the schedule optimality and the need to have a system capable of dynamically optimizing the schedule led to the evolution of a new scheduling paradigm named *Dynamic Scheduling* (or *Dynamic Planning*).

1.2. The need for this research

The Dynamic Scheduling (DS) topic has gone through various researches and publications within the manufacturing industry during the last two decades. However, it is still a quiet new topic in the construction scheduling field; and there is a shortage in the DS literature in relation to construction industry. This can be due to the complex & in-deterministic nature of construction processes which might have concerned researchers about the successful outcomes of researching this topic; or, as generally stated by *Flanagan & Marsh (2000)*, due to the significant barriers preventing construction organizations from investing in IT solutions due to the uncertainty concerning identification and measurement of benefits associated with their development.

The problem of scheduling in the presence of real-time events is of great importance for the successful implementation of scheduling systems in construction enterprises. Various researches should be generated to investigate the issue of how to handle the occurrence of real-time events during the execution of a given schedule, in regard of how and when to run the repair or the optimization algorithms to the current static schedule to bring it back to the optimal or near-optimal state.

In addition, managing construction projects based on single project strategies was found to result in limited success *(Blismas et al, 2004-a, 2004-b)*. Accordingly, including the enterprise dimension in the research will support maximizing the benefits from its outcomes.

1.3. Research aim

The aim of this research is to develop a dynamic scheduling based solution which can be practically used for real time analysis and scheduling of construction projects from design to handing over, in addition to resources optimization for construction enterprises.

1.4. Research objectives

Since the aim of the research is to develop a practical solution, and the current scheduling practice is mainly dependent on commercial project management software packages, then the nature of the proposed solution is dictated to be a dynamic scheduling model, operated through a software tool compatible with the most popular packages available in the market.

The main function of this dynamic scheduling solution and the associated software tool is the optimization of schedules in a dynamic environment; so, for this solution to be functional, the following objectives were to be fulfilled:

1. Performing literature review for static scheduling techniques and the modelling concepts of the scheduling problem.
2. Performing literature review for dynamic scheduling concepts and practices, and study the prospects of their application in construction.
3. Performing literature review for optimisation techniques, and selecting the technique to be used based on the suitability of its characteristics to the problem under study.
4. Developing the proposed solution's framework which suits the investigated construction planning & scheduling process.
5. Developing a mathematical model representing the reality and complexity of the construction scheduling problem.
6. Developing an optimization algorithm based on the formulated model's structure.

7. Defining the functional specifications of the proposed software tool from the experienced opinion of construction field practitioners.
8. Developing the software tool based on the formulated model, the developed algorithm and the gathered functional specifications.
9. Verifying the proposed solution's elements using sample of the problem sets, as well as the application of real projects' data to simulate the real time dynamic environment.
10. Validating the model, as well as the software tool, based on the opinion of field practitioners using validation forms.

1.5. Research approach

To achieve the above mentioned objectives, several processes were conducted as summarized in Figure 1.1.The research approach and methodology will be detailed in Chapter 2, with a justification for the reasons beyond the selection of each of the applied research methods.
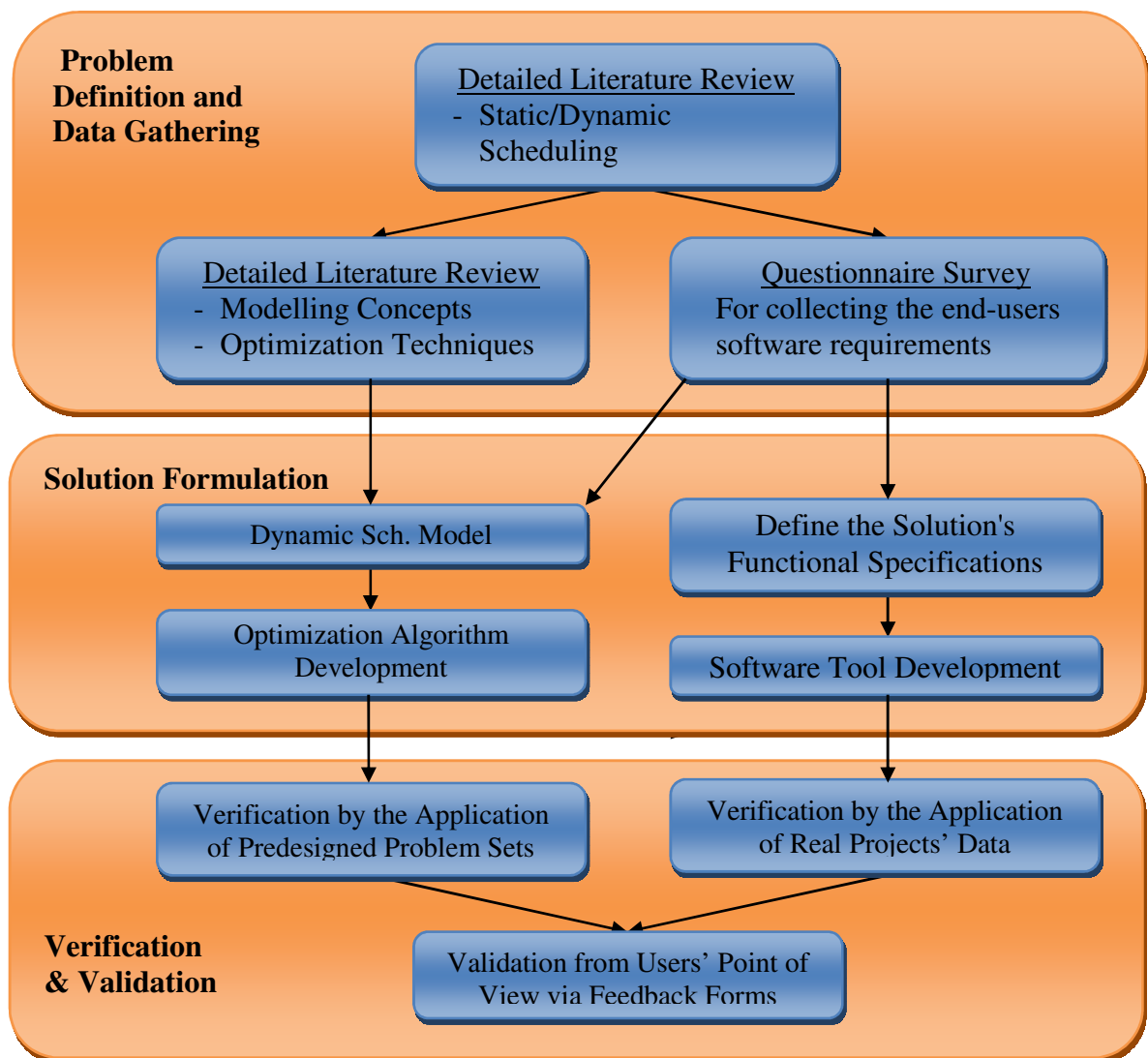
Figure 1.1: Summary of research approach

Chapter 2: Research Methodology

2.1. Introduction

In considering the appropriate research design, researchers must consider to which research community they believe they belong; as well as the assumptions of their research (Remenyi et al. 1998).

This section will briefly review the philosophical communities of research, and accordingly classify to which philosophy this research belongs. It will also define the research methodology adopted, and summarize the other research methodologies reviewed in the context of construction, management and business research methods.

2.2. Research philosophy

Epistemology and Ontology (Crotty, 1998), Research Paradigm (Mertens, 1998; Lincoln and Guba, 2000), Research Worldview (Guba, 1990; Creswell, 2009) and *Research Philosophy (Fellows and Liu, 2008)*, are all synonyms of the same subject, which can be defined as *"The principles that guide the process in extending knowledge and seeking solutions towards the research problems" (Fellows and Liu, 2008).*

In the same trend, various classifications were presented for research philosophies; each categorized the research paradigms from a different conceptual angle. The classification of *Creswell (2009)* was chosen for further elaboration, in which the classification process was presented in almost the same perspective as that of many other research design/methods references. *Creswell* categorized the research philosophies into four main categories (or *Worldviews* as he named them):

- *Postpositivism*

    Positivism, *Postpositivism*, *Scientific Method*, *Empirical Science*, and *Hypothetico-Deductive Method* are all commonly used names for this philosophical school. This approach is what simply will come to most people's mind when the word *Research* is mentioned. It is an applied research through which contends that if variables are isolated and separately manipulated, observations should be repeatable. It is more oriented toward quantitative research strategies. In general terms, this approach involves defining the problem under study, data gathering, hypothesis formulation and empirical verification.

- *Constructivism/Interpretavism*

    Constructivism approach, which is often combined with the *Interpretavism* approach *(Mertens, 1998; Creswell, 2009)*, is a

basic/fundamental research, which contends that real world facts can only be understood through subjective interpretation. It is more oriented toward qualitative research strategies. The outputs of this approach can be in the form of a newly generated theory, or the construction of a historical or social facts interpretation.

- *Pragmatism*

  Pragmatism philosophy is based on using all the available interpretations of the problem under study in order to further emphasize the understanding of the problem details. This approach is commonly used in Social Sciences; it focuses the attention on the research problem, and then derives further knowledge about the problem using pluralistic approaches.

- *Advocacy/Participatory*

  Another social oriented approach, which arose during the 1980s and 1990s from individuals who felt that the *Postpositivism's* assumptions imposed structural laws and theories that did not fit with marginalized individuals *(Creswell, 2009)*. It presented few forms of inquiry which suits diverse groups, a summary of these were presented by *Kemmis and Wilkinson (1998)*.

2.3. Research design

The research design is the process of defining the overall *Research Methodology* (or *Research Strategy*), as well as choosing the *Research Methods* to be implemented for fulfilling the research objectives.

2.3.1. Research methodologies

In contrary of other aspects and terminologies of research, there is a common identification and classification of *Research Methodologies*; which are commonly identified and classified into three types:

- *Quantitative research approach*

  Quantitative approaches seek to find out why things happen as they do; to determine the meanings which people attribute to events, processes and structures, etc. *(Fellows and Liu, 2008)*. As mentioned in the research philosophies, quantitative approaches tend to relate to *positivism* than other research paradigms.

  This approach represents the means for testing theories through the detailed examination of their variables and the inter-variables relations. It uses scientific techniques for obtaining data, analysing them, and producing results and conclusions.

The research path can contain one or more quantitative research methods arranged sequentially or in parallel according to the research plan and objectives.

- *Qualitative research approach*

    In qualitative research, an exploration of the subject is undertaken without prior formulations; the object is to gain understanding and collect information and data such that theories will emerge *(Fellows and Liu, 2008)*. As mentioned in the research philosophies, qualitative approaches tend to relate to *Constructivism (or Interpretavism)* than other research paradigms.

    This approach represents the means for exploring and understanding how different groups or individuals react against certain problems. It uses non-scientific techniques for obtaining data, while the analysis is left to the researcher's interpretations with respect to the meaning of the collected data.

    The research path can contain one or more qualitative research methods arranged sequentially or in parallel according to the research plan and objectives.

- *Mixed research approach (triangulation)*

    From its name, mixed research or the triangulation approach is a combination of both quantitative and qualitative approaches; it benefits from the advantages of both approaches, by eliminating the disadvantages of one approach for certain research process by using a method from the other approach.

    Several mixed strategies were presented in literature; however they can be generalized to three main strategies, which are having other variations and extensions:

    o *Sequential Mixed Methods:* This is a combination of more than one method from both qualitative and quantitative approaches, arranged in certain sequence, so that one method expands or elaborates the results of another method.

    o *Concurrent Mixed Methods:* This strategy aims to produce a comprehensive analysis of a certain process of the research by combining or comparing the data or results of quantitative and qualitative methods.

    o *Transformative Mixed Methods:* Methods involving the use of a theoretical lens or perspective to guide the study; concurrent or sequential methods can be implemented within this lens.

This design gave primacy to value-based, action-oriented research such as in *Participatory Action Research* and *Empowerment Approaches (Creswell, 2009)*.

2.3.2. Research methods

Research methods involve all the research project steps, which make them directly affecting the research inquiries, results, conclusions, validity and reliability of the research. So, the proper selection of research methods is the key for the research success.

The knowledge of different research method alternatives, and consequently the proper selection of the most suitable research methods, can be claimed to lead to the easiest approach for the fulfilment of research objectives, and can also lead to the achievement of highest probable research outcomes. The following points briefly review the most commonly used research methods categorized by the research methodology they belong to, based on a combined review from the classifications of *Nissen et al (1991)*, *Guba (1990)*, *Crotty (1998)*, *Mertens (1998)*, *Fellows and Liu (2008)*, and *Creswell (2009)*:

- *Quantitative methods*
  - *Experimental:* The research method aims to determine the influence of variables and conditions on the outcomes of a certain topic. Experiments are conducted according to an existing theory with variables and conditions manipulation. Then results are concluded for the influence of different variables and conditions.
  - *Quasi-Experimental Research:* It is an Experimental Research method in which the ability to control variables is limited, which might cause accuracy problems in results.
  - *Questionnaire Survey:* This research method aims to provide a numerical description of behaviours, trends or peoples opinion for certain topic. The data to be collected is designed in the form of a list of questions distributed on the participants via post mail, e-mail or even hand delivery. Then responses are statistically analysed for generalizing the results of the surveyed sample on the overall survey population.
  - *Structured Interviews:* In this survey method, the researcher extracts the views and opinions of the interview participants via closed-ended questions. Interviews can take place in a face-to-face form, or through telephonic conversation.

- o *Review Forms:* Review Forms or Feedback Forms are a special case of *Questionnaire Surveys* or *Structured Interviews* in which the researcher aims to collect the participants' opinion about one of his research outcomes/results. The sample to be chosen does not have to represent the entire population, and the participants can be randomly selected or specifically identified based on a certain criteria.

- o *Quantitative Case Studies:* Case Studies can be Quantitative or Qualitative in nature based on the researcher's approach. It involves in-depth, contextual analyses of a single individual, group, organization, process, event, or project. Data is collected over a sustained period of time using a variety of data gathering methods.

- *Qualitative methods*
  - o *Ethnography:* The aim of this method is to collect data for a certain cultural group. The researcher remains studying the group for a prolonged period in its actual natural settings, and develops his research based on the factual realities he observes.

  - o *Grounded Theory:* Is a research method in which the researcher derives a general, abstract theory of a process, action, or interaction grounded in the views of participants *(Creswell, 2009)*.

  - o *Case Studies:* As explained in quantitative methods.

  - o *Qualitative Interviews:* Also called *Unstructured Interviews,* is a research method in which the researcher extracts the views and opinions of the interview participants via open-ended questions. This method is needed mainly when the opinions of the participants are partially or fully unexpected, which makes the researcher unable to put all response alternatives in a closed-ended questions.

  - o *Phenomenological Research:* In this method, the researcher brackets or sets aside his or her own experience in order to understand those of the participants of the study *(Nieswiadomy, 1993)*. This method aims to describe certain phenomenon through gathering and understanding the human experiences of research participants.

  - o *Action Research:* Action research involves active participation of the researcher in the process under study, in order to identify, promote and evaluate problems and potential solutions *(Fellows and Liu, 2008)*.

o *Narrative Research:* The output of this research method is a collaborative chronological narrative which combines the researcher's life with the participants' lives and stories.

2.4. Current research philosophy and methodology

2.4.1. Current research philosophy

According to the summary of research philosophies presented earlier in this chapter, and as presented in Figure 2.1, ***this PhD research can be claimed to follow two paths of the Hypothetico-Deductive (or Postpositivism) approach***; because the research was mainly consisting of two partially interacting paths, where each of them resembles the main steps of the *hypothetico-deductive* approach. The research process can be summarized as follows; while the full research processes will be further detailed and explained in the next sections:

- *The model formulation path:*
  This path contained a problem definition & data gathering (detailed literature review) proceeded by formulating the first section of the proposed solution (the proposed dynamic scheduling model including the mathematical model and the optimization algorithm), which finally was verified through the application of predesigned problems.

- *The software development path:*
  After the problem definition & data gathering (stated in the first research path), a separate data gathering (the questionnaire survey) was also included. This was proceeded by formulating the second section of the proposed solution (the developed software tool for applying dynamic scheduling in construction projects), which finally was verified through sample of the same problem sets used in the verification process of the formulated model, as well as a case study application using real projects' data.

- *Research validation:*
  Finally, both paths were validated through presenting the verification results to field experts, and collecting their opinions (via validation forms) about the validity and practicality of using the proposed dynamic scheduling solution in the construction industry.

2.4.2. Selection and justification of the research methods

According to the pervious review of research methodologies and methods, and as presented in Figure 2.1, ***this PhD research followed a triangulated quantitative/qualitative approach***, where most of the research methods were quantitative with the need of some qualitative measures in the case study and the validation process.

The research was conducted in two concurrent research paths, the following points explain the research processes and the objective of each; and accordingly explain and justify the selection process of the various methods adopted in this research:
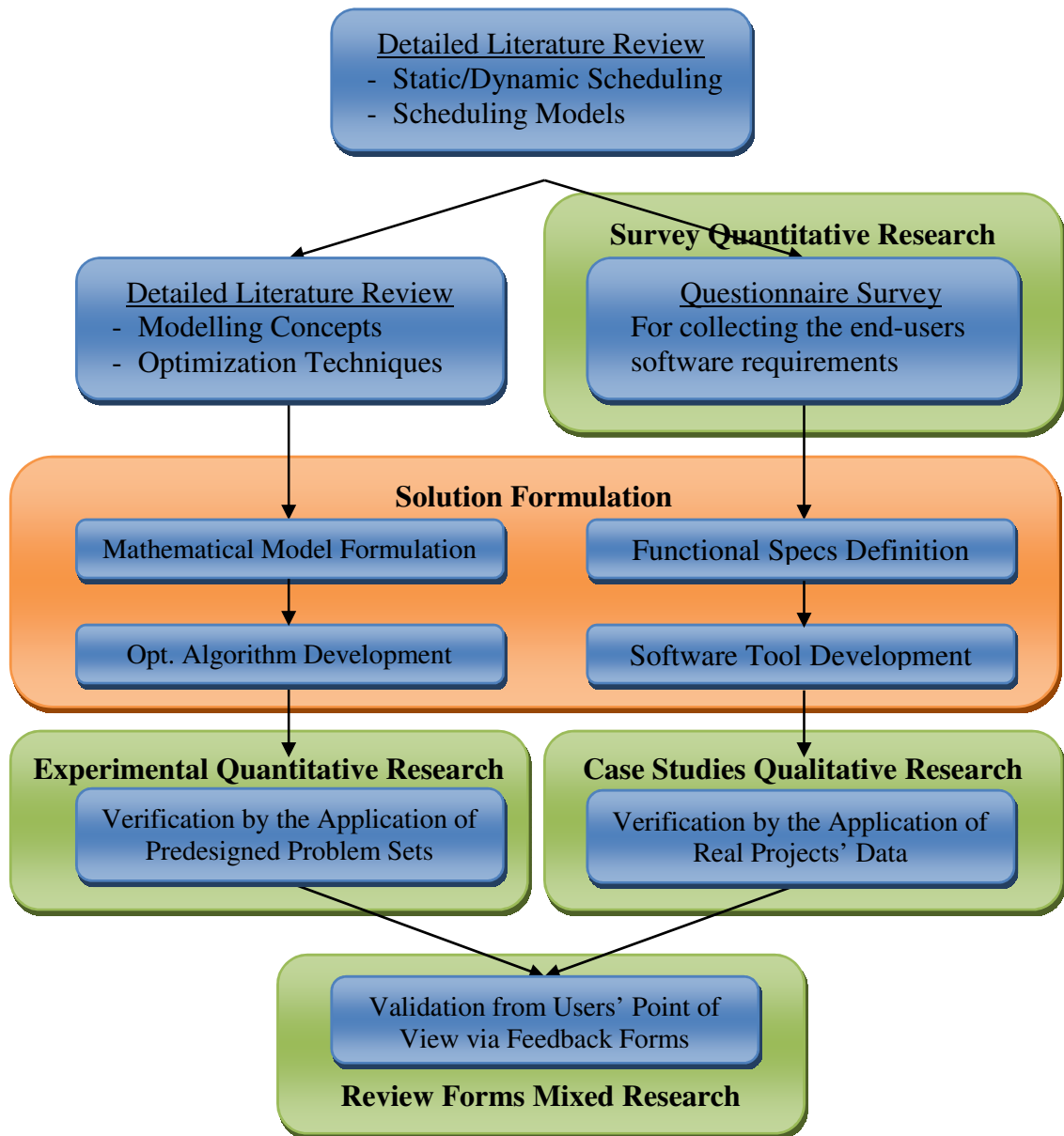
Figure 2.1: Adopted research methodology

o *Collecting end-user's requirements:* In this process, the research aims to collect a group of data to investigate the problem under study from a practical perspective, and identify certain features for the proposed solution. The problem variables (activities, resources, logic relations …etc.) are clearly identified in the scheduling literature, which makes the questions to collect the participants experienced opinions about the practicality of each feature *closed-ended questions*. So, collecting the

data with closed-ended questions can be done by either *Questionnaire Survey* or *Structured Interviews*. Structured Interviews will cover few planners/experts which might make the opinions biased towards the specific opinions of the selected participants, and with the opinions of the researcher's surrounding environment. So, in order to have wide geographical spread and several opinions from different expertise levels and roles, the *Questionnaire Survey* is the most appropriate method for the required purpose, and publishing the survey on the internet ensured the spread of participation.

- o *Solution formulation:* There is a considerable deficiency in the current scheduling practice in regard of the large time required by planners to optimize their schedules during preparation of baseline schedules, revised schedules, and schedule updates. So, the required solution needs to take care of this optimization process, and be consistent with the current practice in order to ease the familiarization process with the new tool.

  The current practice is mainly dependent on commercial project management software packages, which dictates that the research *hypothesis* to be a dynamic scheduling model, operated via software tool compatible with these packages. And for this tool to be operational in optimizing schedules, a built in optimization technique needs to be programmed as well. This optimization technique cannot work directly on the raw data present in the projects' databases, it needs variables, constraints and a single/multi objective function to optimize, which is typically the definition of a Mathematical Model.

  In summary, to solve the above mentioned research requirements, a *Mathematical Model* needs to be formulated representing the scheduling problem, an *Optimization Algorithm* needs to be generated to optimize schedules dynamically, and a *Software Tool* needs to be designed and programmed to receive the project related inputs, analyse them, produce optimized solutions, and present them.

- o *Model verification process:* The aim of this process is to check that the formulated model produces acceptable solutions in terms of optimization quality and in terms of analysis time. For this to be efficiently done, the optimum/near optimum solution needs to be identified before applying the problem to the model. So, the problems need to be set, the solutions need to be identified, and the efficiency and the influence of the problem size need to be tested; this gives us the clear definition of *Experimental Research Method*.

- o *Verification of the software tool:* The outputs of the model were tested in the previous process with respect to its optimization capabilities; so,

this process is only concerned with verifying the model and the optimization algorithm; this is done mainly using defined problem sets, and accordingly this verification can be considered as static. However, an additional process is required to test the software tool, as well as the dynamic features of the model.

The ideal solution for this verification process is to apply a case study using actual data from real project(s), and check the software's stability under real-time conditions, and the optimization capabilities of the model under dynamic environment. The projects' data to be applied are activities, relationships, resources, progress figures, etc.; where the optimization results cannot be verified under the large size of project schedules; which makes the research method as a *Qualitative Case Study.*

o *Validation of the model & the software tool:* The aim of this process was to get the feedback of field experts about the verification outputs quality, and the practicality of the proposed solution. This feedback must not represent all the fields' experts, but it needs only to give an indication whether or not the solution developed solved the deficiencies present in the current practice. This makes the *Review Forms Research Method* the ideal method for this process with a mixed *Quantitative/Qualitative* approach based on the survey design.

2.5. Research process

The research process is the definition of the research detailed steps and their interrelationship. Figure 2.2 is a self-explanatory chart showing this research's process, where each step in the research is clearly identified, and a number was marked beside each process to indicate in which chapter it will be explained in details. The following points briefly summarize the work performed under each of the research processes:

- *Dynamic planning/scheduling literature review:* A detailed review of the dynamic planning/scheduling field; current status and future prospects, mainly oriented towards construction industry.

- *Scheduling optimization models literature review:* A detailed review of the models generated for the optimization of different scheduling problem types.

- *Optimization techniques literature review:* A detailed review of the optimization techniques used in the scheduling context; and selection of the technique that suits the generated model. In addition to review of the scheduling optimization algorithms presented in literature, and review of their performance with respect to standard benchmarks.
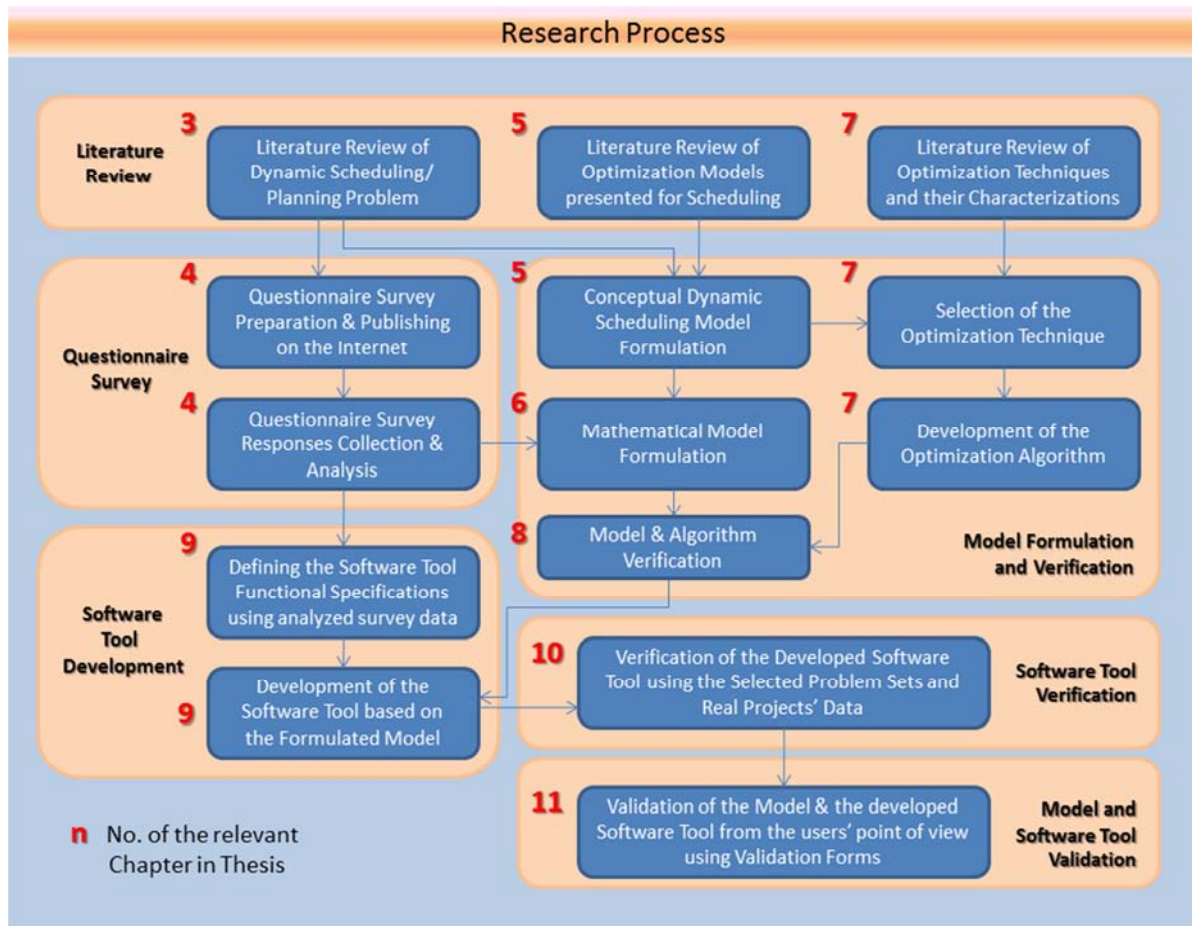
Figure 2.2: Research processes chart

- *Questionnaire survey design and distribution:* The process of investigating the details of the problem from a practical perspective, and collecting the proposed solution's functional variables, through a questionnaire survey distributed to field experts. The survey was published on the internet to ease the process of invitations distribution, as well as the responses collection.

- *Conceptual model formulation:* The process of building the concepts of the proposed dynamic scheduling model based on the reviewed modelling theory and state of the art practices, along with the collected and analysed survey data.

- *Mathematical model formulation:* A generalized problem mathematical model was compiled from the relevant literature review, and then the model was adjusted with few inputs from the survey to match practical construction related considerations.

- *Optimization algorithm development:* The process of selecting the optimization technique, and developing an optimization algotithm which suits the required operability of the dynamic scheduling model.

In addition, few modifications were performed and presented for the scheduling algorithm's elements and the optimization technique to improve the output solutions quality.

- *Model & algorithm verification:* Applying predefined examples for testing the ability of the model and the algorithm in reaching, statically, the optimal / near-optimal solution. The examples were selected from the most popular benchmark problem sets presented in literature. In parallel, continuous attempts were made for adjusting the model and the algorithm in order to increase their optimization capabilities and reduce the analysis time.

- *Defining the software tool's functional specifications:* The responses of the questionnaire survey were collected, grouped and analysed. Then, the analysed data was used to identify the functional specifications of the software tool which was used to verify & validate the model.

- *Development of the software tool:* The generation of the software tool to be used as a user interface for interacting with the model. This involved compiling the developed model & algorithm with the created user interface developed to enable entering the projects/enterprise details required for optimization, as well as viewing the analysis results. The software was also programmed with import/export capabilities to enable a fully integrated solution, as advised by the survey participants.

- *Software tool verification:* Applying a case study using real projects' data to verify the outputs of the software tool, and the dynamic features of the model under simulated real-time conditions.

- *Model & software tool validation:* A combined validation process for both the model and the software tool via validation forms. Where the verification results were grouped and presented to field experts and their opinions were collected for the practicality of the proposed solution.

2.6. Research scope

The dynamic scheduling model was formulated to contain almost all aspects (or variables) required for the optimization process of construction project schedules. The developed software tool was based on the formulated model, and functionally developed based on the construction industry's requirements.

However, the model and the software tool were developed project oriented; so, the proposed solution can be applicable to construction industry, as well as any other industry with project-based scheduling process.

Chapter 3: Dynamic Scheduling Review

Project Scheduling, especially in the construction field, is inherently complex and dynamic, involving multiple feedback processes and nonlinear relationships. While problems encountered during construction are fundamentally dynamic, they have been treated statically within a partial view of a project *[Lyneis et al, 2001]*. As a result, schedule delays and cost overruns are common in construction projects in spite of advances in construction equipment and management techniques. To overcome these chronic symptoms, enormous efforts have been devoted to the planning and control aspects of construction management *[Lee et al, 2006]*.

Most of the research efforts presented in the project scheduling context, whether oriented for construction industry or for other industries, are concentrating on performing the scheduling analysis in a static deterministic environment, assuming all the required information is well known, and assuming that the actual physical work will run on the predefined track during execution. However, this static approach of scheduling is impractical to real world scheduling, and the optimal or near-optimal solutions generated will become obsolete from the beginning of the project execution when actual regular or irregular events start occurring.

The concept of solving the limitations of static scheduling is termed *"Dynamic Scheduling" (Suresh & Chaudhuri, 1993)*, *"Real-time Scheduling" (Kim, 1994),"Dynamic Planning" (Lee et al, 2006)*, or *"Scheduling under uncertainty" (Herroelen & Leus, 2005)*. However, the term *Dynamic Scheduling* is the most commonly used in recently presented researches (*Ouelhadj & Petrocic, 2009; Aissani et al, 2009; Fattahi & Fallahi, 2010*).

Dynamic Scheduling, as many other scheduling concepts, started and developed in the manufacturing industry; consequently, the majority of approaches, strategies and policies presented in the literature were mainly focusing on manufacturing systems and applications. However, the approach followed in this chapter was to explain the concepts of dynamic scheduling as presented in the literature, and to orient the explanation, as much as possible, toward the construction industry perspective.

3.1. Real-time events

Real-time events which cause disruptions to static scheduling were discussed and categorized differently in several surveys and researches *(Suresh & Chaudhuri, 1993; Stoop & Wiers, 1996; Cowling & Johansson, 2002; Vieira et al, 2003; Ouelhadj & Petrovic, 2009)*. From a construction industry point of view, real-time events can be classifies into three main categories:

- *Project related events:* Additions or omissions to the project's original scope (through change orders, or design changes), changes to the project's due dates or milestones, changes to the predefined sequence of work due to changes in priorities of the project's deliverables, delays in governmental or authorities approvals, effects of inclement weather, force majeure events (ex. floods or earthquakes), etc.

- *Resource related events:* Shortages of material, arrival of defective material/equipment, breakdowns of construction machinery on site, delayed arrivals of specialized resources, insufficient capacities of assigned resources, sickness or death of key resources, etc.

- *Operations related events:* Quality rejection of outputs, changes in deliverables specifications, prolongations in operations durations (due to incorrect estimates for resources productivities, incorrect estimates for equipment set-up times, or manpower learning curves), unexpected behaviour of predefined design elements (for example unsatisfactory results of soil tests after the completion of ground improvement works), etc.

3.2. Dynamic scheduling categories

The effect of any of the above mentioned real-time events to the efficiency or even the correctness of a predefined schedule might be drastic; which, in some cases, might require a complete rescheduling of the project. Dynamic Scheduling defines the strategy of how to generate the original baseline and the strategy of how to respond to real-time events.

There are three main categories (or strategies) for Dynamic Scheduling which have been listed in the reviews of *Aytug et al [2005]*, *Herroelen and Leus [2005]* and *[Ouelhadj & Petrovic, 2009]*:

3.2.1. Completely reactive scheduling

In this category, no baseline schedule is required, and real-time decisions are made locally, on the resource level, where the next activity to be executed by the resource is selected based on its priority (or predefined criteria) from the list of activities ready for execution. The benefits of this approach can be clearly acknowledged from the extremely low computational burden required for the analysis; in addition to the ease of
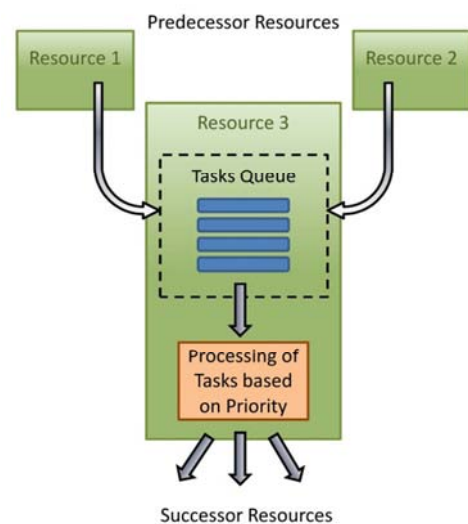
Figure 3.1: Completely reactive scheduling

explanation and understanding of its concepts and rules to the system users.

This type of scheduling is mainly used in manufacturing for on-spot scheduling of machine operations, and termed as *"Dispatching" [Bhaskaran & Pinedo, 1991]* or *"Priority Rule-based Scheduling" [Haupt, 1989]*. Extensions to this approach were made in the direction of allowing the system to select the dispatching rules dynamically based on the current system conditions (approach introduced by *Wu and Wysk [1989]*).

Despite the fact that the concept of working without a schedule and prioritizing the work on a real-time basis is widely present in small construction companies and projects; however, the use of dispatching rules and a computerized system for the selection process, which is the core of this technique, is not used in the construction industry; concluding that the whole approach is not implemented in construction. In addition, the concept of not having a baseline schedule sounds like a disaster for moderate/high controlled construction projects.

3.2.2. Robust pro-active scheduling

This scheduling approach is based on building predictive schedules with studying the main causes of disruptions and integrating them into the schedules which, predictably, can accommodate changes in a dynamic environment. The disruptions are measured based on actual completion measures compared to the originally planned completions; then the mitigation of these disruption are mitigated through simple adjustment to the activities durations. *Mehta and Uzsoy [1998, 1999]* and *Vieira et al [2000-a, 2000-b]* proposed various analytical models for predictive schedules preparation. This was followed by the development of a mathematical programming model by *Herroelen and Leus [2004]* for the generation of a stable project baseline schedule.
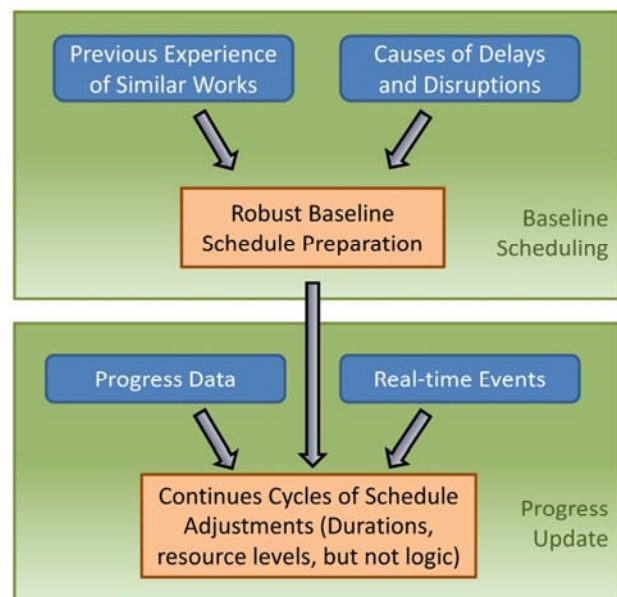
Figure 3.2: Robust pro-active scheduling

The conditions of this technique can be assumed to be similar to many cases in construction planning, where a baseline is produced, then updated periodically with actual progress figures and remaining durations, without adjustments to the original schedule logic. This case is common in traditional

and regular construction projects, where the work sequence is clearly deterministic and the disruption probability is relatively low.

3.2.3. Predictive-reactive scheduling

The most common dynamic scheduling approach used in manufacturing systems *[Ouelhadj & Petrocic, 2009]*. The main concept of Predictive-reactive Scheduling is that a simple (or predictive) baseline schedule is generated initially, then rescheduled (logically revised) based on real-time events. The time, triggering event type and the magnitude of the schedule revision should be predefined in the system through a rescheduling policy and strategy (as explained in the next sections).

Similarly to the case in manufacturing industry, the predictive-reactive scheduling

Figure 3.3: Predictive-reactive scheduling

is the most commonly used technique in construction industry. However, there are two major deficiencies which can be easily spotted in the implementation of this approach in construction. First, the preparation of a predictive (or robust) schedule is purely dependent on the planners' opinion and experience. Secondly, rescheduling process is always performed manually, and again its quality depends on the planners' opinion and experience, which in many cases (especially large scale projects) will produce solutions far from the optimal solution, and in some cases the revised schedule will cause further disruptions to the project's earlier defined plans and strategies (resource levels, subcontractors time frames, material/equipment delivery dates, etc.). *So, this research is aiming to tackle this deficiency and work on automating the rescheduling process in a predictive-reactive environment*.

Since the predictive-reactive scheduling is the most common and professional dynamic scheduling technique followed in construction, and that the approach of the model to be presented in this research will be based on its concepts. The following sections present a further review performed to investigate rescheduling policies, strategies and techniques.

3.3. Rescheduling policies

The rescheduling policy, in general terms, is an answer to the question of **when** to respond to real-time events. Three policies were presented in this context *(Church and Uzsoy, 1992]; Sabuncuoglu and Bayiz, 2000; Vieira et al, 2000-a, 2003; Aytug et al, 2005)*:

- *Periodic rescheduling policy:* Where the rescheduling process is started every predefined time interval regardless of the amount of real-time events which occurred during this period.

- *Event-driven rescheduling policy:* The scheduling process is triggered with the occurrence of any disruptive real-time event.

- *Hybrid rescheduling policy (Rolling time horizon): T*he rescheduling process takes place periodically regardless the in between events; however, certain predefined events can trigger the start of a new intermediate rescheduling process.

In construction industry, scheduling/rescheduling processes are performed in a periodical basis, grouping all events which occurred in between. Accordingly, the Periodic rescheduling policy is the most suitable policy for the construction industry, because it covers the main requirements of construction real-time environment: rescheduling when major events occur (as defined by the system users), and periodical minor rescheduling which is usually required to optimize the resources usage based on the current project status. This statement will be further investigated in the construction practitioners survey presented later in this research.

3.4. Rescheduling strategies

The *rescheduling strategy* & the r*escheduling techniques* represent the answer to the question of **how** to respond to real-time events. The *rescheduling strategy* is concerned about the mass of the changes to be made, while the *rescheduling technique* is concerned about the method or the approach to be followed to revise the schedule. Two main strategies were presented in this context *(Sabuncuoglu and Bayiz, 2000; Cowling and Johansson, 2002; Vieira et al, 2003)*:

- *Schedule repair:* The schedule repair is the process of mitigating the real-time event through minimum adjustments to the schedule portion related to the event. The major benefit of this strategy is the saving of computational burden.

- *Complete rescheduling:* Is the process of regenerating the project schedule from scratch. This strategy is practically not preferred due to the required computational time and effort, despite of the fact that it helps in maintaining the near-optimum solution.

For construction industry, both strategies must be implemented depending on the type and magnitude of the corresponding real-time event, and also depending on the allowable changes from a contractual perspective.

3.5. Rescheduling techniques

The rescheduling technique represents the methodology or algorithm which a computerized system will use to repair/reschedule the project plan. The following techniques were presented in the context of dynamic scheduling:

3.5.1. Heuristic techniques

A heuristic is a technique that seeks good solutions at a reasonable computational cost without being able to guarantee either feasibility or optimality, or even in many cases to state how close to optimality a particular feasible solution is *[Reeves, 1995].*

In dynamic scheduling heuristics are problem specific, and are mainly used as schedule repair methods. As per *Ouelhadj & Petrovic [2009]* survey, the most common dynamic scheduling heuristics are:

- *Right-shift schedule repair:* The most common, but not efficient, schedule repair method. It is simply the process of updating the status of progressed activities, and shifting the remaining works forward in time based on their schedule logic. This is the regular update process used in construction, and almost all software packages available in the market use this repair method as a part of the CPM concepts.

- *Match-up schedule repair:* This method is oriented towards repairing the impacted schedule in order to match-up the repaired schedule with the original schedule at some point in the future. This concept is mainly used in construction under the name *Recovery Scheduling*; where the schedule is repaired in selective occasions when the mass of time impact of real-time events is larger than acceptable thresholds.

- *Partial schedule repair:* Only the impacted portion of the schedule is rescheduled. This is also common in construction industry, where the impacted portion is rescheduled, and either presented along with the progress updated schedule or sometimes presented separately from the controlled schedule, in order to expedite the related site works without impacting the contractually tracked schedule.

- *Dispatching rules:* It is the rescheduling method used with the *Completely Reactive Scheduling* approach, where decisions are made locally at the resource level without working with a main schedule. As explained before, this scheduling approach, and consequently the *Dispatching Rules*, is not used in construction field; however, its

concepts can be applied inside certain portions of constructions sites having architecture similar to that of manufacturing, such as precast yards and carpentry/rebar fabrication workshops.

3.5.2. Meta-heuristic techniques

These are high level heuristics which guide local search heuristics to escape from local optima. Meta-heuristics used in schedule repair/rescheduling are: *tabu search (Mehta and Uzsoy, 1999), simulated annealing (Zweben and Fox, 1994), genetic algorithms (Rossi and Dini, 2000; Chryssolouris and Subramaniam, 2001)*, and *Ant Colony (Xianga and Lee, 2008).*

These techniques are usually called Heuristic Techniques in other fields; however, dynamic scheduling is having few simple heuristic techniques as explained in the previous section; so, these were called Meta-Heuristics in the dynamic scheduling context because they are actually higher in complexity level than the other simpler heuristics.

3.5.3. Other artificial intelligence techniques

Dynamic scheduling is an ideal problem for studies in the AI field. Various researches adopted the problem and presented different AI approaches for its solution; these studies used *Knowledge Based Systems (Fox, 1994; Park et al, 1996; Le Pape, 1994; Henning and Cerda, 2000), Case-based Reasoning (Miyashita and Sycara, 1995), Neural Networks (Suresh and Chaudhuri, 1993; Meziane et al, 2000), Fuzzy Logic (Schmidt, 1994; Petrovic and Duenas, 2006)*, and some studies used hybrid systems between different AI techniques *(Jahangirian and Conroy, 2000; Li et al, 2000).*

3.6. Dynamic scheduling architectures

3.6.1. Single-agent dynamic scheduling

In most common planning and scheduling systems, the analysis process is done via centralized agent (central computer or database server), in order to ensure consistency of data and results. The centralized approach of the single-agent dynamic scheduling architecture can be claimed to create bottle-necks in the system work flow, and it consists of a single point of decision making which, if failed, causes the failure of the whole system (refer to *Parunak, 1996; Tharumarajah & Bemelman, 1997*).

3.6.2. Multi-agent dynamic scheduling

The multi-agent based technique proposes the introduction of several local decision points (or schedule analysis points) within the functional/supervision level, in order to deal with the analysis of local real-time events and perform local schedule repairs.

Two main architectures were presented for multi-agent based system: Autonomous architecture (Figure 3.4) and Mediator architecture (Figure 3.5). *Parunak [1987]* presented the concept of autonomous architecture, where local agents are completely responsible for generating and maintenance of their own schedules, and they cooperate directly with each other to generate optimal overall schedule for the entity (or project). This architecture is very effective in optimizing the analysis and decision time; however, it has one main drawback in the relative failure of local agents to produce near optimal solution for the entity. This drawback was addressed in mediator architecture (originally proposed by *Ramos, 1994*), where a mediator agent is introduced to support in the communication process between local agents for improving the efficiency of the overall schedule, which will also show further improvement with the increase in the application size.
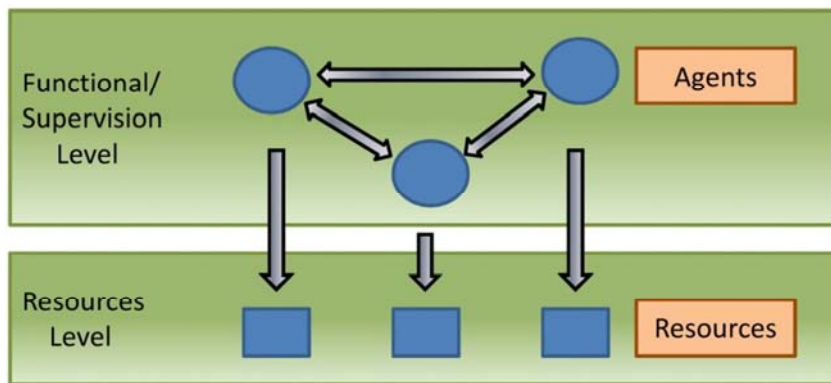
Figure 3.4: Autonomous dynamic scheduling architecture
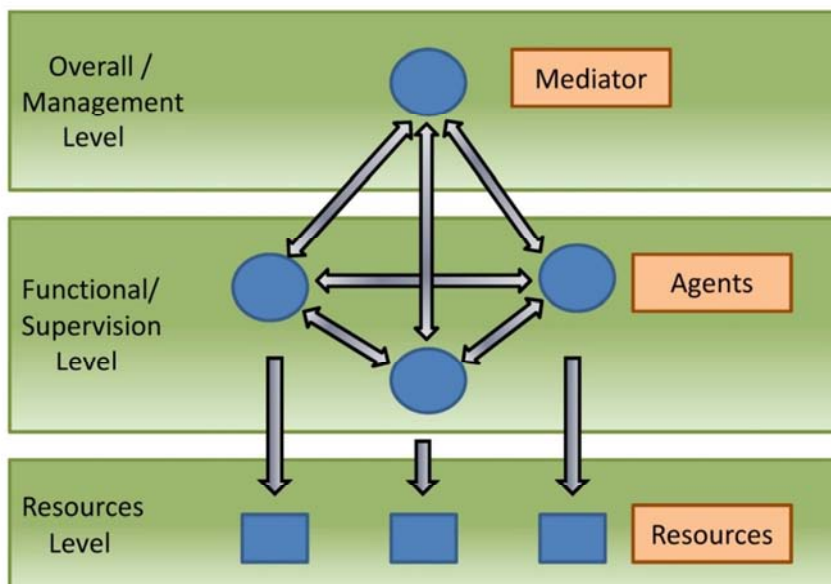
Figure 3.5: Mediator dynamic scheduling architecture

In manufacturing/other industries, which adopted dynamic scheduling in their applications (as shown in next section), *Mediator/Agents/Resources* are all computer based entities, where conditions are analyzed and decisions are made automatically.

In construction industry, the *Mediator* architecture is the common practice for the on-going planning process; however, it is implemented in a non-automated environment, and the project planner takes the responsibility of presenting the different alternatives with its advantages/ disadvantages to management level, and then manually incorporates the decisions made into the project's schedule. In a non-automated environment, this process becomes purely dependent on the capabilities of the planner to capture the different alternatives for all functional levels (*agents*) and to properly present it to management to support decision making; which might make the outputs of the overall process far beyond the optimum/near-optimum solution.

3.7. Dynamic scheduling applications

The dynamic scheduling concepts are widely used worldwide in various industries as stated below. The following examples are not intended to list all applications of dynamic scheduling; however, they only represent samples of how the dynamic scheduling concepts were implemented in different industries:

- *Manufacturing Industry:* Dynamic scheduling started and developed mainly in the manufacturing industry *(Ouelhadj & Petrovic, 2009)*; so, it is not fair to show the examples of dynamic scheduling applications without starting with the applications performed in the manufacturing industry.

  Applications in manufacturing can be categorized under two main production concepts: Make-to-order and Make-to-stock. Make-to-order, or the shop floor detailed scheduling (short term planning), is focusing on arranging the shop floor processes which have a predefined operations sequence in a multi-machine environment, in order to meet the supply orders received by the shop; while, the make-to-stock is focusing on the medium term planning and ensuring the continuity of machines operations, where the production in excess of the received supply orders will be stocked in the shop's warehouses.

  How to schedule the factory shop floor is mainly depending on the type of production and the constraints of the production processes. For instance, in steel production factory, the make-to-stock concept must be taken into consideration during assessing real-time events in order to ensure the continuity of work for the steel casting machines, which if scheduled to stop, will require long time to re-operate. *Cowling and Johansson [2002]* discussed how dynamic scheduling concepts can be applied to solve this problem.

  Where, in most cases, the better approach is to take into consideration both medium and short term schedules in the job floor scheduling.

Lagodimos et al [2004] presented this concept in an application on the production of commercial refrigeration units.

- *Computer Engineering:* Parallel computing, or the scheduling of parallel computer machines analysis is one of the famous optimization problems in the Computer Engineering field *(Jovanovic & Maric, 2001).* Applying real-time events caused by users' transactions requires the implementation of dynamic scheduling concepts. *Webster & Azizoglu [2001]* proposed solution algorithms & methodologies for solving this problem in real-time environment.

- *Logistics Industry:* The nature of logistics industry is very dynamic, where most of the required information is presented very shortly before its required processing time. *Liang et al [2009]* addressed the issue with an application on the dynamic scheduling of a quay crane in order to minimize the containers handling time, the waiting time and the delay time for each ship in a sea port.

- *Airline Industry:* Similarly in airline industry, *Warburg et al [2008]* presented a dynamic airline scheduling technique that is able to change departure times and reassign aircraft types during the booking process, in order to accommodate the fluctuating passengers' demands into the airline schedule.

- *Petroleum Industry:* In petroleum industry, safety regulations dictate irregular additions/omissions to the petroleum facilities maintenance schedules. Some maintenance tasks are done repeatedly, while others are identified dynamically. *Aissani et al [2009]* presented a multi-agent technique for the dynamic scheduling of maintenance tasks for petroleum production systems.

- *Construction Industry:* Despite of the wide practical applications of dynamic scheduling in many industries, the review performed was not able to locate automated dynamic scheduling applications within the construction industry, only few researches were found presenting frameworks for Dynamic Planning (such as *Lee et al, 2006*), and few resource allocation field practices especially in the maintenance and service based companies. ***So, the main purpose of this research is to present an easy to use, scalable and practical dynamic scheduling solution, which can be used in construction contracting enterprises without the need for additional tailoring efforts***.

Chapter 4: Prospects of Dynamic Scheduling in Construction Industry

The RCPSP has been categorized as NP-Hard problem since the mid of 1980s *[Blazewicz 1983]* & the problem characteristics have been deeply investigated and listed in various researches (as detailed in chapter 6). These characteristics are applicable to static schedule analysis, as well as dynamic schedule analysis (taking into consideration that the dynamic analysis is a periodical static analysis but with varying inputs for the analysis variables).

However, for construction industry, a survey was required to measure the mass of the problem under study from a practical perspective; and to group the analysis variables and output requirements from the day to day users' point of view, which will support the formulation of any model to be used for solving the Dynamic Scheduling problem from the perspective of construction industry.

This chapter will start with a quick review for the general processes performed within construction planning & scheduling. Then, the performed questionnaire survey will be reviewed, from design to results analysis; and the proposed solution's functional specifications will be extracted accordingly. And finally, an initial framework for the proposed dynamic scheduling solution will be presented, which will be further detailed in the next chapter.

4.1. Construction planning & scheduling process

For the construction industry, or any project based industry, the planning & scheduling process is almost the same. According to the Programming section of the construction contracts template defined by the International Federation of Consulting Engineers (known as *FIDIC*; acronym for its French name *Fédération Internationale Des Ingénieurs-Conseils*), figure 4.1 was prepared under this research as a generic chart to explain the details of project based planning & scheduling process.

The process starts with the preparation of a master schedule, which involves the collaboration of several functions within the project to produce a workable time plan respecting all contractual constraints, as well as the contractor's internal constraints. The master schedule is then submitted for approval; in construction industry, the approval party is usually the project's main consultant, but for some other project based industries or even for few cases in construction where the project is owned by the contractor, the approval party is the contractor's project and/or top management. If the schedule is commented, another approval cycle is added to the process, including the comments incorporation and the schedule resubmission. After the schedule is approved, it is then passed to execution process.

In each project, the progress reporting process is either defined contractually or through mutual agreement at the project's initial stages. The reporting process mainly defines how and when the schedule progress updates are going to be prepared and submitted.
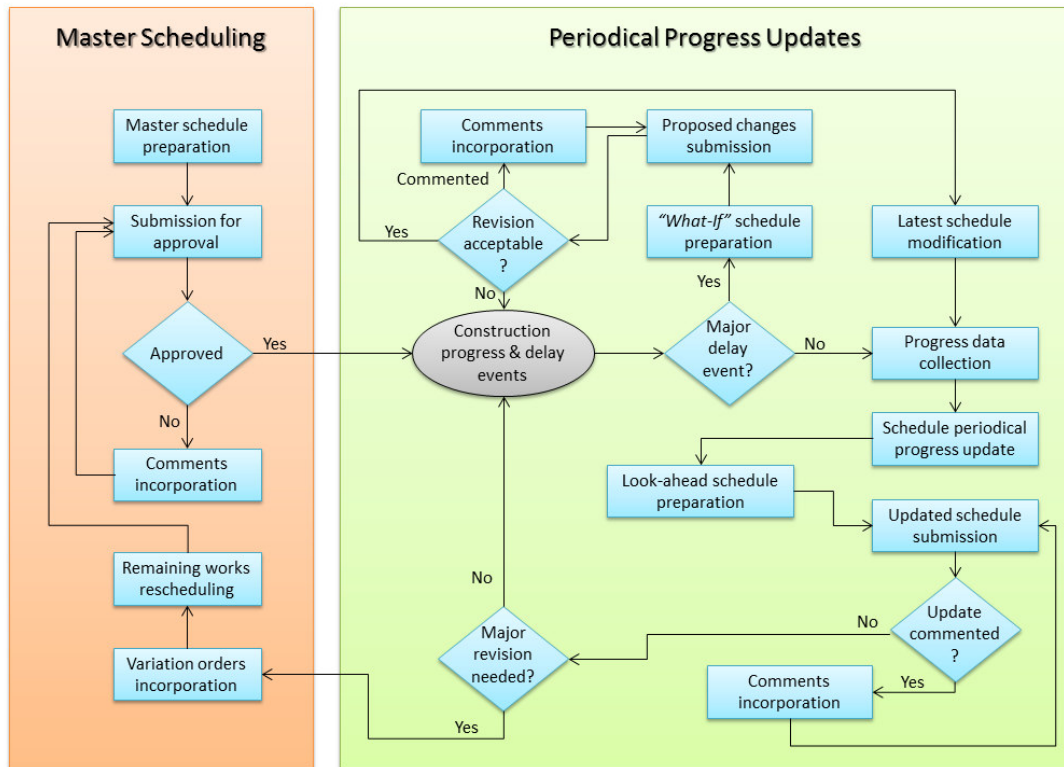
Figure 4.1: Project based planning & scheduling process

During each periodical progress update, four main processes are performed, which are subjective to the level of time control required: (1) checking the need for a *What-If* schedule and preparing it, (2) the regular progress update, (3) preparing a look-ahead schedule, and (4) checking the need for a major schedule revision. The *What-If* schedule is a minor schedule revision, and it is basically needed if a major delay event occurs (or a group of minor delay events with the effect of a major one), which causes partial disturbance to the schedule logic and requires partial re-arrangement. The *What-If* schedule is prepared using the latest progress update schedule, and submitted for approval. If the concept of producing a minor schedule revision is not acceptable to the approval party, then it is discarded, otherwise it undergoes an approval cycle(s), and then to be used for next progress update.

The regular periodical schedule progress update involves collecting progress data, updating the status of activities, performing progress analysis, and submitting the progress update. In closely monitored projects, each progress update might undergo a separate approval cycle which ensures the

validity of the included progress data, and that the progress update did not mess up with the main schedule logic (or the contractor's original intent).

In construction projects, there is usually a contractual, as well as practical, requirement to produce look-ahead schedules; which represent a schedule extract for the upcoming 2 to 6 weeks (depending on the agreed process) to be issued to construction team for implementation. Look-ahead schedules can either be a separate scheduling process with more details than the master schedule, or it can be prepared and extracted from the progress updates (if the schedule contains the sufficient details). For the sake of generalizing the process, look-ahead schedules were included here as part of the progress update process.

Finally, after the progress update is issued and approved (if applicable), the schedule is checked for the need of major revision. The need for issuing a major schedule revision can be caused by several reasons: the receipt of important/considerable number of variation orders, the receipt of an extension of time, or due to the occurrence of several separate delay events which largely disturbed the integrity of the baseline schedule. The schedule revision preparation includes incorporating all received variation orders until the schedule cut-off date, and then the remaining works are re-scheduled within the acceptable time/resource levels. The revised schedule is dealt with as a new master schedule; so, it undergoes a similar approval cycle, and it is issued for construction as a baseline after approval receipt.

4.2. Dynamic scheduling questionnaire survey

4.2.1. Questionnaire design

- *Objective:* The objective of the questionnaire was to gather the experienced opinion of field practitioners about the main problems they face with respect to schedules optimization and rescheduling processes, as well as their opinion about their expectations of what functions/features to be present in any proposed solution. This main objective was divided into few sub-objectives as explained in details in the following section (Questionnaire Details).

- *Population:* The problem under study is purely a construction scheduling problem; so, the population for the survey was mainly construction planners with their different levels of expertise.

- *Sample Design:* The purpose of the questionnaire was not to represent the opinion of all planners worldwide about the scheduling problems, but to get a general practical opinion about the problem and the proposed solution's outputs. In addition, the planning/scheduling process is now having some sort of common

practice concepts due to the presence of commonly accepted knowledge guidelines and the use of common software packages sharing same modelling concepts. So, the sample size just needed to represent different types of directly involved users (contractors/consultants planners), different expertise levels (senior/junior planners and management) which will identify different levels of requirements, as well as planners with different nationalities & with different working locations in order to have a broad opinion about the expected features of the proposed solution.

For the sample size, the decision can be very complex and this question does not have one definitive answer (Bryman & Bell, 2003). Several ranges were proposed in literature defining the effective sample sizes (refer to Brewerton & Millward 2001; Mbugua, 2000). Alternatively, Easterby-Smith, Thorpe & Lowe (2002) proposed a rough formula for calculating the appropriate sample size (n) in terms of the maximum error (E) which can be accommodated.

$$n = 2500 / E^2$$

As per this equation, and if a maximum error is assumed as 5%, then the minimum sample size would be 100. As per the results presented in Section 4.3, the survey's participants were 364, which yields to a very small error factor of less than 0.5%.

- *Questionnaire Style:* For the ease of data manipulation after the survey is completed, most of the questionnaire was designed as *Closed Questions* (i.e. multiple choice), which were designed carefully to include all possible opinions. *Open Questions* were only used in few cases where the question style was required to be in the form: *Any Other Item*; for these cases, questions were left open for participants to list additional items to the items mentioned in the main questions.

4.2.2. Questionnaire details

The questions were carefully phrased, ordered and categorized under four sections: *General Information*, *Scheduling Problem*, *Proposed Solution's Features* and *Future Communications*. Each section was designed to serve a certain purpose; whether to collect group of data, or to guide the survey elements in a specific direction required for the accomplishment of the survey's objectives. The following points review the survey's sections' detailed sub-objectives and how they were addressed within the questions:

General Information Section

The main objective of this section was to collect the survey participants' information required for properly categorizing their opinions based on their organization type, level of experience and their location. The followings were the objectives of the section:

- *Categorize survey results by organization type:* This objective was required to identify the organization types to which the proposed solution is applicable. Question 1 was added for this purpose.

> 1. What is the category of your current organization?
>   ☐ Project Management Consultants
>   ☐ General Engineering Consultants
>   ☐ General Contractors
>   ☐ Specialized Contractor (please state specialty field) …………...

- *Categorize survey results by level of experience:* Replies were expected to be different based on the participants' level of experience, especially questions related to the method of solution integration or related to contractual matters. Questions 2 to 5 were introduced to collect information required for this purpose; each reply will have a certain weight, and the total answers will be averaged into a 3 steps scale for experience (Small, Medium and High experience).

> 2. What is the level of your current occupation?
>   ☐ Top management   ☐ Department management
>   ☐ Senior level   ☐ Junior level
>
> 3. What are your total years of experience within Project Management different fields?
>   ☐ More than 15 years   ☐ From 10 to 15 years
>   ☐ From 5 to 10 years   ☐ Less than 5 years
>
> 4. What are your total years of experience within Planning/Scheduling field?
>   ☐ More than 15 years   ☐ From 10 to 15 years
>   ☐ From 5 to 10 years   ☐ Less than 5 years
>
> 5. What is the scale of your current/previous projects? (More than one choice can be selected)
>   ☐ Mega projects (equal or greater than 1 billion US dollars)
>   ☐ Large scaled projects (between 100 million to 1 billion USD)
>   ☐ Medium scaled projects (between 10 to 100 million USD)
>   ☐ Small scaled projects (less than 10 million USD)

- *Categorize survey results according to location:* This was required for measuring the diversity of survey participation, in order to ensure that it was attended by several project management backgrounds and practices, and to help in classifying the level of suitability of the proposed solution to practices of different locations. Questions 6 & 7 were added for this purpose.

> 6. What is your nationality? (The question is required only to check that the survey was attended by various PM backgrounds, in order to ensure that the questionnaire's results represents the planning population)
>
> ....
>
> 7. Please list the countries where you have worked before (starting from your current location):
>
> 1. .... 2. .... 3. ....
>
> 4. .... 5. .... 6. ....

Rescheduling Problem Section

There were three objectives for this section:

- Refresh the memory of the surveyed planners with respect to the rescheduling problem, and to pull their attention that the survey's background study is dealing with one of their main nightmares; which will hopefully motivate them to answer the questions with good care. The headings of questions 8-10 (schedule optimization) and 12-17 (real-time events) were carefully written to support this objective.

> 8. In how many cases during the baseline schedule / revised schedule preparation you had the time to properly check the resources distribution and tried to level/smooth the resource histograms, and avoid gaps on the time frame between different assignments?
>
> ☐ Always had the time to optimize all resource assignments
>
> ☐ Usually had the time to optimize assignments of scarce/critical resources
>
> ☐ Never had the time for it   ☐ I don't think it is required
>
> 9. In how many cases during the baseline schedule / revised schedule preparation you had the time to check the project's cash flow and may be go back and change certain sequence to match a certain cash flow requirement or to reduce negative troughs?
>
> ☐ Always had the time for it
>
> ☐ Usually had the time to view it, but not to change the schedule accordingly
>
> ☐ Never had the time for it   ☐ I don't think it is required
>
> 10. In how many cases during the baseline schedule / revised schedule preparation you had the time to check the critical/near critical paths for their flexibility (note: a flexible path is the one having most of its activities with normal un-crashed durations. This path gives the ability to apply some crashing measures upon its delay/disruption events)?
>
> ☐ Always had the time for it   ☐ Usually had the time for main CP
>
> ☐ Never had the time for it   ☐ I don't think it is required

- Collect the participants' experience/opinion on what they usually face in regard of schedule optimization and the rescheduling process; these opinions will be then added to the problem definition along with the same subject's literature review. The answers alternatives given for questions 8-10 and 12-17 can be claimed to cover all possible replies required to collect the information needed for this objectives.

---

12. *In how many cases, after the baseline schedule / revised schedule preparation, an unexpected event occurs disturbing your schedule and causing portion of it to be incorrect and awaiting a future revision?*

    ☐ Always happens   ☐ Usually happens

    ☐ Rarely happens   ☐ Never happened

13. *In how many cases, after the baseline schedule / revised schedule preparation, an unexpected request from the client or company top management occurs disturbing your schedule and causing portion of it to be incorrect and awaiting a future revision?*

    ☐ Always happens   ☐ Usually happens

    ☐ Rarely happens   ☐ Never happened

14. *Which one of the following real-time events <u>usually</u> occur causing portion of your schedule to have incorrect logic and needs quick revision? (More than one choice can be selected)*

    ☐ Delayed engineering inputs   ☐ Delayed material delivery

    ☐ Equipment breakdowns   ☐ Elongated construction activities

    ☐ Other reasons …………………………………………………

15. *How many times the previously mentioned real-time events occur during the updates, and you didn't have the time to check the integrity of your resource distribution before officially issuing the schedule update?*

    ☐ Always had the time to check it

    ☐ Usually had the time only for scarce resources

    ☐ Never had the time to check it

    ☐ I don't think these checks are required with each update

16. *In how many cases during the schedule update you had the time to check the project's cash flow and may be go back and change certain sequence to match a certain cash flow requirement or to reduce negative troughs?*

    ☐ Always had the time for it

    ☐ Usually had the time to view it, but not to change the schedule accordingly

    ☐ Never had the time for it

    ☐ I don't think it is required during schedule update

17. *In how many cases during the schedule update you had the time to check the critical/near critical paths for their flexibility (note: a flexible path is the one having most of its activities with normal un-crashed durations. This path gives the ability to apply some crashing measures upon its delay/disruption events)?*

    ☐ Always had the time for it   ☐ Usually had the time for main CP

    ☐ Never had the time for it   ☐ I don't think it is required

- Check with the participants the need for a tool to support in the optimization of their schedules, and to test their willingness to trust a software tool for this purpose. Questions 11 & 18 were included to serve this objective; question 11 for the baseline / revised schedule optimization and question 18 for the updated schedule optimization.

> 11. *So, in general, do you think it will be a good solution to prepare your baseline / revised schedule, and then pass it to an optimization software to give some suggestions on how to optimize it?*
>
> ☐ Yes, it will save a lot of time and produce more professional output
>
> ☐ Yes, in all cases it will have some added value
>
> ☐ It's always good to try
>
> ☐ I think this will add more time to the schedule preparation period without having an added value

> 18. *So, in general, do you think it will be a good solution to prepare your schedule update, and then pass it also to an optimization software to give some suggestions on how to optimize it?*
>
> ☐ Yes, it will save a lot of time and produce more professional output
>
> ☐ Yes, in all cases it's good to try, it might produce good solutions
>
> ☐ It's a good idea, but in many cases, logic changes might not be acceptable from contractual point of view
>
> ☐ No, I think this will add more time to the update process without having an added

Proposed Solution's Features Section

This section was designed to let the planners answer to one main question: *"What do you dream of"*. The questions were designed to collect the field planners' requirements with respect to inputs, expected outputs, and features of the final product; while responses alternatives were designed to include the two extremes of opinions and two intermediate choices. For this section, mainly, the collected responses must be weighed according to the elements' experience in order to support the decision of what features are *actually required* (i.e. involves large time/effort for manual analysis. The sub-objectives of this section can be summarized as follows:

- *Frequency & mass of analysis:* Questions 19, 20 & 21 were added to collect the planners' opinion about the required frequency for running the optimization analysis. Question no. 19 surveys how to measure the mass of changes of each alternative, while questions 21 & 22 check the mass of changes which can be allowed in different scheduling phases.

19. *As explained in the Introduction of the survey, the proposed software will be running in the background attempting to optimize the project schedule and searching for alternative solutions in case of problems. So, how often do you think these alternatives needs to be proposed?*
    - ☐ Along with each periodical schedule update
    - ☐ In case of resource requirements crossing predefined thresholds
    - ☐ In case of delays to one of predefined milestones
    - ☐ Only when requested by the planner

20. *Sometimes the optimum solution will involve large amount of changes to the schedule, how often do you think large mass of changes to be allowed for the sake of optimization of the project's resources/time/cost?*
    - ☐ Depends on the benefits associated with the optimized solution
    - ☐ Large changes can be accepted on a predefined periods (schedule updates).
    - ☐ Large changes can only be accepted as *What-If* schedules for separate contractual approvals.
    - ☐ Large changes can only be accepted when a schedule revision is under preparation (i.e. upon the planner's request)

21. *The optimization process takes large processing time, and if you knew that increasing the number of activities to be optimized will dramatically increase the hardware requirements where the software operates; in your opinion, which portion of the schedule should take the concentration of the background optimization calculations?*
    - ☐ Only critical activities affecting the project completion
    - ☐ Critical/near critical activities affecting one or more of the project predefined milestones
    - ☐ Critical, near critical and activities with start date close to the data date
    - All activities. A completely optimized schedule worth the costs of additional hardware

- *Practicality of optimization features & objectives:* This objective is one of the main objectives of the survey. It aims for checking the practicality of different features of the proposed solution. Four questions were added for this purpose: Question no. 22 for checking the practicality of using activity modes, question no. 24 for enterprise resource analysis, question no. 25 for few cost issues, and question no. 26 for criticality and flexibility indices.

22. *"Activity modes" is the option where you can define different arrangement of resources for each activity, so that the optimization software can choose from while arranging the project's resource distribution. Do you feel it is practical to use Activity Modes as an option during the optimization process, bearing in mind that each mode must be separately defined by the planner?*
    - ☐ Activity modes will add to the optimization software another level of flexibility in reaching the optimum solutions, so it must be used along with each optimization process.
    - ☐ Can be used for critical/scarce resources.
    - ☐ It is only needed when a major rescheduling process is required.
    - ☐ Activity modes are not practical in real life, once a certain mode is set for an activity, it will cause confusions to change it

24. *The key issue of optimizing the project schedule is the proper utilization of resources; so, one of the key strategies a construction company can take is to properly utilize its resources between the running projects. Do you think the resources allocation between predefined projects can be a practical optimization tactic?*

   ☐ Yes, as long as there is a benefit in the background of the allocation.

   ☐ Yes, but the mobilization/demobilization time and cost must be taken into consideration

   ☐ Yes for tools/manpower resources, but not for large equipment.

   ☐ Resource allocation between running projects can show a theoretical savings, but practically it is not a good approach.

25. *The cost and cash flow are very important issues in the project management field, an improper distribution of resources or large usage of hired resources can have large impact on the project budget. Which of the following measures do you think is important to be investigated while searching for optimum solutions? (More than one choice can be selected)*

   ☐ Monitoring costs on the cost codes level along with each optimization trial is the hardest but the best solution for keeping the project within budget

   ☐ The total cost of the project including internal equipment rental values in order to measure the mass of resource idleness

   ☐ Project cash flow is important to monitor, in order to avoid unplanned large negatives which might require additional funding

   ☐ Loading costs on schedules will complicate the analysis/ decision making processes, so it should be checked separately.

26. *An optimum/near optimum solution does not only mean a properly resources schedule meeting the target date/budget, there are also few other measures which can be used to weight the solutions resulting from the analysis. Which one of the followings you feel can be practically taken into consideration while choosing the alternative solutions? (More than one choice can be selected)*

   ☐ *Criticality Index:* The less the number of critical activities in the project, the better the solution is.

   ☐ *Float Index:* The larger the float of predefined (or all) activities/resources, the better the solution becomes.

   ☐ *Activities Flexibility Index:* Each activity can have three duration values which vary according to its level of resources: minimum, maximum and preferred. Then, the closer the duration value from the preferred value, the more flexible (i.e. better) the solution is.

   ☐ *Resources Flexibility Index:* Each resource can have three defined values within the project: minimum (the amount of resources fully available for the project and must be utilized), maximum (including rented/hired) and preferred (the best utilization of the company's resources. Then, the closer the value of assigned resources to the preferred value, the flexible (i.e. better) the solution is.

- *Solution integration with current Project Management practices:* Questions 27, 28 & 29 were added to investigate the preferences of the field practitioners on how the proposed solution should be integrated with existing practices, and which software packages should be considered in the integration process.

27. Please list any other practical features/factors which you feel should be included in the optimization process:

    1. ....
    2. ....
    3. ....

28. How do you feel the new software should be integrated with current project management practices?

☐ Completely dependent software. No need for integration with existing software packages (i.e. current software packages will not be used in parallel).

☐ Dependent software which contains inputs, analysis and outputs. But projects can be converted to the formats of the commonly used software packages.

☐ Dependent software which communicates with common software packages in the form of their file formats. Data inputs and updates are done in the existing software packages then passed to the new software tool for optimization analysis; then returned back to the original software for presentation of outputs.

☐ An integrated solution with common software packages, where the tool can read from the existing packages' databases to produce schedule alternatives, and have the ability to write back to the same databases if changes were accepted for implementation, or to store the alternatives as *What-If* schedules.

29. Which software packages do you think the new solution should be compatible and/or integrated with?

- *Primavera Project Management*

☐ Must be compatible with   ☐ Strongly recommended
☐ It's good to be considered   ☐ Compatibility not required

- *Microsoft Project*

☐ Must be compatible with   ☐ Strongly recommended
☐ It's good to be considered   ☐ Compatibility not required

- *Asta Power Project*

☐ Must be compatible with   ☐ Strongly recommended
☐ It's good to be considered   ☐ Compatibility not required

- *Please list any other software which you feel that it is* **<u>strongly recommended</u>** *to have the new solution integrated with*

    1. ....   2. ....
    3. ....   4. ....

Future Communications Section

The objectives of this section were:

- *Encourage the participants to complete and send their responses* by asking them (question no. 1) for their willingness to receive a free copy of the developed software, which was claimed in the survey

contents that will solve a considerable portion of their scheduling problems.

> 30. Would you like to receive a FREE copy of the Dynamic Scheduling software after the completion of its development?
>   ☐ Yes   ☐ No

- *Testing the survey's success in collecting reliable information:* This was planned to be checked by asking the participants (questions 2 & 3) if they would like to receive a copy of the survey results or future related research works. If their replies were oriented towards the willingness to receive future communications, then the survey succeeded to pull their attention to the topic (i.e. they have carefully responded to survey questions). On the other hand, the reverse replies might be an indication that the schedules optimization and dynamic scheduling issues does not represent a great concern to the planning community.

> 31. After the analysis completion of this survey's responses, would you like to receive a summary of the survey's results?
>   ☐ Yes, I need it for other research topic in the same/similar field
>   ☐ Yes, it's good to know the common opinions
>   ☐ No, not interested
>
> 32. Would you like to receive any updates in future for researches with similar topics? (More than one choice can be selected)
>   ☐ Yes, for any innovative works in the planning/scheduling field
>   ☐ Yes, for research topics related to Schedules Optimization
>   ☐ Yes, for research topics related to Dynamic Scheduling
>   ☐ Not interested

- *Spread the survey within the participants' contacts:* Question 4 provides a platform for the participants to add few of their contacts which they believe might be interested in the topic.

4.3. Analysis of survey responses

4.3.1. Survey distribution and responses demographic analysis

A webpage was developed for the questionnaire survey and published on the internet to facilitate its spreading. Then invitations were sent to major construction companies and consultancy offices; in addition, other invitations were sent to the members of few popular planning forums.

The total number of participants was 345, with a response rate of about 4% of sent invitations. Table 4.1 shows the summary statistics of the received responses.

Total Questionnaire Participants:	364
Participants Nationalities:	52
No. of Countries where Participants worked:	131
Total Sent Invitations:	8,980
Response Rate:	4.1%

Table 4.1: General info on survey responses

The participants were fairly distributed among different organization categories as shown in Table 4.2.

Participant's Organization Category	No.	%
Project Management Consultants	114	31.3%
General Engineering Consultants	44	12.1%
General Contractors	119	32.7%
Specialized Contractors	84	23.1%
(Unspecified)	3	0.8%
TOTAL	364	100.0%

Table 4.2: Responses distribution on organizational category

Their distribution was also ideal with respect to seniority and experience levels (tables 4.3 & 4.4), where all roles/experience levels were required to participate, especially Senior Level and high/medium experience planners because they will be the main target users for any proposed technical solution.

Seniority Level	No.	%
Top Management	43	11.8%
Department Management	93	25.6%
Senior Level	204	56.0%
Junior Level	24	6.6%
TOTAL	364	100.0%

Table 4.3: Responses distribution on organizational roles

Experience Level	No.	%
High	125	34.3%
Medium	175	48.1%
Low	64	17.6%
TOTAL	364	100.0%

Table 4.4: Responses distribution on experience levels

4.3.2. Reliability and validity of responses

With respect to geographical distribution, the following table shows that the participants were well distributed all over the world. The distribution was even close to the worldwide population distribution as per the UN population reports [UN Pop. Report 2011], except for Asia & Europe; this is reasonable because the higher the countries' prosperity, the higher the need from project management and planning. So, in light of the above, the results can be claimed to represent the worldwide planning population.

Survey Participants			2010 Population		Variance
Location	No.	%	Millions	%	
Africa	58	15.9%	1,033	14.9%	1.0%
Asia	124	34.1%	4,167	60.3%	-26.2%
Europe	114	32.1%	733	10.6%	21.5%
North America	33	9.1%	352	5.1%	4.0%
South America	11	3.0%	589	8.5%	-5.5%
Oceania	21	5.8%	36	0.5%	5.2%
TOTAL	345	100.0%	6,910	100.0%	

Table 4.5: Comparison of responses distribution by location and the world's population distribution on 2010 (as per UN population report 2011)

With respect to validity of responses, the analysis of responses to certain questions having certain answers expected not to be selected regardless of the role and experience of the participant (for ex.: reply no. 4 to questions 12 & 13: 'Disruption to schedules never happed'), shows that the frequency of selection to these answers was very low (less than 1%) which was considered as a sign of validity to the responses to other questions. In addition, 92-95% of the participants were interested in either the receipt of the final results of the survey, the receipt of a copy of the developed software tool, and the receipt of further updates for the same and/or similar works; this interest in the subject can be considered as another sign to the seriousness (i.e. validity) of the responses.

4.3.3. Responses statistical summary

The following tables summarize the statistical analysis of responses in a combination between frequency distribution (number of responses to each answer and percentage distribution of responses) and descriptive statistics (mean and standard deviation for overall responses and categorized by experience levels and organization types).

Questions 1 to 7 were used for categorizing results, so they were excluded from the analysis below. Also question 14 was excluded, because it was only used to refresh the participants' memory about the real time events causing disruption to schedules so that they can answer the related questions

effectively. And finally, question 27 was excluded because it was an open ended question for the participants to provide their suggestions.

Qs. No.	Answers					Overall		Categorized by Experience Level						Categorized by Organization Type							
	1	2	3	4	Total	Mean	Std. Dev	High Mean	High S.D.	Medium Mean	Medium S.D.	Low Mean	Low S.D.	PM Consultants Mean	PM Consultants S.D.	Gen. Eng. Consult. Mean	Gen. Eng. Consult. S.D.	General Contr. Mean	General Contr. S.D.	Specialized Contr. Mean	Specialized Contr. S.D.
Rescheduling Problem section																					
8	37 / 10.3%	251 / 69.7%	64 / 17.8%	8 / 2.2%	360 / 100.0%	Ans. 2	0.6	2	0.6	2	0.6	2	0.7	2	0.7	2	0.7	2	0.6	2	0.5
9	56 / 15.6%	178 / 49.6%	94 / 26.2%	31 / 8.6%	359 / 100.0%	Ans. 2	0.9	2	0.9	2	0.8	2	1.0	2	0.7	2	0.7	2	1.0	2	0.8
10	150 / 41.8%	171 / 47.6%	33 / 9.2%	5 / 1.4%	359 / 100.0%	Ans. 2	0.8	2	0.7	2	0.8	2	0.8	2	0.6	2	0.6	2	0.8	2	0.7
11	124 / 34.6%	124 / 34.6%	97 / 27.1%	13 / 3.6%	358 / 100.0%	Ans. 2	0.9	2	0.9	2	0.9	2	0.9	2	1.0	2	1.0	2	0.9	2	0.9
12	104 / 29.0%	213 / 59.3%	39 / 10.9%	3 / 0.8%	359 / 100.0%	Ans. 2	0.7	2	0.6	2	0.7	2	0.7	2	0.6	2	0.6	2	0.7	2	0.6
13	94 / 26.1%	216 / 60.0%	48 / 13.3%	2 / 0.6%	360 / 100.0%	Ans. 2	0.6	2	0.6	2	0.7	2	0.7	2	0.5	2	0.5	2	0.6	2	0.6
15	46 / 13.0%	223 / 62.8%	60 / 16.9%	26 / 7.3%	355 / 100.0%	Ans. 2	0.8	2	0.7	2	0.7	2	0.9	2	0.8	2	0.8	2	0.8	2	0.7
16	43 / 12.2%	147 / 41.8%	103 / 29.3%	59 / 16.8%	352 / 100.0%	Ans. 3	1.0	3	1.0	2	1.0	3	0.9	2	1.1	3	1.0	3	1.1	2	0.9
17	113 / 31.8%	179 / 50.4%	52 / 14.6%	11 / 3.1%	355 / 100.0%	Ans. 2	0.8	2	0.7	2	0.7	2	0.9	2	0.9	2	0.9	2	0.8	2	0.7
18	109 / 30.5%	192 / 53.8%	25 / 7.0%	31 / 8.7%	357 / 100.0%	Ans. 2	0.9	2	0.9	2	0.9	2	0.8	2	1.0	2	1.0	2	0.7	2	0.8
Proposed Solution's Features section																					
19	160 / 45.6%	41 / 11.7%	59 / 16.8%	91 / 25.9%	351 / 100.0%	Ans. 2	1.3	2	1.3	2	1.3	2	1.3	2	1.3	2	1.3	2	1.3	2	1.2
20	142 / 40.2%	22 / 6.2%	93 / 26.3%	96 / 27.2%	353 / 100.0%	Ans. 2	1.3	2	1.3	2	1.3	2	1.4	2	1.5	3	1.3	2	1.3	2	1.3
21	29 / 8.4%	176 / 50.7%	59 / 17.0%	83 / 23.9%	347 / 100.0%	Ans. 3	1.0	3	1.0	3	1.0	3	1.1	3	1.0	3	1.0	3	1.0	3	1.1
22	86 / 25.0%	121 / 35.2%	76 / 22.1%	61 / 17.7%	344 / 100.0%	Ans. 2	1.1	2	1.1	2	1.1	2	1.1	2	1.1	3	1.0	2	1.0	2	1.1
23	145 / 22.4%	179 / 27.7%	149 / 23.0%	174 / 26.9%	647 / 100.0%	Ans. 3	1.2	3	1.2	3	1.2	3	1.2	3	1.1	3	1.1	2	1.2	3	1.2
24	102 / 30.3%	124 / 36.8%	25 / 7.4%	86 / 25.5%	337 / 100.0%	Ans. 2	1.2	2	1.3	2	1.1	2	1.2	2	1.1	2	1.1	2	1.2	2	1.1
25	180 / 31.0%	125 / 21.6%	179 / 30.9%	96 / 16.6%	580 / 100.0%	Ans. 2	1.1	2	1.2	2	1.1	2	1.1	2	1.2	3	1.2	2	1.1	2	1.1
26	192 / 27.6%	145 / 20.9%	172 / 24.7%	186 / 26.8%	695 / 100.0%	Ans. 3	1.3	3	1.3	2	1.3	3	1.3	3	1.2	3	1.2	2	1.3	2	1.2
28	20 / 5.9%	57 / 16.8%	77 / 22.7%	185 / 54.6%	339 / 100.0%	Ans. 3	1.0	3	0.9	3	1.0	3	0.9	3	0.9	3	0.9	3	0.9	3	1.0
29a	257 / 73.4%	68 / 19.4%	23 / 6.6%	2 / 0.6%	350 / 100.0%	Ans. 1	0.7	1	0.7	1	0.7	1	0.8	1	0.8	1	0.8	1	0.7	1	0.6
29b	109 / 34.7%	77 / 24.5%	107 / 34.1%	21 / 6.7%	314 / 100.0%	Ans. 2	1.0	2	1.0	2	0.9	2	0.9	2	1.0	2	1.0	2	0.9	2	1.0
29c	101 / 36.1%	141 / 50.4%	38 / 13.6%	0 / 0.0%	280 / 100.0%	Ans. 2	0.7	2	0.7	2	0.7	2	0.7	2	0.6	2	0.6	2	0.8	2	0.6
29d	No more	282 / 77.5% Other	softw.	82 / 22.5%	364 / 100.0%	No more	0.9	No more	0.8	No more	0.9	No more	0.9	No more	0.9	No more	0.9	No more	0.9	No more	0.9
Future Communications section																					
30	Yes	325 / 94.2%	No	20 / 5.8%	345 / 100.0%	Yes	0.2	Yes	0.3	Yes	0.2	Yes	0.2	Yes	0.3	Yes	0.2	Yes	0.2	Yes	0.3
31	79 / 22.3%	248 / 70.1%	27 / 7.6%	- / -	354 / 100.0%	Ans. 2	0.5	2	0.5	2	0.6	2	0.6	2	0.6	2	0.6	2	0.6	2	0.4
32	295 / 62.4%	8 / 1.7%	150 / 31.7%	20 / 4.2%	473 / 100.0%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.6: Summary of statistical analysis for survey's responses

4.3.4. Review of responses summary

Rescheduling Problem section

This section was intended to collect the participants' opinions about scheduling/rescheduling problems. With respect to resources analysis, 97.8% selected that it is required to be performed before baseline schedule submission, from which 87.5% acknowledged that the time was always not sufficient to review all resources distribution. For cash flow analysis, 91.4% selected that it is required, while 75.8% acknowledged that the time was always not sufficient to change the schedule accordingly. Similar response ratios were given to the same issues during schedule updates, but with less importance to cash flow analysis where 16.8% selected that it is not required during schedule updates.

Real time events were selected as the main cause of disruption to schedules, where less than 0.8% of the participants stated the real-time events does not impact schedule integrity, while more than 85% selected that this disruption usually/always happens.

Finally, 96.4% selected that the presence of optimization software might help during baseline scheduling, from which 70% selected that such software will definitely have an added value. A similar response ratio was given to the importance of this optimization software tool during schedule updates.

Proposed Solution's Features section

The results for most of this section's questions were fairly distributed among alternatives, where the most selected answer rarely crossed 60%. This is mainly due to the different practices and interest of participants; where some options were important to few participants, good to considered for others, and not practical for the balance. This leads us to the fact that all the mentioned features must be considered as optional within any proposed solution, and the decision to be left for the user for selection according to his opinion or project's requirements.

For software packages to be integrated with, 77.5% accepted that the 3 mentioned packages are fairly enough, while the rest had few other packages which they suggested for integration with the new tool, but none of these packages exceeded 2.5% of the participants except for regular spreadsheet packages which were suggested by 4.4% of the responses.

This portion of the survey will be further investigated and analyzed in the next chapter for converting the participants' responses into functional specifications of the proposed software tool.

Future Communications section

The results shown in table 4.6 shows the general interest of participants in the subject under study, where 94.2% were interested to receive a copy of the developed software tool, 92.4% of the participants were interested to receive the final results of the survey, and 95.8% were interested to receive further updates for the same subject or similar innovative works in planning/scheduling.

4.4. Defining the functional specification of the proposed dynamic scheduling software tool

The "Proposed Solution's Features" section of the questionnaire survey was intended to collect the opinion of project management practitioners on the proposed tool's functionality. And as mentioned earlier in this chapter, the survey participants' opinions on what features to be included in the software and how it should be managed was fairly distributed among all alternatives. So, all features presented in the survey must be included in the software; the default value for each feature will be coded as per the alternative with highest response ratio, and other alternatives will be also coded to enable the users to choose the most suitable option for their projects' requirements.

4.4.1. Frequency of optimization

Table 4.7 shows a summary of responses to question no. 19 in the survey; the question was investigating how frequent there is a need for dynamically proposing optimized schedule alternatives. 'Along with periodical updates' was the most preferred choice for survey participants (45.6%), while the balance of responses was distributed on the other three choices. The response distribution was almost the same when responses were categorized according to organization type and experience level.

Questions / Response Alternatives		Total Responses		Responses Categorization						
				By Organization Type				By Experience Level		
		No.	%	PM Cons.	Eng. Cons.	Gen. Contr.	Spec. Contr.	High	Med.	Low
19. Frequency of proposing optimized alternatives										
1	Along with each periodical update	160	45.6%	44.1%	46.5%	46.5%	46.9%	44.4%	47.0%	44.1%
2	Crossing resource thresholds	41	11.7%	11.7%	9.3%	12.3%	11.1%	7.3%	14.3%	13.6%
3	Delay in a predefined milestone	59	16.8%	18.0%	14.0%	12.3%	23.5%	20.2%	14.3%	16.9%
4	Only when requested by planner	91	25.9%	26.1%	30.2%	28.9%	18.5%	28.2%	24.4%	25.4%
	TOTAL	351	100%	31.6%	12.3%	32.5%	23.1%	35.3%	47.9%	16.8%

Table 4.7: Summary of responses to question no. 19

In light of the above, the following statement can be considered as the first functional specification of the software tool:

"1. The software tool must be able to check for optimized alternatives along with each update with the focus on activities with forecast progress in the coming period, so that the user can be prompted with the available optimized alternatives after he completes the update based on his selection for the 'Frequency of Optimization' option".

4.4.2. Frequency of large changes

Question 20 was focused on the acceptable frequency of large changes to schedule. Large rate of responses (40.2%) selected that large changes can be accepted at any time dependent on the benefits of these changes; but also this ratio was a bit less to experienced planners when responses were further categorized, where high experienced participants as well as Consultants were less preferring this choice but still in average it is the most selected, this is mainly because large experienced planners will know that majorly changed schedules are not that easy to pass frequently to project team to execute, even if the benefit of change is high.

Questions / Response Alternatives		Total Responses		Responses Categorization						
				By Organization Type				By Experience Level		
		No.	%	PM Cons.	Eng. Cons.	Gen. Contr.	Spec. Contr.	High	Med.	Low
20. Frequency of large changes										
1	Depends of the output benefits	142	40.2%	39.1%	32.6%	43.5%	42.2%	36.3%	42.6%	41.7%
2	Along with periodical updates	22	6.2%	4.5%	7.0%	7.0%	7.2%	6.5%	7.1%	3.3%
3	Separate What-If schedules	93	26.3%	31.8%	18.6%	22.6%	27.7%	29.0%	26.0%	21.7%
4	Along with schedule revision	96	27.2%	24.5%	41.9%	27.0%	22.9%	28.2%	24.3%	33.3%
	TOTAL	353	100%	31.2%	12.2%	32.6%	23.5%	35.1%	47.9%	17.0%

Table 4.8: Summary of responses to question no. 20

Most other responses discarded the choice that large changes can be made along with periodical update, and accepted to have such changes either with schedule revisions or as separate What-If schedules. So, the second functional specification can be phrased as follows:

"2. The software must always have to tracks of optimization, one with minimum changes to schedule and the other with no constraint on mass of changes. Then the user can see both options and decide whether or not he can accommodate large changes on his update/revision of schedule".

4.4.3. Mass of optimization

Optimization of medium and large scale schedules involves large computational burden, and the number of activities/resources to be optimized is exponentially proportional to the optimization time. Question no.21 was intended to give the user this bit of information and get their feedback on how to minimize the number of activities/resources to be optimized without affecting the purpose of the optimization process.

	Questions / Response Alternatives	Total Responses		Responses Categorization						
				By Organization Type				By Experience Level		
		No.	%	PM Cons.	Eng. Cons.	Gen. Contr.	Spec. Contr.	High	Med.	Low
	21. Portions of the schedule to be analyzed for optimization									
1	Critical activities for completion	29	8.4%	8.5%	4.7%	7.0%	12.3%	6.5%	9.6%	8.8%
2	Critical/near critical activities leading to milestones	176	50.7%	51.9%	46.5%	55.7%	45.7%	53.2%	48.8%	50.9%
3	Critical/near critical activities & close to data date	59	17.0%	16.0%	20.9%	15.7%	17.3%	14.5%	19.9%	14.0%
4	All activities	83	23.9%	23.6%	27.9%	21.7%	24.7%	25.8%	21.7%	26.3%
	TOTAL	347	100%	30.5%	12.4%	33.1%	23.3%	35.7%	47.8%	16.4%

Table 4.9: Summary of responses to question no. 21

More than 50% of the responses accepted the idea that optimizing critical and near critical activities (i.e. and resources) leading to milestones will be enough to produce acceptable optimized schedules with less computational burden. But still 17% added activities close to data date to the optimization process, and even 24% preferred that all activities should be used. This will lead to creating the related spec as follows:

"3. The software tool should work by default on optimizing critical/near critical activities/resources leading to project milestones; but it should also contain the flexibility of increasing/decreasing the optimization size based on the user's requirements".

4.4.4. Optimization tactics

The tactics to be used during optimization are one of the most important aspects that build the core of the optimization solution; questions 22 to 24 were added to the survey for this purpose.

As shown in table 4.10, opinions for activity modes was not oriented to a clear choice, but there was a larger response rate towards implementing activity mode to critical resources (i.e. critical activities driven by resources).

"4. Activity modes will not be considered in the optimization process before the user has already added different activity modes to one or

more activities. When few modes are added, the software will consider by default the modes related to critical activities/resources in each schedule update/revision, unless the user has specified a different mass or frequency for using activity modes".

	Questions / Response Alternatives	Total Responses		Responses Categorization						
				By Organization Type				By Experience Level		
		No.	%	PM Cons.	Eng. Cons.	Gen. Contr.	Spec. Contr.	High	Med.	Low
22. Practicality of using activity modes										
1	Must be used for all resources	86	25.0%	27.8%	14.3%	29.7%	21.0%	24.2%	26.9%	21.1%
2	To be used only for critical resources	121	35.2%	31.5%	33.3%	36.9%	38.3%	34.2%	35.9%	35.1%
3	Along with major schedule revision	76	22.1%	20.4%	33.3%	18.9%	23.5%	20.8%	21.6%	26.3%
4	Activity modes are not practical	61	17.7%	20.4%	19.0%	14.4%	17.3%	20.8%	15.6%	17.5%
	TOTAL	347	100%	30.5%	12.4%	33.1%	23.3%	35.7%	47.8%	16.4%
23. Optimization tactics										
1	Resource levels adjustment	145	22.4%	22.0%	16.9%	26.6%	19.7%	21.8%	23.0%	21.9%
2	Re-sequencing similar activities	179	27.7%	25.5%	27.7%	29.0%	28.6%	25.6%	28.7%	29.2%
3	Lags manipulation	149	23.0%	26.0%	24.1%	21.5%	21.1%	23.9%	21.8%	25.0%
4	Tactic selection depends on optimization objectives	174	26.9%	26.5%	31.3%	22.9%	30.6%	28.6%	26.5%	24.0%
	TOTAL	647	100%	31.3%	13.0%	31.6%	23.6%	35.1%	47.5%	17.4%
24. Practicality of using resource allocation between projects as an optimization option										
1	Yes if there is benefit from allocation	102	30.3%	32.7%	22.5%	33.6%	25.9%	28.8%	34.0%	22.8%
2	Yes with considering mobilization/demob. cycles	124	36.8%	31.8%	47.5%	34.6%	42.0%	33.9%	38.3%	38.6%
3	Yes for tools/manpower, but not for equipment	25	7.4%	9.3%	5.0%	6.5%	7.4%	5.1%	9.3%	7.0%
4	Not a practical option	86	25.5%	26.2%	25.0%	25.2%	24.7%	32.2%	18.5%	31.6%
	TOTAL	337	100%	31.8%	11.9%	31.8%	24.0%	35.0%	48.1%	16.9%

Table 4.10: Summary of responses to questions 22, 23 & 24

With respect to optimization tactics proposed in question 23, the responses were evenly distributed among the four given choices; which means that none of the given tactics was felt by the participants to be the most suitable choice, so all of them can be used separately or combined depending on the optimization process requirement.

"5. 'Resource levels adjustment', 'Re-sequencing similar activities' and 'Lags manipulation' can be used as the optimization tactic. An optimized

alternative can be presented for each one of them separately, and another alternative for their combined usage, unless the user specifies that certain tactic or the combined optimization should be used as the default approach".

And finally for cross-projects resource allocation, more than 67% accepted this concept, where more than half of this ration constrained this with the consideration of mobilization and demobilization cycles. Most of the participants did not accept that resource allocation between projects should be constrained to tool and/or manpower; so, equipment resources should also be considered.

"6. Cross-projects resource allocation can be selected by users according to their companies' requirements, but they should first specify for each resource to be optimized the average time and cost required for each mobilization/demobilization cycle. This time and cost can be further elaborated to the time and cost related to the route between two specific projects if this relocation was found to be optimum".

4.4.5. Optimization objectives

For any optimization process one or more objectives must be predefined, then the optimization algorithm will try to find the best possible value for the main objective, or optimize the value of an objective function combining the group of objectives based on a predefine weights between them.

The classical objective for scheduling problems is optimization of time (minimum project duration and/or earlier milestone dates); other objectives can also be used like resource levels, overall cost, cash flow, schedule indices, etc. Questions 25 & 26 collected the experience opinion of survey participants for which criteria should be practically used beside / in lieu of time objectives.

Questions / Response Alternatives		Total Responses		Responses Categorization						
				By Organization Type				By Experience Level		
		No.	%	PM Cons.	Eng. Cons.	Gen. Contr.	Spec. Contr.	High	Med.	Low
25. Using cost as one of the optimization objectives										
1	Monitoring costs on cost codes level	180	31.0%	34.4%	27.9%	28.8%	31.9%	32.7%	30.6%	29.0%
2	Monitoring the project's total cost	125	21.6%	20.8%	17.6%	23.0%	22.2%	17.1%	25.3%	20.0%
3	Monitoring project's cash flow	179	30.9%	30.1%	30.9%	32.5%	29.6%	29.1%	30.2%	36.0%
4	Loading costs to schedule is not practical	96	16.6%	14.8%	23.5%	15.7%	16.3%	21.1%	13.9%	15.0%
	TOTAL	580	100%	31.2%	12.2%	32.6%	23.5%	35.1%	47.9%	17.0%

26. Using schedule indices in the optimization objectives									
1	Criticality Index	192	27.6%	26.5%	23.8%	28.9%	29.0%	28.2%	27.7%	26.0%
2	Float Index	145	20.9%	20.5%	19.0%	22.4%	20.4%	18.1%	22.1%	23.0%
3	Activities Flexibility Index	172	24.7%	25.6%	27.4%	20.3%	28.4%	27.7%	23.8%	21.0%
4	Resources Flexibility Index	186	26.8%	27.4%	29.8%	28.4%	22.2%	26.1%	26.3%	30.0%
	TOTAL	695	100%	31.3%	12.1%	33.2%	22.8%	34.4%	48.5%	17.2%

Table 4.11: Summary of responses to questions 25 & 26

For using cost and cash flow within optimization objectives, more than 83% of the responses suggested that cost should be used, but there was no common agreement on how it should be used.

"7. If cost is loaded to the schedule, then it must be included to optimization objectives based on the user's predefined criteria for which cost aspect to be monitored and optimized: cash flow, overall cost and/or costs on cost codes level".

With respect to schedule indices, the responses were evenly distributed among available choices; so, it should be left to the users to decide which indices to be used.

"8. All schedule indices can be used as optimization objectives based on predefined criteria from the user for which indices to be monitored and optimized".

4.4.6. Integration with other software packages

One of the main objectives of this research was to produce a software tool practically compliant with the existing planning and scheduling practices worldwide. This objective cannot be achieved without integrating the tool with the existing software packages. Question 28 was concerned about the method of integration, while question 29 investigated the popularity of existing packages, to enable the use of the most spread package(s) for testing the integration process.

For the integration method, the response rate presented in table 4.12 show the clear trend of participants to prefer the fully integrated solution. And since the software tool integration is one of the basic concepts required to start the software's architectural design, only one option can be selected.

"9. The software tool should be an integrated solution with common software packages, where the tool can read from the existing packages' databases to produce schedule alternatives, and have the ability to write back to the same databases if changes were accepted for implementation or to store the alternatives as What-If schedules".

Questions / Response Alternatives	Total Responses		Responses Categorization						
			By Organization Type				By Experience Level		
	No.	%	PM Cons.	Eng. Cons.	Gen. Contr.	Spec. Contr.	High	Med.	Low
28. How the new software should be integrated with current project management practices?									
1 Completely dependent software	20	5.9%	9.4%	2.3%	4.7%	5.0%	3.4%	9.3%	1.7%
2 Dependent for all planning features, with conversion ability to other file formats	57	16.8%	14.2%	20.5%	16.8%	18.8%	10.1%	18.6%	25.4%
3 Dependent for optimization only & communicate through well-known file formats	77	22.7%	19.8%	25.0%	26.2%	21.3%	21.8%	23.0%	23.7%
4 Completely Integrated	185	54.6%	56.6%	52.3%	52.3%	55.0%	64.7%	49.1%	49.2%
TOTAL	339	100%	31.3%	13.0%	31.6%	23.6%	35.1%	47.5%	17.4%

Table 4.12: Summary of responses to question 28

Questions / Response Alternatives	Total Responses		Responses Categorization						
			By Organization Type				By Experience Level		
	No.	%	PM Cons.	Eng. Cons.	Gen. Contr.	Spec. Contr.	High	Med.	Low
29a. Make the new software compatible with **Primavera Project Management** software?									
1 Must be compatible with	257	73.4%	73.4%	72.7%	74.6%	73.2%	73.9%	70.6%	80.3%
2 Strongly recommended	68	19.4%	17.4%	18.2%	19.3%	23.2%	18.5%	23.5%	9.8%
3 It's good to be considered	23	6.6%	9.2%	6.8%	5.3%	3.7%	7.6%	5.3%	8.2%
4 Compatibility not required	2	0.6%	0.0%	2.3%	0.9%	0.0%	0.0%	0.6%	1.6%
TOTAL	350	100%	31.1%	12.6%	32.6%	23.4%	34.0%	48.6%	17.4%
29b. Make the new software compatible with **Microsoft Project** software?									
1 Must be compatible with	109	34.7%	30.1%	48.8%	33.3%	35.5%	34.5%	33.8%	38.0%
2 Strongly recommended	77	24.5%	24.3%	19.5%	25.8%	26.3%	20.9%	27.9%	22.0%
3 It's good to be considered	107	34.1%	37.9%	22.0%	37.6%	30.3%	35.5%	32.5%	36.0%
4 Compatibility not required	21	6.7%	7.8%	9.8%	3.2%	7.9%	9.1%	5.8%	4.0%
TOTAL	314	100%	32.8%	13.1%	29.6%	24.2%	35.0%	49.0%	15.9%
29c. Make the new software compatible with **Asta Power Project** software?									
1 Must be compatible with	101	36.1%	35.1%	20.0%	48.1%	32.4%	41.7%	35.5%	26.1%
2 Strongly recommended	141	50.4%	47.4%	60.0%	41.8%	58.8%	46.9%	51.4%	54.3%
3 It's good to be considered	38	13.6%	17.5%	20.0%	10.1%	8.8%	11.5%	13.0%	19.6%
4 Compatibility not required	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TOTAL	280	100%	34.6%	12.5%	28.2%	24.3%	34.3%	49.3%	16.4%

29d. Make the new software compatible with any other software?											
1	Spreadsheet packages	16	4.4%	3.5%	2.3%	5.9%	4.8%	4.8%	4.6%	3.1%
2	Others (each < 2.5% of participants)	66	18.1%	20.2%	22.7%	16.0%	15.5%	24.0%	17.1%	9.4%
3	No more software is required	282	77.5%	76.3%	75.0%	78.2%	79.8%	71.2%	78.3%	87.5%
	TOTAL	364	100%	31.3%	12.1%	32.7%	23.1%	34.3%	48.1%	17.6%

Table 4.13: Summary of responses to question 29

With respect to the software packages to integrate with, the responses shown in table 4.13 are self-explanatory; 73.4% selected *'Primavera Project Management'*[®] as 'Must be integrated', and 50.4% selected *'Asta Power Project'*[®] as 'Strongly recommended'. Most of the participants did not agree on a category for *'Microsoft Project'*[®], but nevertheless only 6.7% selected that 'Compatibility is not required', which doesn't exclude it from the most popular list.

It was also clear from the responses that the above mentioned 3 packages are enough for integration; where more than 77% of the participants clearly selected this (question 29d), while the rest mentioned more than 30 other packages, from which none exceeded 2.5% of the responses.

So, for the purpose of the research, the most popular package, 'Primavera Project Management', will be used for integration; while the integration with other popular packages can be performed in future works, after successful completion of the verification and validation of the model (the core of this research).

4.4.7. Other possible features

Finally, question 27 was an open ended question for the survey participants to suggest any other features or objectives which were not listed in the questionnaire. About 70 participants (19%) responded to this question with various statements, 47 of which were good advices for general project management software development but irrelevant to the scope of this research; the balance 23 responses were most of them were related to the final user interface of the proposed software. The followings are the main categories of these comment, and how they were taken care of in the overall system design:

a) *Publishing a 'Change Report ' for the particular optimizatio*n: This is definitely a part of the software's architecture.

b) *Although the program will perform the optimization, the final decision should be left up to the planner:* All optimized alternatives

will be proposed to the planner, then he has to decide whether to directly incorporate or save as a separate What-If schedule (as stated above in spec no. 9).

c) *Add the ability to turn on & off the various functions to focus processing power where it is needed:* All optimization features will be optional, so users can change any setting or disable them at any time.

d) *Ability to utilize both Critical Path as well as Critical Chain Methods:* This is a very important note, and this is actually the core of the proposed model as will be detailed in Chapter 5.

e) *Options to restrict stretching/crunching selected activities:* The optimization software works on the three durations (max, min and normal) stated by the planner, so if the planner wants one or more activities to remain with fixed duration, he should put these three values the same.

f) *Using Lags Flexibility & Three Point risk analysis of durations:* This is already part of the schedule flexibility objective which will be explained during mathematical modelling in Chapter 6.

g) *If the software could offer options level the cash flow to avoid large spikes, this can often please the client:* This was already taken care of in the cost monitoring features (spec no. 7).

4.4.8. Summary of solution's functional specifications

The following points summarize the proposed solution's functional specifications as identified in the previous sections:

a) The software tool must be able to check for optimized alternatives along with each update with the focus on activities with forecast progress in the coming period, so that the user can be prompted with the available optimized alternatives after he completes the update based on his selection for the 'Frequency of Optimization' option.

b) The software must always have to tracks of optimization, one with minimum changes to schedule and the other with no constraint on mass of changes. Then the user can see both options and decide whether or not he can accommodate large changes on his update/revision of schedule.

c) The software tool should work by default on optimizing critical/near critical activities/resources leading to project milestones; but it should also contain the flexibility of increasing/decreasing the optimization size based on the user's requirements.

d) Activity modes will not be considered in the optimization process before the user has already added different activity modes to one or more activities. When few modes are added, the software will consider by default the modes related to critical activities/resources in each schedule update/revision, unless the user has specified a different mass or frequency for using activity modes.

e) 'Resource levels adjustment', 're-sequencing similar activities' and 'Lags manipulation' can be used as the optimization tactic. An optimized alternative can be presented for each one of them separately, and another alternative for their combined usage, unless the user specifies that certain tactic or the combined optimization should be used as the default approach.

f) Cross-projects resource allocation can be selected by users according to their companies' requirements, but they should first specify for each resource to be optimized the average time and cost required for each mobilization/demobilization cycle. This time and cost can be further elaborated to the time and cost related to the route between two specific projects if this relocation was found to be optimum.

g) If cost is loaded to the schedule, then it must be included to optimization objectives based on the user's predefined criteria for which cost aspect to be monitored and optimized: cash flow, overall cost and/or costs on cost codes level.

h) All schedule indices can be used as optimization objectives based on predefined criteria from the user for which indices to be monitored and optimized.

i) The software tool should be an integrated solution with common software packages, where the tool can read from the existing packages' databases to produce schedule alternatives, and have the ability to write back to the same databases if changes were accepted for implementation or to store the alternatives as What-If schedules

4.5. Initial dynamic scheduling framework for construction enterprises

According to the results of the questionnaire survey and the extracted functional specifications, an initial framework for the solution can be

established as shown in this section. This framework will be further elaborated in the next chapter to develop the details of the proposed dynamic scheduling solution model for construction enterprises.

As shown in figure 4.2, there are four processes within the overall construction planning & scheduling process which involve schedules preparation; and accordingly, can be considered as four schedule optimization levels (or quality gates) where the implementation of a dynamic scheduling system can achieve better schedule quality:

1. Preparation of master schedule
2. Preparation of revised schedules
3. Preparation of what-if schedules
4. Preparation of look-ahead schedules
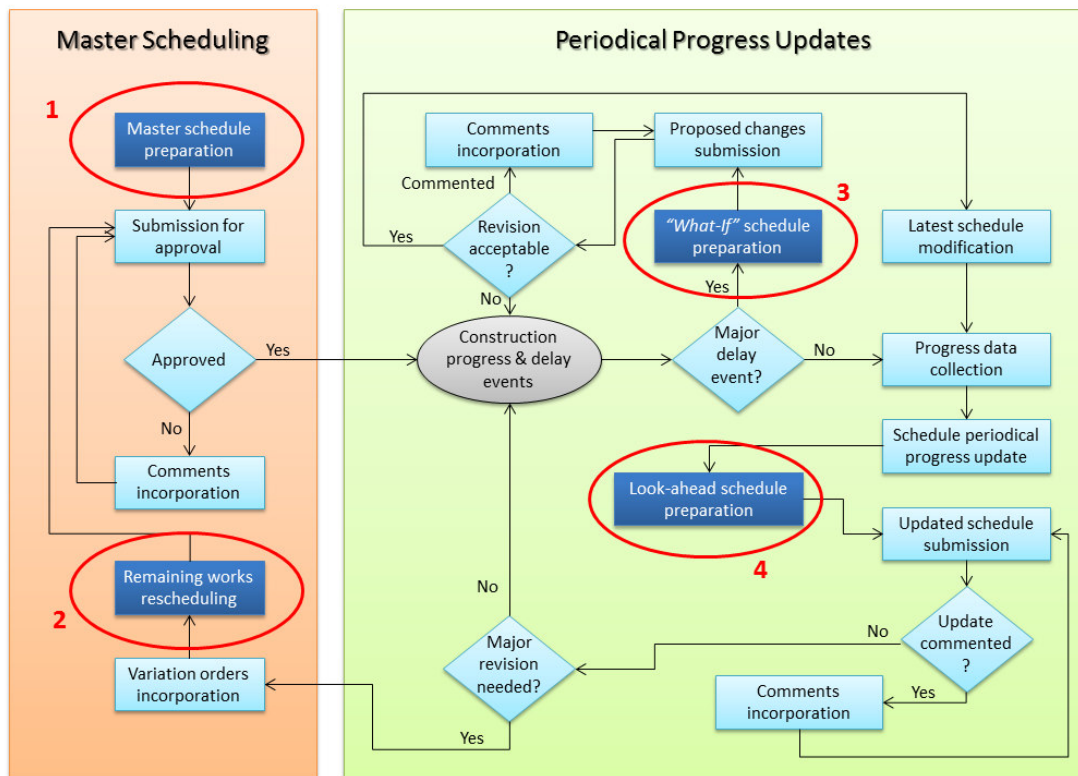
Figure 4.2: Scheduling quality gates in construction planning & scheduling process

A dynamic scheduling application in any construction project can utilize one or more of these levels. Each level is a single static optimization process, where if combined with another level(s), especially the combination of one level from "master scheduling" with another from "progress update", can form a general dynamic scheduling framework. However, the implementation of all levels will ensure the integrity of the dynamic scheduling process, and will

minimize the double entry of optimization related inputs if the framework is partially utilized.

4.5.1. The dynamic scheduling solution architecture

In order to design the architecture of the proposed solution, three main points should be primarily considered according to the earlier defined functional specification: fully integrated solution with current practices, the ability to view and/or alter optimization parameters and optimization results, and the ability to store optimization results for future reference.

Figure 4.3 shows the general architecture of the proposed solution which respects the above mentioned architectural requirements; where the proposed solution (titled as *Dynamic Scheduler*) is fully integrated with the database of the main planning & scheduling software package, to avoid double entries for project's data or progress updates, and avoid the need for an additional step within the system for the transfer of optimized solutions back. The *Dynamic Scheduler* contains a user interface which allows the manipulation of optimization parameters, viewing optimized solutions, confirming changes, as well as storing/retrieving optimized data into/from the *Dynamic Scheduler Database (DSDB)*.
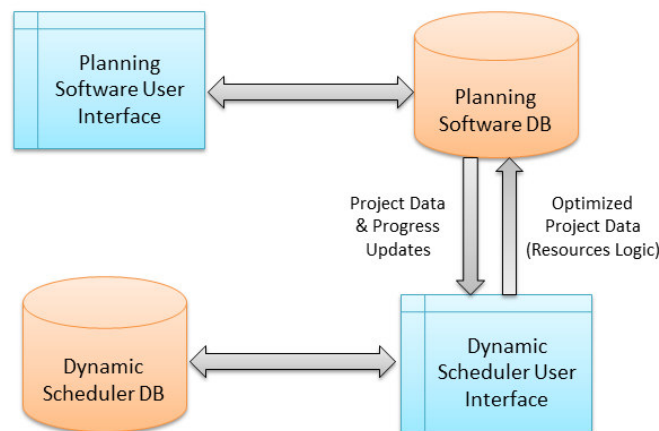
Figure 4.3: Initial dynamic scheduling solution architecture

This software tool is a prototype for the proof of concept, so it did not have to be integrated with all commonly used planning software packages; accordingly, it was integrated with the most commonly used package, which is *Primavera Project Management*® software (as defined in the functional specs). The software tool's architectural design will be further elaborated in Chapter 9, along with its functionality description.

4.6. Summary

This chapter reviewed the general processes performed within construction planning & scheduling. Then, details of the questionnaire survey performed to collect the construction project management practitioners' opinions about the problem under study and its proposed solution were explained. The survey responses were analyzed, and then used to define the proposed solution's functional specifications. And accordingly, an initial framework for the proposed dynamic scheduling solution was developed.

Chapter 5: Dynamic Scheduling Solution Modelling

5.1. Problem Definition

In principle, and according to the *Project management Institute's PMBOK® (Project Management Body of Knowledge guide, 2013), Scheduling* is the process of dividing the scope of work into several small elements (activities), then defining who will do them (resources), and their inter-dependencies (logic); and finally performing the time analysis to define various time properties for each element (early dates, late dates, floats, etc.).

Various scheduling methods were presented for implementing the time analysis concepts, starting from the US Navy's *PERT (Program Evaluation & Review Technique)* method in 1957, up to the *CCPM (Critical Chain Project Management)* method by *Goldratt (1997)*. The properties of the three main scheduling elements (activities, resources & logic) are usually not fully deterministic during initial stages of the project; these uncertainties caused the split of scheduling methods into two main paradigms: *Deterministic Methods* and *Un-deterministic Methods*.

Deterministic methods assume the initial availability of all schedule details. Critical Path Method (CPM), Resource-Constrained Project Scheduling (RCPS), Line of Balance (LOB), and Critical Chain Project Management (CCPM) are the most famous and commonly used deterministic methods in the research and practical fields of scheduling; while Un-deterministic Methods (such as PERT, GERT, and other Stochastic methods) deal with the schedule uncertainties, mainly processing times (or durations), with probabilistic approach. The information required for the analysis with un-deterministic methods (probability figures and duration possibilities) negatively affects the amount of inputs, as well as the complexity of the process, which makes these methods, in many cases, impractical for the use in regular day to day scheduling practices, especially in construction industry.

Dynamic Scheduling, as explained in the chapter 3, can be summarized as *a continuous dynamic process of updating, checking and revising the schedule according to the selected scheduling architecture and based on predefined rescheduling strategy, policy and rescheduling technique.* The scheduling/rescheduling processes involve regular deterministic scheduling methods for the analysis, while effects of real-time events and uncertainties are mitigated with the continuous schedule adjustments and/or optimization.

5.2. The Dynamic Scheduling solution's design

The proposed Dynamic Scheduling solution's design processes, as shown in figure 5.1, can be arranged into two main phases: Modelling Phase and

Implementation Phase. The modelling phase involves the selection of a scheduling method which will be used for the analysis of schedule alternatives, development of a mathematical model for the problem elements (variables, constraints and objectives), selecting the rescheduling technique which suits the characteristics of the problem and the construction industry, and designing the architecture of the dynamic scheduling solution.

The *rescheduling strategy and policy* are dependent on the industry, project requirements & conditions, and end users' requirements; so, they will be defined by users during the implementation phase according to their project's specific conditions and requirements. Consequently, the solution must be designed to accommodate all possible rescheduling strategies and policies in order to give the flexibility to users to set the most suitable strategy and policy for their application.
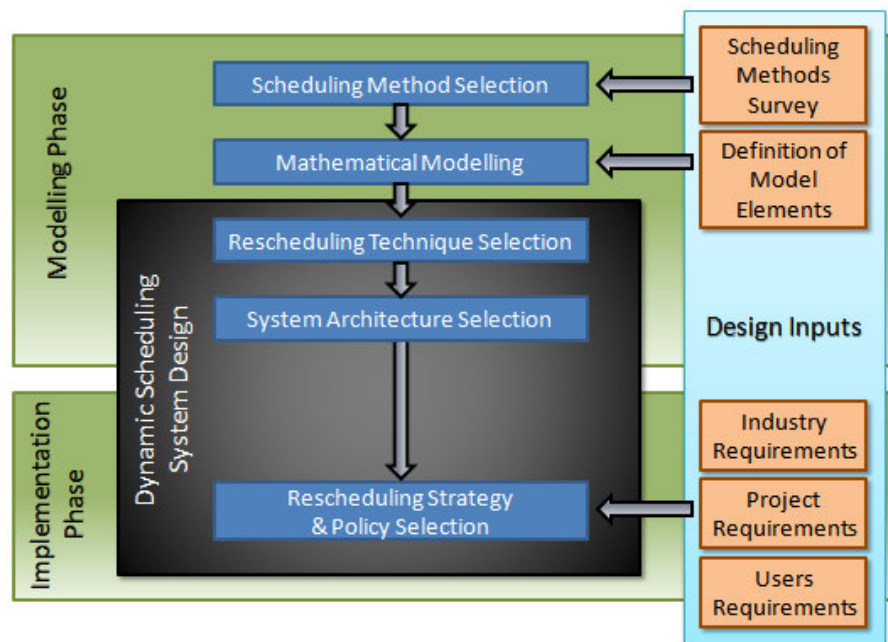
Figure 5.1: Dynamic scheduling solution design

5.3. Scheduling method selection

According to the literature review performed, the *Resource-Constrained Project Scheduling (RCPSP)* and the *Critical Chain Project Management (CCPM)* are currently the basis for almost all analysis/optimization models in the scheduling research field; especially RCPSP method with all of its extensions. The following section will review the history and the details of these two methods, and will accordingly analyse their suitability to the problem under study.

5.3.1. Resource-Constrained Project Scheduling Problem (RCPSP)

RCPSP, in principle, is an improved version of the original CPM after taking the resource limitations into consideration. It has become a well-known standard problem in the context of project scheduling, and has attracted numerous researchers who developed both exact and heuristic scheduling procedures *(Hartmann, 2010).*The *Job-Shop* problem in the manufacturing industry is one of the first problems which used the RCPSP concepts.

Due to the complexity of the problem, RCPSP became a very attractive field for researchers either in scheduling field or in operations research. *Herroelen (1998)* and *Brucker (1999)* reviewed RCPSP literature, and classified RCPSPs accordingly. They also proposed various optimization models for the problem's analysis. Another detailed survey was lately presented by *Hartmann (2010)* for variants and extensions of the RCPSP.

The original (or basic) RCPSP can be summarized, without mathematical notations, as the presentation of a project's activities, resource requirements for each activity and the limitations of each resource; with the assumption that all information about durations, precedence, resources requirements and resources availability are deterministic and known in advance.

Several extensions to the RCPSP were presented during the last two decades attempting to improve the problem's presentation to match the real life problem's characteristics. The following points briefly summarize the main RCPSP's extensions:

- *Pre-emptive Scheduling:* The basic RCPSP assumes uninterruptable execution of each activity. *Demeulemeester and Herroelen (1996b)* presented a solution in the modelling of Pre-emptive Scheduling, where each activity can be interrupted after each integer time unit of its duration. The number of interruptions can be limited by an additional variable *(Ballestin, 2008). Frank et al. (2001)* proposed calendar scheduling including pre-emptive concepts.

- *Multi-Mode Scheduling: Elmaghraby (1977)* started the approach of working with activity networks where each activity can be executed by one or more alternatives (modes). Each mode represents different duration and different resource requirements. *Multi-mode Resource–Constrained Project Scheduling (MRCPSP)* became one of the main extensions of the RCPSP. MRCPSP was adopted by large number of researchers, who developed the multi-mode concept with various other extensions. For instance, *Li (2008)* developed a MRCPSP model taking quality measures into consideration, where each mode is associated with a value representing the quality of its outputs, and one of the problem objectives is to maximize the overall solution quality.

- *Time-Cost Trade-off Problem (TCTP) [or the Resource Investment Problem (RIP)]:* In the basic RCPSP and the MRCPSP, non-renewable resources (such as budget) were not considered in the initial problem models. One of the main objectives of the RCPSP is to minimize the project overall duration; so, in the multi-mode analysis, if the cost is not considered, the mode with minimum duration will be selected in all activities. However, in most cases, adding more resources to reduce duration, or replacing resources with more productive ones, will add additional costs to the project; which must not be entertained in excess of the available budget. So, to overcome this, either to add budget to the model as a non-renewable resource (which must not be consumed above a predefined value), or to add the cost as the model objective (if the time can be constrained to a predefined completion date). Various models were generated to present and solve the TCTP (such as *Demeulemeester (1998)* and *Ranjbar (2008)*).

- *Time/Resource Trade-off Problem (TRTP) [or the Resource Levelling Problem (RLP)]:* A similar approach to the TCTP was required to handle the balance between resource availability constraints of renewable resources and the project time frame. TRTP modelling examples were presented by *Demeulemeester (2000)* and *Ranjbar (2007, 2009)*.

- *Minimum & Maximum Time Lags:* Basic RCPSP deals with activities relations on a *Finish-to-Start (FS)* basis; however real-life scheduling is way beyond that. Minimum time lags are generally required for activities overlapping, while maximum time lags are required for representing deadlines or maximum execution period of a group of activities (for example a group of activities sharing a scarce resource). *Neumann et al (2003b)* surveyed the characteristics and models presented for time lags implementation.

- *Resources Irregularities:* Various practical concepts for resources irregularities were added to the RCPSP, such as the varying capacities with time for renewable resources. Cumulative Resources is another resources irregularity, it was introduced by *Neumann (2002)* as a resource which is produced by some activities, cumulated in a storage area, and then used by other activities (for example: precast elements in construction projects).

- *Non-Regular Objective Functions:* As mentioned in the context, the objective function for the original RCPSP was to minimize the time span; however, many other objectives were introduced to the problem

models, such as minimizing cost, minimizing negative cash flows, and increasing the schedule quality and robustness (flexibility).

- *Stochastic activity durations:* Stochastic resource-constrained project scheduling is a probabilistic approach which aims at scheduling project activities with uncertain durations *(Herroelen, 2005)*. The duration of activities is defined in the problem model by random vectors of durations, which are distributed according to a deterministic probability distribution *(Brucker, 1999)*. This approach aimed to close the gap between deterministic and un-deterministic methods.

5.3.2. Critical Chain Project Management (CCPM)

Eliyahu Goldratt introduced in his novel *"The Goal" (Goldratt, 1984),* an approach for operations management which he called the *Theory of Constraint (TOC).* His management philosophy was that any manageable system is limited in achieving more of its goal by a very small number of constraints, and that there is always at least one constraint. The TOC process seeks to identify the constraints and restructure the rest of the organization around them.

The book was a best seller for years, and the TOC concept opened a large field of debate. Sometime the concept was resisted *(Duncan, 1999)*, and sometimes acknowledged as a source of discipline to Project Management *(Elton, 2001)*. In addition, there are some indications that this technique is increasingly being used *(Steyn, 2001)*.

Goldratt further elaborated the TOC concepts toward project management and introduced the concepts of *Critical Chain Project Management (CCPM)* in his book *"Critical Chain"* in *1997*. The book explained the CCPM concept through a simple novel, not in the regular scientific or mathematical explanations approach.

In general, CCPM is a method of planning and managing projects that puts the main emphasis on the resources required to execute project tasks. It involves the analysis of both activities and resources dependencies; however, in the monitoring process, the Critical Chain (CC) should always take the focus, not the Critical Path (CP).

CCPM focuses on the constraints of a project which prevent achieving its goals *(Rabbani, 2007)*. It uses a deterministic schedule integrated by a buffer mechanism to deal with both resource constraints and uncertainty *(Long, 2008)*.The Critical Chain is the sequence of both activities precedence and resources dependencies that prevents the project from being completed in a shorter time, given finite resources. If resources are always available in unlimited quantities, then a project's critical chain is identical to its critical path.

Critical Chain analysis *(Goldratt, 1997)* is used as an alternative to Critical Path analysis. The main features that distinguish the critical chain from the critical path are:

- Resource dependencies are not shown in the network as logic links, but they are implicitly used through visual presentation (colouring).

- Removal of all contingency periods included within activity durations, and inserting them back to the project network as clearly identified buffers. In addition to usage of 50% probable activity durations.

- Monitoring project progress and health by monitoring the consumption rate of the buffers rather than monitoring individual tasks performance.

Goldratt classified buffers into three categories: project, feeding & resource buffer. *Leach (2005)* added two more buffer categories: strategic resource buffer and drum buffer. The following definitions explain the location and purpose of each buffer type:

1. *Project buffer:* Added at the end of the project as a contingency period for the delays of the Critical Chain.

2. *Feeding buffer:* A contingency period located at the end of each path in the project (except the Critical Chain), it resembles the Total Float of non-critical paths in the CPM.

3. *Resource buffer:* Added to any critical resource before its use on the Critical Chain. The buffer will not interrupt the predecessor usage of the resource; however, it will run parallel to it as a warning that the resource should complete on-time before its scheduled start on the critical activities.

4. *Strategic Resource buffer:* A time period during which the critical resource will have no scheduled work. This insulates each project that uses the strategic resource from impacts of previous projects and ensures that future projects will not be impacted by uncertainty affecting the strategic resource.

5. *Drum buffer:* A period of time placed between projects to avoid projects contention on a Drum resource (the Critical resource used for inter-projects scheduling).

5.3.3. RCPS vs. CCPM

Elton and Roe (2001) stated that the TOC & the CC concepts work well when dealing with individual projects, but they short fall in explaining how companies could best manage a portfolio of projects, which requires further advice to be given in parallel with *Goldratt's* guidelines.

Despite of the large debate on the CCPM, the research efforts around its concepts is few and scattered. Although several implementations to the CCPM concepts were presented during the last two decades (such as integrating CC concepts to EPC projects by *Yeo, (2002)*), only few researches were presented for improvement or extending this technique (such as the Critical Resource Chain framework presented by *Liu and Shih (2009-a)*).

On the other hand, RCPS detailed almost all possible constraints and complexities of the scheduling problem; in addition, all these details were mathematically modelled and tested in many researches, which makes the life easier for any researcher in the field to pick and implement readymade and tested models. However, nothing is perfect, when *Goldratt* presented the CCPM in 1997 he was looking on the main shortfall of the RCPS, practicality. It is hard to present that the RCPS or its base CPM lack practicality; and I believe this is the main reason why *Goldratt* presented his new modelling concept in the form of a novel, just to prove that in real life things happen in a bit different way than the concepts of RCPS or CPM.

It is also unfair to judge RCPS to be impractical, while almost all practical implementations of scheduling worldwide are based on its concepts. In my opinion, the key issue in this dilemma is that originally CPM was built on the concept that activities are the main element of scheduling, while resources, as the secondary element, are assigned to activities and scheduled based on the logic of the main element, activities. This concept caused many hidden difficulties in the scheduling field, such as the need for resource limitation constraints, and the need for segregating hard logic (or sequence logic) from soft logic (or resource logic) in order to facilitate the manipulation of soft logic while optimizing the schedule, whether manually or via an automated system.

CCPM tried to overcome this issue by highlighting (graphically) that resources are as important as activities, and in most cases resources are leading the critical path of projects. In addition, it added some concepts like buffers, which uncovered some practically hidden difficulties in the projects control processes.

Originally, the judgment on CCPM was that *"the technique can be considered as an innovation that would be useful to organizations capable of accepting a new paradigm" (Steyn, 2001)*. However, in later researches, another opinion was expressed as *"Although, this methodology has acted as an important eye-opener, its pitfalls in oversimplification of the problem have been revealed recently" (Herroelen, 2005)*.

5.3.4. The need for a new scheduling method

Before detailing the concepts of the new proposed scheduling method, let's review the definition of modelling and use it to measure the efficiency of models available for current scheduling methods (mainly RCPS):

"Modelling, or the process of constructing a model, is the representation of a designed or actual object, process, or system, a representation of a reality. A model must capture and represent the reality being modelled as closely as its particle, it must include the essential features of the reality, in respect of the purpose of constructing the model, whilst being reasonably cheap to construct and operate, and easy to use." (Fellows and Liu, 2008)

Two main characteristics of a model were included in the previous definition: *capture and represent the reality being modelled*, and *being reasonably cheap to construct and operate.* RCPSP with its extensions was mostly successful in the concept of representing reality; however, it partially failed with respect to resources and resource assignments modelling, and this is the main concept on which the CCPM was built on.

In addition, RCPSP modelling can also be deemed to partially fail with respect to being cheap for optimization (i.e. requires large calculation time). Most of the RCPS researchers might not accept the previous statement. But if we thought from a practical point of view, most of the researches verified their models and tested the performance of their algorithms using problem sets with average number of activities between 30 to 120 activities (mainly *Patterson (1984)* and *Kolisch (1995)* problem sets) and up to a maximum of 500 activities in few special case problems; while in reality, especially in construction industry, a medium sized schedule will have an average of 500 to 1,000 activities. Very few researches expanded the size of the schedules under testing to the medium sized schedules, and the analysis in some cases with genetic algorithms exceeded 24 hours *(Fahmy, 2004)* with normal processing power (it might be a bit less with current processing power). So, it can be concluded that the required analysis time will almost be impractical to optimize a regular large scale project with an average of 5,000 to 20,000 activities, even with the current high processing power. For a dynamic scheduling solution, having interaction with users on hourly basis, models and algorithms with such performance will usually be unacceptable.

Based on the above literature review and without going further into more details and examples of the pros and cons of these two techniques, the difference can be summarized in one general statement: *RCPS is a well-defined system, properly modelled and successfully implemented, but it falls into few practical traps with respect to resource management and processing time. While CCPM highlighted most of the resource issues and presented concepts for integrating them, but it was not properly modelled to cover all*

field complexities, and consequently it was not professionally implemented in large scale applications.

So, the successful combination of the concepts of these two methods into an innovative method can be a breakthrough in the project management field practices. ***This research will attempt to present a new scheduling method which benefits from the pros of both scheduling paradigms (RCPS & CCPM), and develop a related mathematical model aiming to improve schedule analysis performance.***

5.4. Multi-Layer Scheduling (MLS) Modelling

It was obvious from the literature review that scheduling theories since their start were not giving resources the appropriate attention. And it was also obvious that there was always a continuous trend in the research and field practices to increase resources importance, starting from the resource-free CPM, to resource constrained techniques (RCPS), and finally to resource driven schedules of CCPM.

Various researches were presented to differentiate between sequence logic and resource logic. Other researchers presented and modelled the difference in calendars of activities and resources. In addition, it became a regular practice to create two different breakdown structures for each project: *Work Breakdown Structure (WBS)* for activities and *Organisational Breakdown Structure (OBS)* for resources. Based on the above analysis, it can be concluded that: ***Each schedule consists of two interlinked schedule layers: Activity Schedule Layer and Resource Schedule Layer.***

Many complex approaches were designed and practically implemented to accommodate both schedule layers in one layer presentation, without facing the fact that they are actually two different schedules. They have different breakdown, different behaviour, different logic type, different logic attitude, and different calendars.

It will not be a correct judgement to go to the other extreme of the discussion and state that there is only one schedule, *Resources Schedule*; and that activities are assigned to resources and not the reverse. This can be accepted and modelled theoretically, but not practically. Although any activity in the world is executed with resources, it is not practical for any organisation to model and schedule resources of other organisations. For example, a project for the construction of a power plant will contain many activities for design inputs, equipment procurement, and authorities approvals; and it will not be feasible for the contractor of the project to model in his schedule the designer's, the equipment manufacturers', or the governmental authorities resources which will be involved in the project's

activities. So, for practical purposes, the *Activity Schedule* must exist in the modelling process.

The fact that the currently implemented approaches for presenting activities and resources in one schedule are successfully implemented does not change the fact that there are actually two separate schedules, and that modelling them separately might simplify the whole scheduling process.

For the ease of presentation, and for the sake of avoiding terminology confusions, these two different schedules will be termed *Schedule Layers*; so that the term *schedule* is reserved to the overall schedule, which internally consists of two different layers: *Activity Layer* and *Resource Layer*. Each layer is presented, analysed and scheduled separately; then both layers are integrated together into a *Multi-Layer Schedule (MLS)*.
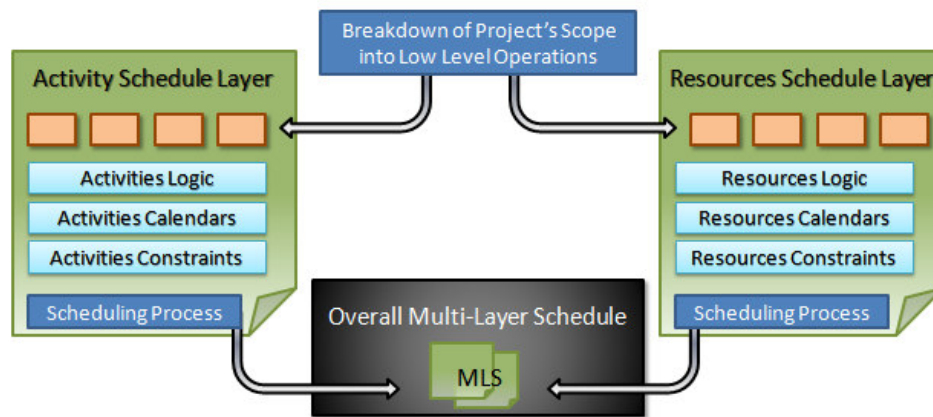
Figure 5.2: Multi-Layer Scheduling (MLS) architecture

Multi-Layer Scheduling (MLS), a new scheduling technique presented under this research, aimed to combine the benefits of the main techniques available in the scheduling context and to simplify the scheduling process. The details of this technique will be presented in the next section along with the model mathematical formulation, while its pros and cons will be reviewed later in the research after its concepts are modelled, and its performance and efficiency are tested.

The following section will go through the concepts of proposed MLS. The mathematical model will be formulated accordingly in chapter 6, and then a basic comparison with the RCPSP model will be performed to outline the compatibility with all RCPSP problem types.

5.4.1. Multi-Layer Scheduling (MLS) concepts

The main concept (or assumption) of the MLS is that there exist two schedule layers associated with each schedule, activity schedule layer, and resources schedule layer. Each layer is having its own characteristics: from the

breakdown structure, to types of logic and calendars, and down to the details of how each one is scheduled separately from the other.

As illustrated in figure 5.2, the project's scope should be broken down to the level of operations (ore resource assignments), where each operation is performed via single type resource crew, and consumes one or more non-renewable resources (a crew represents one or more proportionally related renewable resources, mainly driven by a single primary resource). These operations are then assigned on several WBS levels in the activities schedule layer, and again assigned to different Organisational Breakdown Structure (OBS) levels in the resources schedule layer.

The OBS represents the breakdown structure of renewable resource crews; while the non-renewable resources are loaded directly on operations, and can be viewed and accessed from both schedule layers.

The activities schedule layer is a presentation layer for the project's scope, while all optimization processes will be performed on the resources schedule layer. This is mainly because all problem objectives are resource related: resource distribution and levelling optimization, cost or budget optimization (which are represented as non-renewable resource), and even time limit constraints can be normally analysed on operations loaded in the resources schedule layer.

From the previous explanation there seem to be no added value, but the forecast strength of this method lies in its simplicity and less processing time.

With respect to simplicity of application, presenting the resources operations in a separate schedule allowing the ease of resource assignments rearrangement without going through the other schedule complexities can be a great added value to planners, even if they are doing the schedule optimization manually. This will be further investigated along with the model and the software validation process.

While for processing time, splitting the activities precedence and constraints from that of resources can reduce the calculation time during optimization; because, as shown in figure 5.3, the activities schedule layer will be processed only one time during the overall optimisation run, while its data will be merged with the resources outputs in a simpler process along with each analysis cycle.

The MLS basically contains three processes: *Activity Layer Scheduling*, *Resource Layer Scheduling* and *Layers Merging*. Balance processes shown in figure 5.3 are related to the *Optimization Algorithm* and will be explained in detail in later chapters.
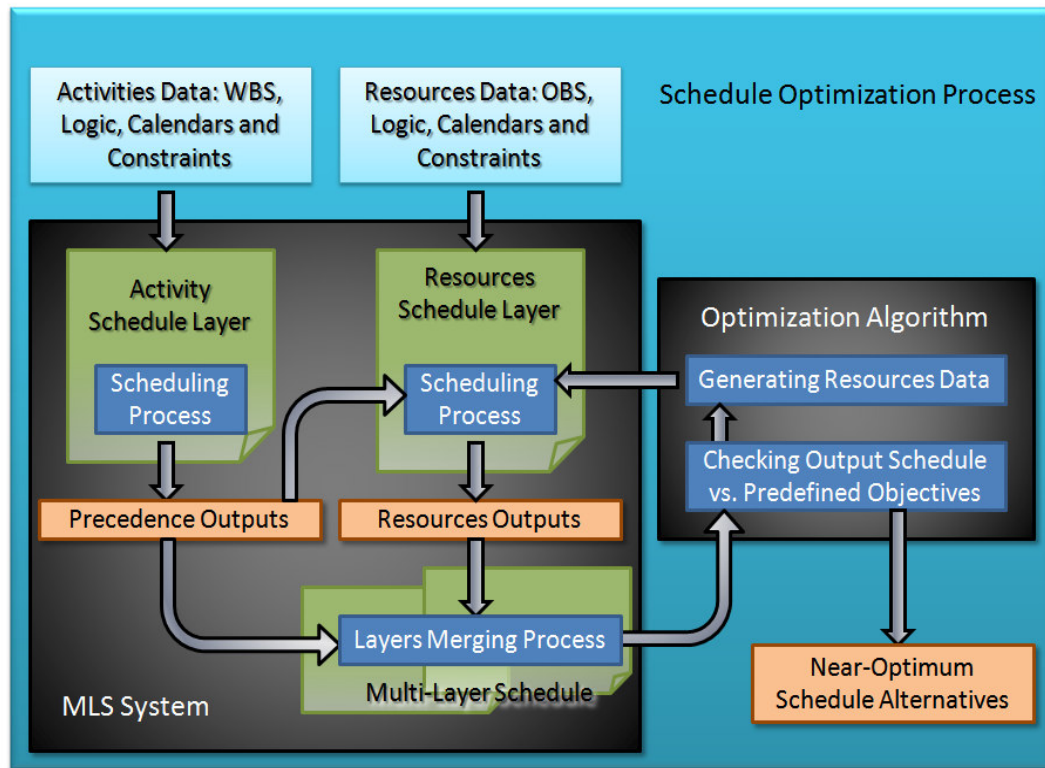
Figure 5.3: Multi-Layer scheduling optimization process

Activity Layer Scheduling process is nothing beyond the well-known CPM scheduling process. *Layers Merging* involves combining the logic and the calendars from both schedule layers, and then performs another CPM scheduling process. All the new concepts presented in MLS lay inside the *Resource Layer Scheduling (RL Scheduling)* process.

As shown in figure 5.3, the RL scheduling involves the generation of the schedule from a predefined activity layer outputs (precedence logic, constraints & dates) and from *resources data* generated by the optimization algorithm. These resources data can be in the form of resources logic, or in the form of operations scheduling sequence.

The most famous presentation of optimization algorithms outputs in the scheduling context is the activities sequence. Using this sequence to generate the schedule is called the *Schedule Generation Scheme (SGS)* and as presented by *Kelly (1993)* can either be in parallel (PSGS) or in series (SSGS). SGSs will be reviewed and discussed in detail in chapter 7.

This presentation will be adopted as the optimization algorithm's output, and the generated schedule will be used afterwards to define a set of resources layer logic (or the soft logic).

The following example will simply demonstrate the basic concepts of RL Scheduling:

The example which *Herreoelen (1998)* used to explain basic RCPSP concepts is simple enough and sufficient to be used from an MLS perspective to illustrate how RL scheduling works.

The project consists of 7 activities + 2 dummy activities (as required by RCPSP modelling), and 1 resource type (with maximum availability of 5 units). The resource requirements are indicated below each activity on the activity network in figure 5.4. The target of the optimization process is to minimize the overall network's duration without exceeding the resource availability constraint (the optimum solution for this example is 7 time units, as shown in the resource profile in figure 5.4).
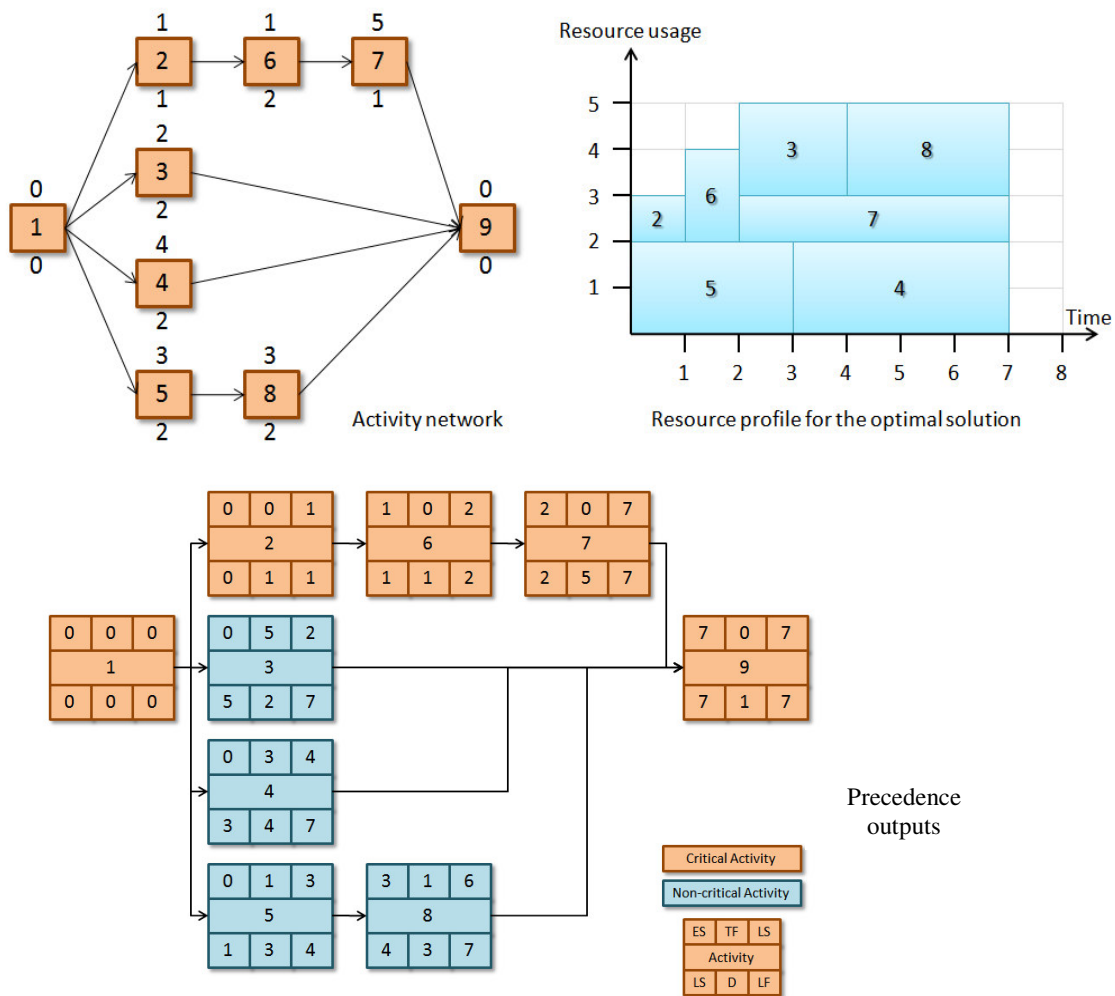
Figure 5.4: Example 5.1 activity network, optimum resource profile & precedence outputs

The first step in the MLS is to breakdown the scope into operations. The main characteristic of a single operation is that it requires a single resource (or single crew) to be processed. So, there is no work required to prepare the

network of example 5.1 for MLS analysis except calling the activities as operations. The second step is to schedule the ALS and generate the *Precedence Outputs*, or the operations' early and late dates.

If we refer back to figure 5.3, the RLS requires two inputs to commence: *Precedence Outputs* and *Resource Data*. *Resource Data* is basically the planned resources sequence, and the alternative operations resource modes; both are either prepared manually or generated via the optimisation algorithm.

In this example, there are few operations sequences which can achieve the optimum solution as shown in figure 5.4, such as: 5-4-2-6-7-3-8, 2-6-7-5-4-3-8, 5-2-6-4-7-3-8 ...etc. This solution can be translated into the following resource logic set: 5-4, 6-3, and 3-8.

5.5. The Dynamic Scheduling solution framework

An initial framework for the proposed dynamic scheduling solution was defined in the previous chapter. This framework will be further elaborated in this section with the MLS concepts and the detailed design of the model framework as per the construction industry's functional requirements.

5.5.1. The general architecture of the DS model

In section 4.5, four schedule optimization levels (or quality gates) within the construction planning & scheduling process where identified as the possible levels of dynamic scheduling implementation: Preparation of master schedule, preparation of revised schedules, preparation of what-if schedules, and preparation of look-ahead schedules. All four levels are common in one thing, that they can be treated almost the same from the solution's general architectural framework perspective. Within each of the four levels, the inputs are prepared in the planning software, then the schedule is passed to the optimization software tool to optimize it, alternatives are presented, user makes selection, and optimized schedule is returned back to the planning software.

Figure 5.5 details the above mentioned summary framework, where the original practice processes shown in the left side of the figure (within the user interface block of the planning software) consists of *preparing schedule*, *manual optimization*, *final review and adjustment*, and *schedule submission*. According to the survey results, in 75-90% of the cases, the planners did not have the time to perform this step, either partially or fully. Thus, the proposed framework is conceptually based on replacing the *manual optimization* process with an automated optimization process with all its associated processes.
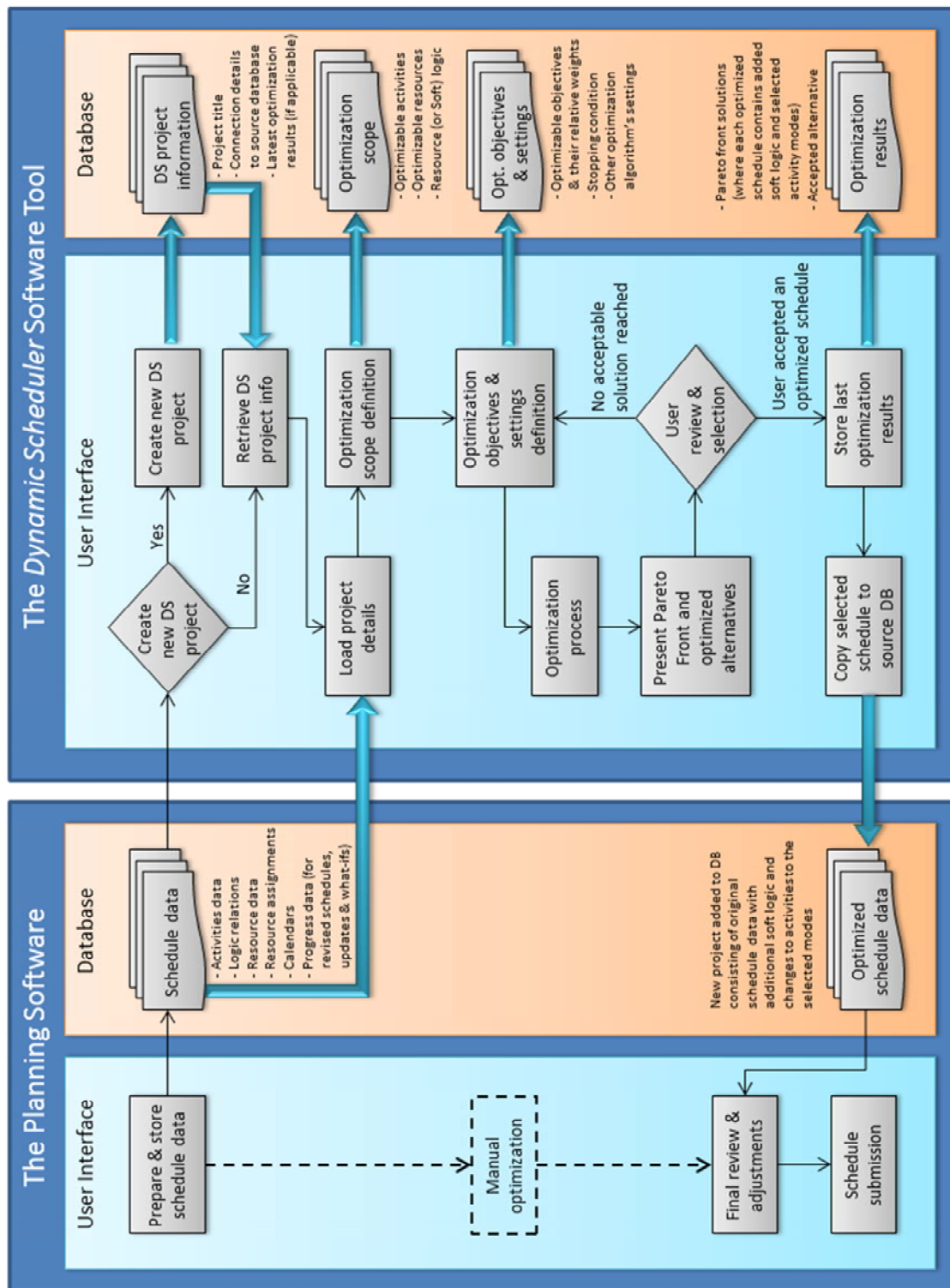
Figure 5.5: The general architectural framework for the proposed dynamic scheduling solution

The proposed dynamic scheduling framework start after the planner completes the initial preparation of his/her schedule, where all schedule data (activities, logic relations, resources, resource assignments, calendars, and progress data) are stored in the planning software's database. Then the planner

connects to the database from the *Dynamic Scheduler (DS)* software tool's user interface and creates a new DS project associated with his schedule. This DS project can be either new or existing (if the schedule to be optimized is a revised version or update of an old schedule already loaded in the DS).

The DS project will mainly contain information about the schedule it is associated with (with its different versions, if applicable), and about the connection details to the planning software database; in addition to the last optimization results, if the schedule already went through a previous optimization cycle. Then, the DS loads the necessary schedule's data directly from the planning software's database.

5.5.2. The optimization process

The optimization process starts with the definition of three main inputs groups: *optimization scope*, *optimization objectives*, and *optimization settings*. The *optimization scope* represents which activities to be optimized, which resources to be optimized, and the original schedule's soft logic; and accordingly, it can be considered as a definition of the dimensions of the search space. The activities to be optimized, or the *optimizable activities*, should by default include all schedule activities; however, in various cases, these will have to include a subset from the total set of activities. For example, for look-ahead schedules, this subset will contain the activities within the time frame of the look-ahead schedule. The resources to be optimized, or the *optimizable resources*, are a subset of the total set of resources representing the scarce resources to be considered during optimization. This functionality supports minimizing the computational burden of the optimization process. The last optimization scope element is the *soft logic*, where the planner must categorize all schedule logic relations into *hard* and *soft logic*. Basically, the *soft logic* will be manipulated by the optimization algorithm, whenever necessary, to achieve better optimization results. Optimization scope will be discussed further in the next chapter during the mathematical model formulation.

The second optimization inputs group is the *optimization objectives*, where the planner defines the purpose of the optimization process through defining the required objectives and providing relative weights between them. Optimization objectives will be explained in detail in the next chapter, starting from the objectives available in literature, to the additional objectives to be added due to practical considerations.

And finally, the *optimization settings* represent how the optimization algorithm will operate. It includes the optimization stopping condition (either

by analysis time or by the number of generated schedules), and any other algorithm's parameters (based on the selected optimization technique).

5.5.3. Alternatives presentation

After the stopping condition is reached, optimization process terminates, and the DS should present the optimized alternatives in the form of a *Pareto Front*, where each objective will have its best optimized solution, and there will be an overall best solution according to a weighted objectives assessment. This calculation & presentation structure will be also discussed in the mathematical model formulation.

The DS should have at least few basic user interface capabilities to represent the main characteristics of the optimized alternatives to enable the user (or the planner) to choose either to select one of the presented solutions, or to make some adjustments to the optimization objectives and/or settings to improve the next optimization results.

When an optimized schedule is selected, the DS stores the optimization results to the DS database (including the *Pareto Front* and the selected alternative), and then copies the optimized schedule back to the planning software's database. Taking into consideration, that according to the survey's results, the optimized schedule should be copied as a new project and not to modify the original project; which gives the ability to the planner to review the schedule in the planning software, and make any necessary final adjustments before submission.

For any optimized schedule, the data to be stored is the added/deleted soft logic and the selected activity modes (if activity modes are selected). And accordingly, the new project to be stored in the planning software is basically the original schedule with added/deleted resources (or soft) logic, and with changes to activities based on the selected modes.

5.6. Rescheduling technique selection

The MLS model formulation process was mainly oriented towards the simplification of the problem and the reduction of solutions space; so, a decision on whether to use a *Heuristic Technique* or a *Meta-Heuristic Technique* cannot be made without examining the performance of the model under different project scales.

So, the rescheduling technique selection will have to follow the model verification section of the research (chapter 8). The ideal situation will be that a regular heuristic algorithm using an exact technique such as Branch & Bound method *(Land & Doig, 1960)* can be used for large schedules. But, it

will be illustrated in chapter 8, that the need for *Meta-Heuristics* is a must for large scale schedules.

5.7. Dynamic scheduling architecture selection

The need for Multi-Agent architecture is mainly to reduce calculation burden, and remove bottle necks in decision making which occur when any decision needs to be sent back to the main central system for overall optimization checks. In the construction industry, the non-automated implementation of the *Mediator* architecture *(Parunak, 1987)* makes the scheduling process efficiency purely dependent on the capabilities of the planner (*mediator*) to capture the different alternatives from all functional levels (*agents*) and to properly integrate them present the final solution to management to support decision making; which might result, in most cases, that the outputs of the overall process become far beyond the optimum/near-optimum solution.

So, this research will concentrate in the Software Tool development phase on modelling the concepts of *Multi-Agent Mediator* architecture in an automated system which can be easily used in the day to day planning and scheduling practices, by involving the different decision levels and automating the decision process based on optimized alternatives.

5.8. Rescheduling strategy and policy selection

As explained in section 5.2, the *rescheduling strategy and policy* are dependent on the industry, project, and users requirements; so, during the implementation phase, users will define the required strategy and policy according to the variant conditions and requirements. According to the defined framework, this selection is to define which combination of the four levels of optimization will be adopted within the project planning & scheduling process.

5.9. Summary

In this Chapter, the proposed dynamic scheduling solution's design process was explained, along with a literature review to the main scheduling models. The details of the proposed solution were identified starting from the general framework, down to the details of the solution integration and the dynamic scheduling solution's elements details. Each of the proposed solution's detailed elements will be developed, verified and validated in the following Chapters.

Chapter 6: Mathematical Model Formulation

6.1. Formulation objectives

The *Project Scheduling Problems (PSPs)* has attracted large number of researchers during the last two decades due to the challenging characteristics of the problem with respect to modelling, solution methods and algorithms. Numerous numbers of researches were presented within the *PSP* context, the vast majority of which focused on one *PSP* problem type, the *Resource Constrained Project Scheduling Problem (RCPSP)*. Although researches in the *PSP* field might seem to be different, but according to the detailed surveys of the problem developments and extensions (*Icmeli et al, 1993; Herroelen et al, 1998; Brucker et al, 1999; Kolisch & Padman, 2000; Neumann et al, 2003a; Hartmann et al, 2010)* there is almost a common agreement about the concepts of how the problem should be mathematically modelled; however, the main differences were in the various problems classifications and the different mathematical notations used.

The *PSP* model was always presented in literature under several categories with different mathematical arrangements based on the problem's objectives. The multi-objective scheduling was initially introduced to the *PSP* literature by *Slowinski (1981)*; but despite of the numerous researches presented in the *PSP* context, there are only few papers dealing with the multi-objective scheduling problems *[c.f. Ballestín & Branco, 2011]*. In many practical applications, the optimization target is usually a combination of several objectives which might be with clearly deterministic importance (i.e. weight), or their importance might differ with time according to real-time conditions. So, *the first objective* of the model formulation is to combine the most important construction related optimization objectives under one generic model to be used by the dynamic scheduling algorithm.

Since the research is construction oriented, the need for the combined model can be further elaborated on the process of construction schedules optimization. For example, the purpose of construction projects baseline schedules optimization will usually be a combination of several objectives from the followings: minimizing completion date, minimizing overall project cost, reducing negative cash flow, increasing resources utilization, increasing schedule flexibility, ... etc. The weight of each of the previous objectives in the overall solutions evaluation will differ according to project conditions, client requirements, company strategy, and many other factors beyond the scope of this research.

During the life cycle of the project, schedule updates optimization objectives and their weights might dramatically differ; for example, if the client requested acceleration, cost objective weight should be reduced or even

dropped from the objectives of a *what-if schedule* optimization, because additional costs will be claimed to the client for approval along with the accelerated schedule. Or in some cases the cash flow weight might be increased when the project or the company is facing liquidity problems.

Since this research is construction oriented, the literature was reviewed for construction related dynamic scheduling mathematical models. The review outcomes identified very limited applications to construction, such as *Liu & Shih (2009)* and *Bakry et al (2014)*. *Liu & Shih (2009)* presented a general mathematical model for construction, with the option to choose from two objectives: minimize time and minimize cost; while, *Bakry et al (2014)* presented a model for specific application in repetitive construction projects. The questionnaire survey's results identified several objectives (beyond time & cost) to be taken into consideration, in addition to few other day-to-day practical requirements that must be considered in any construction oriented scheduling mathematical model. So, **the second objective** for the model formulation is to extend the structure of the multi-objective *PSP* mathematical model to match the construction industry requirements as defined in the survey's results.

6.2. Review of PSP mathematical models

This section will present a summarized literature review of the different mathematical modelling of PSP and their main extensions.

6.2.1. Basic RCPSP model

From the literature review and from the above mentioned surveys, a general model formulation of the basic RCPSP can be summarized as follows:

Objective:
$$\text{Minimize} \quad F_n \tag{6.1}$$

Subject to:
$$F_1 = 0, \tag{6.2}$$

$$F_j - d_j \geq F_i \; \forall (i,j) \in H; \; i,j \in V, \tag{6.3}$$

$$\sum_{i \in S_t} r_{ik} \leq a_k \; \forall k \in K; t = 1,2 \dots T, \tag{6.4}$$

Where:
V = Set of activities 1 to n, where 1 & n are dummy activities added for simplicity of calculations

H = Set of pairs of activities indicating their precedence

K = Set of renewable resources

F_j = Finish date for activity j

d_j = Duration of activity j

T = Time span of the schedule

S_t = Set of activities in progress within time interval *[t-1, t]*

r_{ik} = Activity *i* per period requirement from resource *k*

a_k = Available units from resource *k*

6.2.2. RCPSP model extensions

Several extensions to the RCPSP were presented to overcome the short falls of the basic RCPSP model and attempting to improve the problem presentation to match the real life problem's characteristics. The following points will go through the main changes presented to the basic model to accommodate the required extensions:

- *Pre-emption:* By allowing activities to be pre-empted at integer points, each activity *i* can be split into *j* sections equal in number to the activities duration d_i, then each reference for activity *i* in the equations will be in the form F_{ij} *or* d_{ij} . Related publications: *Demeulemeester & Herroelen [1996-b], Brucker & Knust [2001], and Ballestín et al [2008].*

- *Generalized Precedence Relations & Minimum/Maximum Time Lags:* The basic RCPSP assumes that all relations are Finish-to-Start with zero lag. So, in order to include other relation types and the lag period all relations will be transformed into Start-to-Start relations SS_{ij} with time lag l_{ij} corresponding to the original logic, and all constraints will have to refer to activities start dates S_i instead of their finish dates F_i . Related publications: *Chassiakos & Sakellaropoulos [2005], Klein & Scholl [2000], Vanhoucke [2006],* and *Demeulemeester & Herroelen [1996a].*

- *Multi-Mode Scheduling:* If each activity *i* will be having a set of activity modes M_i, then each activity in the constraints portion will be having an additional suffix *m* representing the activity mode. Related publications: *Kolisch & Drexl [1997], Hartmann [2001], and Alcaraz et al. [2003].*

- *Time/Resource Trade-off Problem (TRTP):* Several researches were introduced for TRTP for modelling an additional problem case for exchanging time with additional resources or vice versa. Additionally, time/resource trade-off can be extended with adding possibility for time/resource trade-off within activities by defining extra activity modes with different requirements of the same resource with corresponding activities durations *(Fahmy, 2004).* Related publications: *Deckro et al. [1995], Demeulemeester et al [2000] and Ranjbar & Kianfar [2007].*

By combining all the impacts of these extensions to the basic model, the problem formulation can be presented as follows:

Objective:

$$\text{Minimize} \quad S_{n,0} \tag{6.5}$$

Subject to:

$$S_{1,1} = 0, \tag{6.6}$$

$$S_{i,0} + l_{ij} \leq S_{j,0} \ \forall (i,j) \in L; \ i,j \in V, \tag{6.7}$$

$$S_{i,j-1} + 1 \leq S_{i,j}, i = 1,2 \dots n; j = 1,2 \dots d_{im}; m \in M_i, \tag{6.8}$$

$$\sum_{i \in S_t} r_{ijkm} \leq a_k \ \forall k \in K; j = 1,2 \dots d_{im}; m \in M_i; t = 1,2 \dots T \tag{6.9}$$

Where: V = Set of activities 1 to n, where 1 & n are dummy activities added for simplicity of calculations

L = Set of pairs of activities indicating their precedence (or logic relations) including time lags

K = Set of renewable resources

S_{ij} = Start date for section j of activity i

d_{im} = Duration of activity i in execution mode m

l_{ij} = Time lag between activities i and j

S_t = Set of activities in progress within time interval *[t-1, t]*

T = Time span of the schedule

r_{ijkm} = Section j of activity i per period requirement from resource k in execution mode m

a_k = Available units from renewable resource k

6.2.3. PSP objectives extensions

All previous extensions and models were related to minimizing the project's make-span; however, in some special cases of the PSP, other cost related objectives and constraints were introduced. The following points summarize the RCPSP extensions related to different problem objectives (i.e. different objective functions):

- *Time-Cost Trade-off Problem (TCTP):* Non-renewable resources (such as budget) can be considered in the initial problem models as an objective to be minimized. But in the literature, both objectives (reduce make-span and minimize cost) were not introduced as one objective function; they were introduced as one objective function and one extra constraint:

    Case 1: Minimize make-span, and constraint total costs with a predefined budget:

Objective Function: Minimize F_n (same as Eq. 6.1)

New Constraint: $\sum_{i \in V} c_i \leq C_{max}$ $\qquad\qquad$ (6.10)

Where: c_i = Cost of activity i

$\qquad\qquad C_{max}$ = Project maximum allowed cost

Case 2: Minimize total costs, and constraint total project make-span with a predefined target date or deadline date:

Objective Function: Minimize $\sum_{i \in V} c_i$ $\qquad$ (6.11)

New Constraint: $F_n \leq \bar{d}$ $\qquad\qquad$ (6.12)

Where: c_i = Cost of activity i

$\qquad\qquad \bar{d}$ = Project completion deadline

- *Cash flow constraints:* In few cases in reality, a maximum cash flow must be maintained less than a predefined liquidity for the project. To monitor periodical cash flow, several aspects should be loaded such as Advance Payment, Retention, Delay Period (from invoicing to actual payment), etc. Additional constraint can be added for this purpose:

New Constraint: $CF_t \geq -|NCF_{max}| \ \forall \ t = 1,2,..T$ (6.13)

Where: CF_t = Cash flow at period t

$\qquad NCF_{max}$ = Predefined maximum liquidity
$\qquad\qquad\qquad$ (negative cash flow)

- *Maximum Net Present Value (Max-NPV) & RCPSP with Discounted Cash-flow (RCPSP-DC):* Both are special case of problems where the project is self-financed; so, the cash flow location on the project's time frame will matter to the overall project costs. To include this effect in the previous models, a value α representing the discount rate per period is exponentially added to form the overall discount rate for the project $q_t=exp(-\alpha t)$. These can be added to any of the above equations wherever needed, for example: the objective function 4.11 can be modified as $\sum_{i \in V} q_t CF_i$ where CF_i represents the discounted cash flow for activity i, or $CF_i = \sum_{i=1}^{d_i} c_{it} e^{\alpha(d_i - t)}$

6.2.4. Multi-Objective PSP (MOPSP) modelling

Based on the literature review of publications for general definitions and surveys of MOPSP modelling (*Hwang [1979], Slowinski [1981], Tung et al [1999], Hsu et al [2002], Kacem et al [2002a, 2002b], Loukil et al [2005],*

Xia & Wu [2005], and Ballestín [2011]), the modelling approaches can be classified under five main categories:

1) *Weighted Objectives:* Combining different objective functions under one weighted sum.

2) *Prioritized Objectives:* Objectives are ordered according to their priority and optimized accordingly.

3) *Targets Satisfaction:* Objectives are defined with target values for the optimization algorithm to satisfy or reach as close as possible to them.

4) *Pareto Approach:* Several efficient solutions are obtained representing the Pareto front for the decision maker to select the optimum.

5) *Interactive Approach:* A series of interactive steps with the decision maker, where several solutions are proposed in each step and the optimization algorithm will use the solutions considered effective by the decision maker to generate additional improved solutions in the next step.

6.3. Dynamic Scheduling mathematical model formulation

6.3.1. Definition of model optimization objectives

According to the formulation objectives presented earlier, the first purpose for the generation of the dynamic scheduling mathematical model is to combine the various problem objectives under one model which will be used for the schedule optimization process within the Dynamic Scheduling System.

To develop a generic mathematical model, all main objectives presented in the *PSP* context should be taken into consideration. So, the following objectives were considered in the development of the model:

1) Minimize Project time span:

$$Minimize \ \ T = S_n \tag{6.14}$$

2) Minimize Project overall cost, which implicitly includes the Resource Investment or Time-Resource Trade-Off problem objective, as well as Time-Cost Trade-Off problem objective (note: FC_i is the fixed cost of activity i , costs which are irrelevant to main resources defined in schedule):

$$Minimize \ \ C = \sum_{i \in V} FC_i + \sum_{k \in R} c_k * max\{\sum_{i=1}^{n} r_{ik}\} \tag{6.15}$$

3) Maximize resources utilization (i.e. minimize Resources Levels):

$$\text{Minimize} \quad RLI = log\left(\sum_{k \in R}(c_r/T_{min}) \times \sum_{t=0}^{T}\sum_{i \in V}(r_{ikt})^2 + \sum_{k \in N}u_k \times \sum_{t=0}^{T}\sum_{i \in V}(r_{ikt})^2 \right) \qquad (6.16)$$

4) Cash flow improvement (i.e. minimize Negative Cash Flows):

$$\text{Minimize} \quad NCF = abs(\sum_{t=1}^{T}min\{0, CF_t\}) \qquad (6.17)$$

5) Maximizing schedule stability/robustness (represented in its simplest form as the sum of total floats):

$$\text{Maximize} \quad SS = \sum_{i \in V}TF_i \qquad (6.18)$$

Any other financial related objectives such as Net Present Value (NPV), Discounted Cash-flow (DC) …etc., were not considered in the model to avoid unnecessary financial complications.

After the definition of optimization objectives, the next step is to define the approach of handling the multi-objective model. In general, the least complex model would adopt either the *Weighted Objectives* approach or the *Prioritized Objectives* approach, and leave the weights or priority selection to the experience of the decision maker. However, this decision is very hard to perform even for highly experienced practitioners, due to the dynamic nature of construction projects and the complexity of projects' conditions; and any slight change in the weights or priorities will cause considerable impact on the proposed optimum solution.

Furthermore, the results of the questionnaire survey showed that most field experts clearly expressed their interest of receiving several solution alternatives for their decision on which to be implemented; which seems to be logic, because even with very high modelling complexity, the system will never be able to capture all project aspects and stakeholders interests, which will require at the end an experienced opinion to select the most suitable solution to all project or company's conditions.

From the above considerations, the best approach to be used for the system to be practically usable is a combination between the *Weighted Objectives* and the *Pareto Approach*, where the first solution to be presented is the one achieving the best score in a weighted objective function. And the user can explore a set of other proposed solutions representing the Pareto front of the optimized solutions, where each solution is representing the optimum/near-optimum to one or more of the problem objectives.

6.3.2. Extensions for Dynamic Scheduling requirements

In order to achieve the requirements of the Dynamic Scheduling system presented earlier in the research, the following extensions should be included in the final model:

1) Additional objective was added for minimizing the *schedule's deviation* in order to measure the mass of changes (or disturbance) in the proposed solution in comparison to the original schedule. *Schedule Deviation (SD)* objective was modelled to minimize the amount of changed activity modes and the amount of deleted/added resources logic to the original schedule; thus to minimize project execution team's confusions, especially during schedule updates.

$$Minimize \quad SD = \sum_{i \in A} \begin{cases} 0, & where \quad m_i \in OM \\ 1, & otherwise \end{cases} + \\ \sum_{l \in RL} \begin{cases} 0, & where \quad l \in ORL \\ 1, & otherwise \end{cases} \qquad (6.19)$$

(Where: m_i is the selected mode for activity *(i)*, *OM* is the set of originally selected modes, *ORL* & *RL* are the sets of resource logic before & after optimization).

2) Another objective was added for "Maximizing Schedule Flexibility". One of the optimization actions is activities crashing (using activity modes with same resources but different resource levels and durations); and accordingly, the more the schedule is crashed (or durations reduced) the less flexible the schedule becomes:

$$Minimize \quad SC = \sum_{i \in V} (max\{0, OD_i - D_i\})^2 \qquad (6.20)$$

(Where: *SC is the total schedule crashing, OD_i* is original duration of activity *(i)* before starting optimization, and D_i is the duration after optimization).

3) The set of activities *V (*or *A* for simplicity*)* was split into: optimizable and non-optimizable activities, to enable the optimization algorithm to perform partial rescheduling, whenever necessary, by focusing on important activities to reduce the calculation burden *(OA ⊂ A)*. Optimizable activities *(OA)* can be defined by the decision maker as critical activities, near-critical activities, milestone related activities, predefined period look-ahead activities, or even the full schedule activities.

4) The set of resources *(R)* was also split into: Scarce and abundant resources, to enable the optimization algorithm to focus on important resources to reduce the calculation burden *(SR ⊂ R)*.

5) For combining all objectives under a weighted sum, all objectives should be either in a "*minimize*" or "*maximize*" form. So, the maximize schedule stability (SS) objective was transformed to minimize *total float consumption (TFC)* objective (or minimize schedule criticality), and was formulated as follows:

$$Minimize \ \ TFC = \sum_{i \in A}(OTF_i - TF_i) \tag{6.21}$$

(Where: *OTF$_i$* is the original total float for activity *(i)* before optimization)

The following extensions were also considered to match practical requirements of construction projects (as presented in the survey results):

1) The overall project indirect cost (any cost which does not directly relate to construction activities) will vary according to the project's time frame (or make-span); so, for the purpose of improving the outputs of the cost minimization objective, an additional value was added for per period indirect cost *(PIC). PIC* can be added as fixed (eq. 6.22), or variable (eq. 6.22) to be more generic:

$$Minimize \ \ C = PIC * T + \sum_{i \in A} FC_i + \\ \sum_{k \in R} c_k \times max\{\sum_{i \in A} r_{ik}\} \tag{6.22}$$

2) For renewable resources, the RCPSP model assumes that the resource cost is a one-time cost, and whether the resource was utilized for 10 periods or 100 periods, the cost will remain the same. This case might be valid in construction projects in rare cases, where the equipment will be purchased for the project, thus the one-time cost is the summation of equipment purchase value, mobilization cost, demobilization cost and less the salvage value. But this is not valid either for hired equipment, recruited manpower or for consumed construction materials, where the cost will differ according to the number of periods the resource will be used. So, to cover this gap, the resources main costs were split into two cost values: the one-time cost (c_r) and per-period cost or unit rate (u_{rt}). Resources can then have an assignment for one-time cost, unit rate, or both (for ex.: a regular case in construction industry is to purchase equipment for the project, while still pay few periodical expenses for operational expenses and maintenance). In addition, for practical considerations, especially for inter-project resource allocation, two more cost values should be defined: the mobilization cost mc_k and the demobilization cost dc_k.

$$Minimize \ \ C = \sum_{i \in A} FC_i + \sum_{k \in R}\left((mc_k + dc_k + c_k) \times \\ max\{\sum_{t=0}^{T} r_{kt}\}\right) + \sum_{t=0}^{T}(PIC_t + \sum_{k \in R}(r_{kt} \times u_{kt})) \tag{6.23}$$

3) Similar to the previous resources consideration, the resources availability variables should also be defined as either overall resource availability a_k (if the resource is an equipment to be purchased) or per-period resource availability a_{kt} (if the resource is to be hired, recruited or consumed).

6.3.3. Dynamic Multi-constrained Construction Project Scheduling Model (DMCPSM)

Based on the previous sections, the *Dynamic Multi-constrained Construction Project Scheduling mathematical Model (DMCPSM)* can be simplified as follows:

Givens:
>   Mandatory givens (*A, R, N, L, O* and *W*)
>
>   Optional givens (*OA, SR, SN, ORL, M, OM, AP, AS*)

Objective:

$$Maximize\ each\ efficiency\ objective\ function\ E_i \qquad \forall\ i \in COF$$

$$where\ \ E_{Total} = \sum_{i=1}^{n} E_i \times W_i \qquad (6.24)$$

Subject to the following constraints:
>   Mandatory (*Zero start, precedence* and *sectional sequence*)
>
>   Optional ($\overline{T}, \overline{C}, \overline{NCF}, ATC, R_A$ and R_T)

Outputs:
>   *Pareto Front (PF)* or a set of best achieved *Non-Feasible Solutions NFS* (ordered by degree of feasibility)

This summarized model will be detailed and explained in this section, taking into consideration that the objectives were transformed to their related efficiencies (as will be explained later) to give the ability to combine one or more objectives into weighted sum objective functions.

Givens:

Mandatory givens represent all main schedule information sets: *Activities (A), Renewable resources (R),* and *Logic relations (L)*; as well as optimization related sets: *optimization Objectives (O)* and *objectives Weightages (W).*

While optional givens involve two main groups: optional schedule data, and optimization data sets. The optional scheduling data is mainly related to multi-mode and pre-emption. This data includes a *set of activities possible modes (M)*; which if not provided, each activity will be assigned with a single mode with the schedule information provided in the set *(A)*. Additionally, *Original activity Modes (OM)* are required to identify for each activity which

of the possible modes is currently selected. *OM* for each activity is initialized as the first mode in its modes list (*OM$_i$=M$_{i,1}$*). While the *Allow Pre-emption (AP)* parameter provides a choice whether or not the algorithm can use *pre-emption* during optimization; and accordingly, a set of predefined *Activity Sections (AS)* can be provided, which if not given will be assumed as *M if AP=0, M*D if AP=1* (i.e. each activity will have a number of sections corresponding to its duration, each section with one time unit duration).

The optimization data sets are the sets to be defined to minimize the search space and accordingly reduce calculation burden. These sets are *Optimizable Activities (OA), Scarce Resources (SR),* and *Original Resources Logic (ORL).* The *OA* by default equals to *A* and can be adjusted to include any subset of *A* ($OA \subset A, default \ OA = A$); similarly, for resources (*SR = R),* and schedule logic *(ORL) = {}* (or empty set).

Objective:

As explained in the previous section, the model's optimization objective is to obtain the *Pareto Front (PF)*, which consists of the best achieved solution for each combination (one or more) of the provided objectives. For example, if the optimization objectives are *minimize time, minimize cost* and *minimize resource levels (i.e. maximize resource utilization)*; then, the optimization algorithm will run one time for each of the *combined objective functions (COF)* set; which, for this example, contains seven functions: (1) minimize time, (2) minimize cost, (3) minimize resource levels, (4) minimize time & cost, (5) minimize time & resource levels, (6) minimize cost & resource levels, and (7) Minimize time, cost & resource levels. Within each optimization cycle, the objective is calculated as per equation 6.25.

As mentioned earlier, objectives were transformed into efficiencies to be able to combine them into weighted objective functions. Where, for each objective, a minimum and maximum value should be defined; and accordingly, the related efficiency can then be calculated as how much the algorithm achieved from the best result (as shown in the following equation).

$$E_i = \frac{O_{max} - O_{current}}{O_{max} - O_{min}} \tag{6.25}$$

Where O_{max} & O_{min} are the maximum and minimum for the selected objective, and $O_{current}$ represents the current value for the objective. The objectives current value for each of the main model's objectives can be calculated as per equations 6.26 to 6.32; while, the minimums and maximums can be calculated as per equations 6.33 to 6.46.

O$_{current}$ equations:

$$T = S_n \tag{6.26}$$

(Where: S_n is start of the dummy activity n)

$$C = \sum_{i \in A} FC_i + \sum_{k \in R} \left((mc_k + dc_k + c_k) \times max\{\sum_{t=0}^{T} r_{kt}\} \right) + \sum_{t=0}^{T} (PIC_t + \sum_{k \in R} (r_{kt} \times u_{kt})) \quad (6.27)$$

(Where: *PIC* is the periodical indirect cost per unit time, FC_i is the fixed cost of activity *(i)*; mc_k, dc_k, c_k are the mobilization, demobilization, and the one-time costs for resource *(k)*; and u_{kt} is the cost rate for resource *(k)* at time period *t*)

$$RLI = log \left(\sum_{k \in SR} (u_k + c_k/T) \times \sum_{t=0}^{T} \left(\sum_{i \in A_t} r_{ikt} \right)^2 \right) \quad (6.28)$$

(Where: r_{ikt} is resource requirement of activity *(i)* from resource *(k)* at time period *(t)*. Note: The resources set used to calculate this objective is the scarce resource set *SR* and not the total resources set *R*. In addition, the *RLI* value increases exponentially with the schedule size; accordingly, the equation was enclosed in a *log* function to enable proper search space measurement)

$$NCF = abs(\sum_{t=1}^{T} min\{0, CF_t\}) \quad (6.29)$$

(Where: CF_t is cumulative cash flow at time interval *t*)

$$TFC = log(\sum_{i \in OA} (OTF_i - TF_i)) \quad (6.30)$$

(Where: OTF_i & TF_i are the original and current total float for activity *i*)

$$SD = \sum_{i \in A} \begin{cases} 0, & where \quad m_i \in OM \\ 1, & otherwise \end{cases} + \sum_{l \in RL} \begin{cases} 0, & where \quad l \in ORL \\ 1, & otherwise \end{cases}$$
$$(6.31)$$

(Where: *RL* is the set of current resource logic, *ORL* is the set of original resource logic before starting optimization)

$$SC = \sum_{i \in OA} (max\{0, OD_i - D_i\})^2 \quad (6.32)$$

(Where: OD_i is original duration of activity *(i)* before starting optimization; while, D_i is the duration of *(i)* with the currently selected activity mode)

O_{min} & O_{max} equations:

$$T_{min} = S_n \quad (6.33)$$

$$T_{max} = DD + \sum_{i \in A} \{max: D_i\} \quad (6.34)$$

The minimum duration corresponds to the start of the last activity (S_n) which can be obtained after the schedule is recalculated with all activities assigned with their minimum duration modes. The maximum overall duration is simply the sum of the longest duration activity mode in all activities, in addition to the *Data Date (DD)*.

$$C_{min} = \sum_{t=0}^{Tmin} PIC_t + \sum_{i \in A}\{min: FC_i + DC_i\} + \sum_{k \in R}(mc_k + dc_k + c_k) \times max\{r_k\} \tag{6.35}$$

$$C_{max} = \sum_{t=0}^{Tmax} PIC_t + \sum_{i \in A}\{max: FC_i + DC_i\} + \sum_{k \in R}\big((mc_k + dc_k + c_k) \times \sum_{i \in A}\{max: r_{ik}\}\big) \tag{6.36}$$

The minimum cost will occur considering the schedule is executed in its shortest time; activities are performed with lowest fixed cost activity modes and with activity codes with lowest direct cost of resource assignments; and finally, resources assignments are all executed in series. The maximum cost will occur considering the schedule is executed in its longest time; activities are performed with highest fixed cost activity modes and with activity codes with highest direct cost of resource assignments; and finally, resources assignments are all executed in parallel. Note: DC_i is the direct cost of activity i which represented by the cost of non-renewable resources ($\sum_{k \in R} d_i \times r_{ik}$).

$$RLI_{min} = log\big(\sum_{k \in SR}(u_k + c_k/T_{min}) \times \sum_{i \in A} min\{d_i \times (r_{ik})^2\}\big) \tag{6.37}$$

$$RLI_{max} = log\big(\sum_{k \in SR}(u_k + c_k/T_{min}) \times max\{d_i\} \times (\sum_{i \in A} r_{ik})^2\big) \tag{6.38}$$

The minimum resource levelling index will occur when all resource assignments are executed in series; while the maximum resource levelling index will occur when all resource assignments are executed in parallel. Resources were weighed according to their unit rate cost (note that one-time cost was added to unit rate after dividing it by the minimum project duration). In addition, for simplicity, durations in RLI_{max} equation were assumed equal to the duration of the maximum request.

$$NCF_{min} = 0 \tag{6.39}$$

$$NCF_{max} = C_{max} - Advance\ Payment \tag{6.40}$$

The minimum negative cash flow is zero when schedule is optimized to the extent that all project operations are financed from the cash-ins. The maximum negative cash flow is very difficult to assess, and accordingly it can only be theoretical assumed. Here it was proposed as the square of the maximum cost after deducting the advance payment (if applicable). This theoretical assumption considers that maximum negative cash flow will occur if all works are completed in one monitory period.

$$TFC_{min} = 0 \tag{6.41}$$

$$TFC_{max} = \sum_{i \in OA} OTF_i \tag{6.42}$$

The minimum total float consumption is zero when all activities retain their original total floats. The maximum total float consumption will occur if

all activities become critical, and their floats become equal to zero; thus, TFC_{max} is the sum of original total floats.

$$SD_{min} = 0 \tag{6.43}$$

$$SD_{max} = No.\,of\,Multiple\,mode\,activities + No.\,of\,ORL + \\ \sum_{k\in SR}(No.\,of\,assignments - 1) \tag{6.44}$$

The minimum schedule deviation index is zero when no change was performed to schedule. The maximum schedule deviation will occur if all activity modes are changed, all baseline resource logic are changed, and all resource assignments are executed in series which makes the required resource logic, per resource, corresponds to the number of assignments less one.

$$SC_{min} = 0 \tag{6.45}$$

$$SC_{max} = \sum_{i\in OA}(max\{D_i\} - min\{D_i\})^2 \tag{6.46}$$

The minimum schedule crashing is zero when all activities were not crashed, or no duration reduction was performed. The maximum schedule crashing occurs when all activities are changed from their smallest duration activity modes to their largest duration activity modes.

Constraints:

There are three mandatory constraints which should be part of any general mathematical model for *PSPs*: the *Data Date (DD)* (as per equation 6.47, here the zero is replaced with *DD* for consistency with dynamic scheduling) which means that the first activity should start at time interval zero, the *precedence* (eq. 6.48) which defines all schedule logic relations (here in a *start-to-start* relation, as explained earlier in the *PSP* review), and the *sectional sequence* (eq. 6.49) which introduces logic ties between each activity's sections to make sure that they will be planned in sequence if pre-emption is used.

$$S_{1,1} = DD, \tag{6.47}$$

$$S_{i,0} + l_{ij} \leq S_{j,0} \qquad \forall(i,j)\in L;\ i,j \in A\,, \tag{6.48}$$

$$S_{i,j-1} + 1 \leq S_{i,j} \qquad \forall i \in A; j \in AS_{m_i}; m_i \in M_i \tag{6.49}$$

The optional constraints mainly represent project specific requirement, such as a target completion $(\overline{T})$, a target budgeted cost $(\overline{C})$, maximum liquidity available for the project or maximum negative cash flow $(\overline{NCF})$, a set of activities' time constraints *(ATC)*, and two sets of resources availability constraints (R_A) and (R_T).

R_A and R_T are two sets representing the resources availability. R_A represent the per-period availability, where each resource availability constraint can be represented either by a single value for the availability

through the project time frame, or by a set of different availability values variant with time. While R_T represent the total availability, where non-renewable resources can have specific number of units available for the project consumption. For *ATC*, there are 3 main types *Start-On Constraints (SOC)* (including finish-on after conversion to start-on, by deducting duration), *Start-on or Earlier Constraints (SEC)* (including finish-on or earlier after conversion to start-on or earlier), and *Start-on or Later Constraints (SLC)* (including finish-on or later after conversion to start-on or later). Each set of *ATCs* consists of a set of pairs, activity IDs and the related time constraint.

$$S_n \leq \bar{T} \tag{6.50}$$

$$\sum_{i \in A} FC_i + \sum_{k \in R}\left((mc_k + dc_k + c_k) \times max\{\sum_{t=0}^{T} r_{kt}\}\right) + \\ \sum_{t=0}^{T}(PIC_t + \sum_{k\in R}(r_{kt} \times u_{kt})) \leq \bar{C} \tag{6.51}$$

$$CF_t \geq -|\overline{NCF}| \qquad \forall\, t = 1,2 \dots T \tag{6.52}$$

$$\begin{cases} a_k\, is\ a\ set\!: & \sum_{j\in A_t} r_{jkt} \leq a_{kt} \\ otherwise\!: & \sum_{j\in A_t} r_{jk} \leq a_k \end{cases} \quad \forall a_k \in R_A;\ t = 1,2 \dots T \tag{6.53}$$

$$\sum_{i\in A}(d_i \times r_{ik}) \leq a_k \qquad \forall\, a_k \in R_T \tag{6.54}$$

$$S_n = x_n \qquad\qquad \forall\, x \in SOC \tag{6.55}$$

$$S_n \leq x_n \qquad\qquad \forall\, x \in SEC \tag{6.56}$$

$$S_n \geq x_n \qquad\qquad \forall\, x \in SLC \tag{6.57}$$

Outputs:
The optimization outputs will vary depending on the quality of outputs achieved. If the algorithm was able to find any feasible solution, then the *Pareto Front (PF)* will be presented as the optimization output; otherwise, a set of best achieved *Non-Feasible Solutions (NFS)* will be presented. The *PF* consists of a set of pairs of objective (or combined objective) and the corresponding best solution achieved; while the *NFS* consists of a set of best achieved solutions ordered by their degree of feasibility.

6.4. Summary

In this Chapter, the *Dynamic Multi-constrained Construction Project Scheduling Model (DMCPSM)* has been formulated based on the combination of the various scheduling models & objectives in literature. The model is construction oriented, and accordingly it included also few parameters & objectives which has been derived from the practical considerations extracted from the empirical questionnaire survey.

Chapter 7: Differential Density Particle Swarm Optimization (DDPSO) Algorithm

For integrating the *Dynamic Multi-Constrained Project Scheduling Model (DMCPS)*, presented in the previous chapter, into an overall dynamic scheduling solution, an optimization algorithm should be developed with the ability to explore the search space generated by the model for finding the optimum solution as per the model's objectives.

Solving the scheduling problems followed three main approaches within literature: exact (or deterministic), heuristic and meta-heuristic. This chapter will review these three approaches; then an optimization method will be selected and justified; and finally an optimization algorithm will be developed accordingly.

7.1. Deterministic schedule optimization algorithms

Large number of deterministic algorithms was presented in the project scheduling literature. And in order to enable quick literature review of these algorithms without going deep in the details of their functionality, a conceptual explanation for the nature of different problem types will be presented, which will be used to categorize deterministic algorithms.

Based on the review of project scheduling problem types detailed in the previous chapter, the problem types can be categorized according to the nature of their resources profiles under two main categories: Resource Constrained Project Scheduling Problems (RCPSP) & Time Constrained Project Scheduling Problems (TCPSP). This categorization will support in the proper categorization of deterministic optimization algorithms found in literature.

As shown in figure 7.1, the RCPSP is simply fixing resources level(s) and targeting minimum completion time, while TCPSP is about fixing completion time and targeting minimum resources levels. Based on this simple definition, the RCPSP category includes the following problem types: Single mode resource constrained (SRCPSP), single mode resource constrained with maximum time lags (SRCPSP/max), multiple modes resource constrained (MRCPSP), and multiple modes resource constrained with maximum lags (MRCPSP/max). While TCPSP category includes the following problem types: Resource investment (RIPSP) or time/cost trade-off, resource investment with maximum time lags (RIPSP/max), resource levelling (RLPSP) or time/resource trade-off, and resource levelling with maximum time lags (RLPSP/max). Taking into consideration that cost related objectives: minimize cost and minimize liquidity (or negative cash flow) are

also included, where the cost and/or liquidity are modelled as a non-renewable resource; and the related problems can lie under the RCPSP if these cost resources are constrained or under the TCPSP if they are to be minimized.
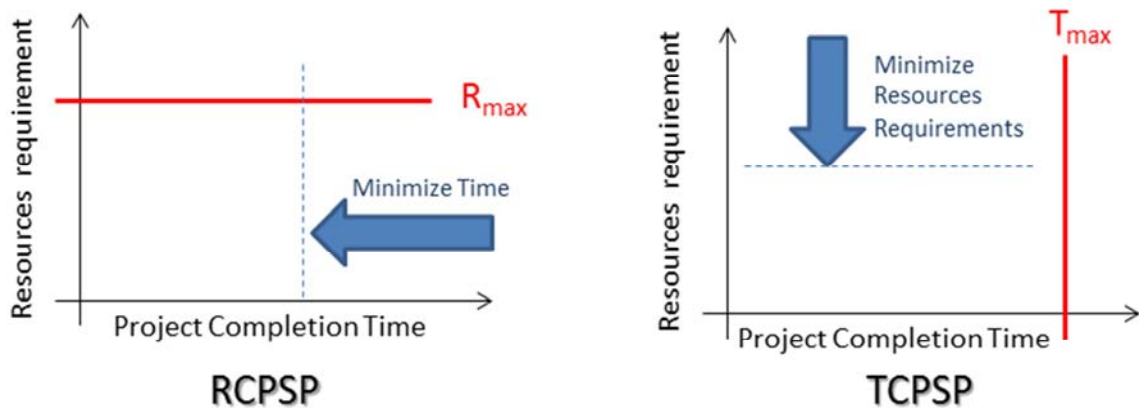
Figure 7.1: Resource profile categorization of Project Scheduling Problems (PSPs)

Accordingly, all deterministic schedule optimization algorithms in literature can be categorized under two corresponding categories: Time Minimization Algorithms (TMAs) for optimization of RCPSPs, and Resources Minimization Algorithms (RMAs) for optimization of TCPSPs. And a third category can also be defined for Multi-Objective Algorithms (MOAs).

Various algorithms in literature were presented under MOAs category using different heuristic solution methods; but, to the best of our knowledge, none was found with a deterministic approach.

Most of the deterministic algorithms found in literature lie under the TMAs category, and nearly all of them adopt the Branch & Bound as the solution method (originally presented by *Land & Doig, 1960*). Several Branch & Bound algorithms were developed and presented for solving RCPSPs deterministically (Demeulemeester & Herroelen, 1992; Brucker et al, 1998; Mingozzi et al, 1998; Klein & Scholl, 1999). A deterministic oriented survey was presented by *Kolisch & Padman (2001)*. For the requirements of this research, only few examples will be mentioned, whenever needed within this chapter (as well as in appendix A), for the purpose of explaining the elements and functional concepts of the newly developed algorithm and comparing them to algorithms existing in literature.

7.1.1. The Multi-Objective Branch & Bound (MOBB) algorithm

Several attempts were made during the research course for using one of the deterministic algorithms existing in literature and modifying it to solve both problems categories RCPSP & TCPSP. Each of the modified algorithms was well performing for most of the problem types under the same category; but

unfortunately, none of these modification attempts were successful to function properly for both categories. So, in order to proceed with the model's verification process, a new branch & bound algorithm was developed to match multi-objectives requirement; and the algorithm was titled the *Multi-Objective Branch & Bound (MOBB)* algorithm.

The results of the MOBB were not to a satisfactory level, especially if compared to the results of other algorithms in literature oriented for solving one scheduling problem type. However, it is not fair to compare a multi-objective algorithm to a single objective one; and for the first attempt for a deterministic algorithm to solve almost all scheduling problem types, the results can be considered reasonable, but should be subjected to several improvement cycles if the algorithm is to be used for practical applications. The details and test results of the MOBB are included in Appendix A.

7.2. Heuristic schedule optimization algorithms

RCPSP has been considered as NP-Hard in the strong sense *(Blazewicz et al, 1983)*, and accordingly for RCPSP (and other scheduling problems) most researches within the last two decades concentrated on heuristics & meta-heuristics for solving RCPSP. An extensive survey of all deterministic as well as heuristic procedures which are presented in the literature for the scheduling problems can be found in Chapters 6 and 8 of the Project Scheduling Research Handbook of *Demeulemeester & Herroelen (2002)*.

In simple terms, most heuristic approaches can be summarized as the process of generating & justifying a schedule from an ordered activity list; and accordingly these heuristics include 3 main elements: a *Priority Rule* to set the priority of each activity based on a predefined criteria, a *Schedule Generation Scheme (SGS)* to create the schedule based on the prioritized activity list, and a *Justification* technique to improve the quality of the generated schedule.

The *Priority rules* function is to arrange the activities list in an order which will generate a good solution. Priority rules were initially presented in the pioneering work of *Kelley (1963)*, which was then followed by many other researches presenting new priority rules and testing their performance (summarized in *Kolisch, 1996*b). After activities are prioritized, the second step is to generate the schedule using a *Schedule Generation Scheme (SGS)*. There are two types of *SGS*: *Serial (SSGS)* presented by *Kelley (1963)* and *Parallel (PSGS)* which have two associated algorithms in literature *Kelley (1963)* and *"Brooks Algorithm" (Bedworth & Bailey, 1982)*. A detailed description of SGSs was presented by *Kolisch (1996a)*.

Additionally, the *Forward-Backward Improvement (FBI)* proposed by *Li & Willis (1992)* was found to improve the results, by applying SGS in a

forward direction and performing another cycle in reverse order and backward scheduling (reversed precedence network).

And finally, the schedule quality can be improved by the simple Justification scheme proposed by *Valls et al (2005)*. Justification involves two successive cycles of shifting the activities in the current project time frame (right shifting then left shifting) without violating the resource constraints; this guarantees that the project makespan will be either the same or shorter. A new justification technique, *Stacking Justification*, was developed and proposed under this research, with a variation to the original technique in the activities selection criteria in each justification cycle in a way to minimize the gaps within resources profiles.

Heuristics can solve scheduling problems in short time, but because these procedures cannot adapt dynamically to the problems constraints, so the resulting solutions cannot be guaranteed to be neither optimum nor of good quality.

The rest of this section will review heuristic scheduling elements in detail, as these elements are the core of most meta-heuristic techniques.

7.2.1. Priority Rules

Priority Rules (or PRs) are a component of local search-based and sampling heuristics *(Kolisch, 1996a),* but they are indispensible for constructing initial solutions for any meta-heuristic *(Hartmann & Kolisch, 2000)*. PRs provide simple and speedy way to obtain solutions, and that's why they are widely used by commercial scheduling software *(Herroelen, 2005)*.

A detailed survey for priority rules can be found in *Lawrence (1985), Alvarez-Valdes & Tamarit (1989)* and *(Kolisch, 1996b)*. Meanwhile, table 7.1 provides quick categorized definition for the most well-known priority rules.

Priority Rule	Description
Activity Related PRs	
EST - Earliest Start Time	Activities are sorted in ascending order based on their earliest start
EFT - Earliest Finish Time	Activities are sorted in ascending order based on their earliest finish
LST - Latest Start Time	Activities are sorted in ascending order based on their latest start
LFT - Latest Finish Time	Activities are sorted in ascending order based on their latest finish
SPT - Shortest Processing Time	Activities are sorted in ascending order based on their shortest processing mode duration
LPT - Longest Processing Time	Activities are sorted in ascending order based on their largest processing mode duration
MSLK - Minimum Slack	Activities are sorted in ascending order based on their slack

Resource Related PRs	
GRWC - Greatest Resource Work Content	Activities are sorted in descending order based on their total resource requests
GCRWC - Greatest Cumulative Resource Work Content	Activities are sorted in descending order based on their total resource requests of the activity and all its direct successors
Logic Related PRs	
MIS - Most Immediate Successors	Activities are sorted in descending order based on the number of their direct successors
MTS - Most Total Successors	Activities are sorted in descending order based on the number of their direct and indirect successors
LNRJ - Least Non-Related Jobs	Activities are sorted in ascending order based on the number of activities which are not directly or indirectly inter-related
GRPW - Greatest Rank Positional Weight	Activities are sorted in descending order based on the total duration of the activity and all its direct successors

Table 7.1: Priority rules categorization and definitions

7.2.2. Schedule Generation Schemes

The schedule generation schemes (SGS) are the core of most of the heuristic and meta-heuristic solution procedures for the RCPSP *(Hartmann & Kolisch, 1999)*. A SGS is an iterative process; where in each iteration, a set of eligible activities are selected for scheduling based on a predefined selection mechanism (*Priority Rule* or *Random Keys*), the eligible activities are defined as per the procedure of the SGS type.

There are two types of SGSs, *Serial SGS (SSGS) & Parallel SGS (PSGS)*. SSGS is activity oriented, in which the *Eligible Set* is defined as the activities where all predecessors are scheduled; and then the selected activity is scheduled at its earliest time without violating resource constraints. While, PSGS is time oriented, where each step is related to a certain time point *t* (selected in ascending order), and in which the *Eligible Set* is defined as the set of activities which can be started at *t* without violating logic constraints.

PSGS has been verified that it can only generate non-delay schedules, and the set of non-delay schedules is just a sub set of all schedules, hence the SSGS is suggested for RCPSP *(Chen, 2011)*.

7.2.3. Forward/Backward Scheduling (FBS)

The Forward/Backward Scheduling (FBS) was introduced by *Li & Willis (1992)*; its procedure consists of iterative cycles of forward and backward scheduling until there is no further improvement in the project completion time. Improvements are achieved during this iterative process through the incorporation of a backward schedule into its succeeding forward schedule.

The forward scheduling is the normal scheduling using the SSGS, where activities are scheduled after all their predecessors are scheduled starting with the project start activity and ending with the project end activity; while the backward scheduling involves the same process but in the reverse direction, where activities are scheduled after all their successors are scheduled starting with the project end activity and ending with the project start activity.

FBS is implemented in meta-heuristic algorithms using one search agent working with forward scheduling and another working with backward scheduling, with the purpose of searching different regions of the search space. In PSO, FBS can be implemented by creating two swarms, one forward and one backward. Both swarms work separately, and the final best solution is considered as the better solution from both swarms. In this research, FBS will be implemented accordingly.

7.2.4. Schedule Justification

Justification is a simple and efficient technique introduced by *Valls et al. (2005)*; the process involves adjusting the start dates of activities (either to left or to right direction) while respecting schedule constraints; where a right justification schedules activities to their latest possible date in order of their finish dates, and left justification scheduled activities to their earliest possible dates in the reverse order. Since all activity movements are governed by logic and resource constraints, the forward/ backward cycles will always guarantee that the overall duration will either get reduced or will remain the same.

Double Justification (DJ) is applying one right justification cycle followed by another left justification cycle. *Valls et al. (2005)* stated and demonstrated that this technique can be incorporated easily into various algorithms and produces notable improvements in the quality of the output schedules.

Finally, *Mapping* is an additional step following justification, introduced by *Chen (2011)*; its purpose is to re-map the activities priorities based on their start dates after the justification process, which will rectify the communication between successive iterations.

7.3. Meta-heuristic schedule optimization algorithms

The use of Meta-heuristics in RCPSP solving involves the generation of activities order list which can produce better solutions based on experience gained in previous generation cycles. Several meta-heuristic techniques were implemented in the RCPSP context, such as tabu search (TS) *(Baar et al, 1998; Thomas & Salhi, 1998; Klein, 2000; Nonobe & Ibaraki, 2001; Kochetov & Stolyar, 2003)*, simulated annealing (SA) *(Rutenbar, 1989;*

Bouleimen & Lecocq, 2003), genetic algorithm (GA) *(Hartmann, 1998, 2002; Alcaraz & Maroto, 2001; Alcaraz et al, 2004; Valls et al, 2005, 2008)*, ant colony optimization (ACO) *(Merkle et al, 2002; Lo et al, 2008)*, and particle swarm optimization (PSO) *(Zhang et al, 2005; Zhang et al, 2008; Chen, 2011)*.

7.3.1. Justification for using Particle Swarm Optimization (PSO)

The main objective of this research is to design, verify and validate a dynamic scheduling system for the construction industry. So, the meta-heuristic method to be used for the verification does not have to be the ideal method; however, it must fulfil the following requirements:

1. Proven good performance in literature, especially for large size problems.

2. The ability to be adjustable to match both scheduling problem categories (RCPSP & TCPSP).

3. Not widely used for scheduling applications; which will increase the possibility of providing a new approach algorithm within this research instead of just copying an existing algorithm.

Based on the above criteria, the PSO method was selected for the following reasons:

1. For method performance, all of the following meta-heuristic methods were proven in literature to perform efficiently: genetic algorithm (GA) (Hartmann, 2002; Valls et al. 2008), simulated annealing algorithm (SA) (Rutenbar, 1989; Bouleimen & Lecocq, 2003), tabu search (TS) (Glover, 1989, 1990; Thomas & Salhi, 1998), ant colony optimization (ACO) (Merkle, Middendorf, & Schmeck, 2002; Lo, Chen, Huang, & Wu, 2008) and the particle swarm optimization (PSO) (Zhang, Li, & Tam, 2006; Chen, 2011). In addition, PSO requires only primitive and simple mathematical operators, and it is computationally inexpensive in terms of both memory requirements and time (Moslehi & Mahnam, 2011).

2. According to our best knowledge, no meta-heuristic was presented to solve both problem categories (RCPSP & TCPSP) with the same algorithm. So, none of the above methods can be claimed to be suitable for this requirement.

3. Based on the dates of the research papers given from the first point, it is clear that the newest method for application in the scheduling context is the PSO; in addition, according to the met-heuristic algorithms comparison introduced by Kolisch and Hartmann (2006), the PSO was almost not present. And finally, and based on the

algorithm presented by Chen (2011), the PSO is performing well with respect to other methods; and still have large room for improvement, which serves the last requirement stated above.

7.4. The Particle Swarm Optimization (PSO) method

The PSO was first introduced by *Kennedy and Eberhart (1995)*, inspired by social behavior of bird flocking or fish schooling. PSO is a multi-agent general meta-heuristic, and can be applied extensively in solving many complex problems *(Chen, 2011)*.

The PSO works by maintaining a swarm of particles (resembling the birds swarm), moving in solutions space; where the position of each particle is an encoded vector for a solution. The swarm size is problem dependent, with the most common sizes of 20–50 *(Hu et al., 2004)*. The velocity of each particle within the solution space is defined based on the experience gained over swarm generations by the local particle and by the global swarm.

In each iteration (or generation), the velocity vector defines the new position of each particle; then, the fitness of each particle is measured based on its current position, and the best local & global solution are updated accordingly. Each particle contains a number of components (related to the number of problem variables), and the velocity and position vectors are two sets of real number values corresponding to the velocities and positions of the particle's components

7.4.1. The PSO mathematical model

One of the main advantages of PSO is the simplicity of its mathematical model. The initial model (or the *Basic PSO,* as will be titled in this research), presented by *Kennedy and Eberhart (1995)*, consisted of two equations (eq. 7.1 & 7.2), which are used in each iteration for updating the *Velocity Vector (V)* and the *Position Vector (X)*.

$$V_{ij}^t = w\, V_{ij}^{t-1} + r_1 c_1\big(L_{ij}^{t-1} - X_{ij}^{t-1}\big) + r_2 c_2\big(G_j^{t-1} - X_{ij}^{t-1}\big) \qquad (7.1)$$

$$X_{ij}^t = X_{ij}^{t-1} + V_{ij}^t \qquad (7.2)$$

Where V_i is the velocity of particle i ($i \in M$ particles), V_{ij}^t & V_{ij}^{t-1} are the velocities of component j of particle i in iterations t & $t\text{-}1$; r_1 & r_2 are two random numbers (from 0 to 1); c_1 & c_2 are two learning coefficients which define the influence of the local and global best solutions on the new velocities; X_{ij}^t & X_{ij}^{t-1} are the positions of component j of particle i in iterations t & $t\text{-}1$; L_{ij}^{t-1} is the position of component j in the positions vector of the best solution found by particle i until iteration $t\text{-}1$; G_j^{t-1} is the position of

component *j* in the positions vector of the best solution found globally in the swarm until iteration *t-1*.

The PSO was reported in literature to have few drawbacks such as parameter dependency, loss of diversity and early convergence. And accordingly, several variations were proposed for the original PSO to enhance its performance and overcome these drawbacks

Vast amount of researches focused on presenting variations to improve the performance of the PSO. However, according to the literature review performed, there were no comprehensive surveys to review and classify these variations. But for the purpose of this research, a brief review and classification was performed and presented in this section to be able to classify the proposed PSO variation and to identify its novelty.

The researches in the context of PSO variations can be generally classified under three main categories: *formulation variations*, *communication topology modifications*, and *procedural modifications for PSO algorithms*.

7.4.2. Formulation variations

First, for the *formulation variations*, proposed modifications involve changes to the velocity and position update equations to either improve exploration capabilities or to tune the algorithm's convergence. The most famous of these variations are that of *Shi & Eberhart (1998)* with the addition of the inertia weight (w) for controlling the influence of previous iteration's velocity to succeeding iteration (equation 7.3); and the *"Standard PSO"* by *Bratton & Kennedy (2007)*, where the velocity update method was modified from *original PSO* by the introduction of the *constriction factor* (γ) as a multiplier to the velocity formula (equation 7.4).

$$V_{ij}^t = w \times V_{ij}^{t-1} + c_1 \times r_1 \times \left(L_{ij}^{t-1} - X_{ij}^{t-1}\right) + c_2 \times r_2 \times \left(G_j^{t-1} - X_{ij}^{t-1}\right) \quad (7.3)$$

$$V_{ij}^t = \gamma \times \left(V_{ij}^{t-1} + c_1 \times r_1 \times \left(L_{ij}^{t-1} - X_{ij}^{t-1}\right) + c_2 \times r_2 \times \left(G_j^{t-1} - X_{ij}^{t-1}\right)\right) \quad (7.4)$$

The adequate tuning of parameters' values is highly important for efficient performance of PSO. *Bratton & Kennedy (2007)* suggested that a value of 0.73 for w or γ and 2.05 for both c_1 & c_2 would result in efficient performance of the PSO, and were implemented accordingly in most of succeeding researches; and adopted accordingly in this research.

Examples of other similar extensions varied from the addition of neighbourhood operators *Suganthan (1999),* modification of the velocity update via random coefficient *(Chen & Li, 2007)*, addition of time-varying acceleration coefficients *(Ratnaweera et al, 2002, 2003),* up to a complete change in all PSO formulation as inspired by quantum mechanics and trajectory analysis *(Clerc & Kennedy, 2002).*

7.4.3. Communication topology variations

Secondly, PSO communication topology represents how gained experience is passed between successive iterations. The original PSO was based on the *"gbest"* topology (figure 7.2a), where velocity is updated as shown in equation (1); this topology is the most common in PSO researches. The *"lbest"* topology was introduced by *Eberhart & Kennedy (1995)* to minimize situations where the algorithm is trapped into local optima (figure 7.2b).

(a) *gbest* topology   (b) *lbest* topology
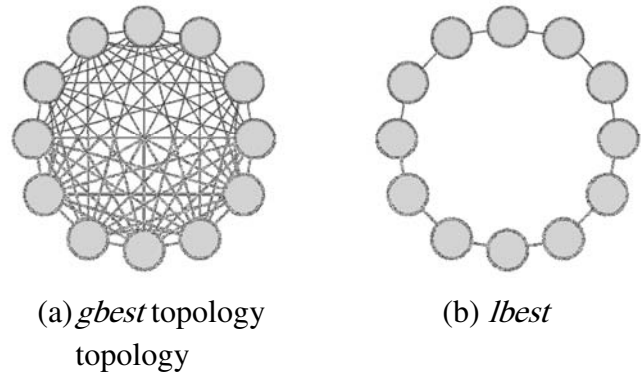
Figure 7.2: PSO communication topologies
[From *Bratton & Kennedy (2007)*]

Several researches focused on the improvement of PSO communication topologies, starting from *Kennedy (1999)*. And accordingly, several topologies were introduced in literature such as the *Von Neumann topology* (Kennedy & Mendes, 2002), and the variable neighbouring topology (equations 5 & 6) presented by *Chen (2011).*

Chen (2011) proposed the modification of the communication topology by the addition of a new parameter, the *gbest ratio (GR)*, to manipulate the trade-off between *gbest* and *lbest* randomly during the optimization iterations with a predefined trade-off range corresponding to the *GR* value. Accordingly, the velocity vector will be updated using equation (7.5), where Y_j is the position vector resulting from the *gbest/lbest* trade-off as per equation (7.6). During each iteration, a random value *rand* is obtained [0, 1] and compared to the predefined *GR*, if the value is smaller than *GR* the *gbest* is used, otherwise the position vector of the best neighbour is used. This

topology will be referenced as *neighbouring topology* through the rest of the thesis.

$$V_{ij}^t = \gamma \times \left(V_{ij}^{t-1} + c_1 \times r_1 \times \left(L_{ij}^{t-1} - X_{ij}^{t-1} \right) + c_2 \times r_2 \times \left(Y_j^t - X_{ij}^{t-1} \right) \right) \tag{7.5}$$

$$Y_j^t = \begin{cases} G_j^{t-1} & rand < GR \\ X_{kj}^{t-1} \; where \; k \; \in best \; neighbor(i) & otherwise \end{cases} \tag{7.6}$$

7.4.4. Procedural variations

And finally, the third PSO variation category involves changes to the procedural steps which the PSO algorithm follows. Several researches focused on the use of mutation with PSO, including the use of *Cauchy* random numbers *(Stacey et al, 2003), Gaussian* mutation *(Higashi & Iba, 2003), bit change mutation (Lee et al, 2007)*, the combination of *Cauchy & Gaussian (Krohling & Mendel, 2009)*, and the combination of *Cauchy*, *Lévy* and *Gaussian* mutations in an adaptive mutation strategy *(Wang et al, 2013)*.

A non-exhaustive review for procedural PSO variations include: dynamic particles hierarchy to define the swarm neighbourhood structure by *Janson & Middendorf (2005)*, using removal/extension of inactive particles from swarm *(Xie et al, 2002, 2003)*, a multi-dimensional PSO by *Kiranyaz et al (2010, 2011)*, a cooperative multiple swarm by *Van den Bergh & Engelbrecht (2004)*, and a self-organized criticality PSO by *Lovberg & Krink (2002)*.

In addition to few other problem oriented procedural modifications, such as the use of classifier swarms for pattern recognition (introduced by *Owechko et al, 2004;* and related works were surveyed by *Nouaouria et al, 2013*), the use of forward/backward swarms for solving RCPSP *(Chen, 2011)*, and the use of combined priority rules during swarm initialization *(Fahmy et al, 2014)* for RCPSP as well.

7.5. The Differential-Density PSO (DDPSO)

7.5.1. Scheduling problem encoding to PSO model

The process of modelling the problem variables and mapping them to the variables of any meta-heuristic method is believed to be the most challenging part in meta-heuristic analysis. The key here is to model the problem with minimum number of variables to minimize the search space (or solutions space), and to define the variables in a way to result in a continuous search

space, where neighbouring solutions (or solutions with minor changes between their variables' values) should have close fitness values; otherwise, the search space topology will be unnatural and consisting of many spikes (representing the optimum and near optima) which are hard to find by any algorithm.

Several models are available in literature for the mapping process, the most common of which is to use the priority of the schedule activities as the problem variables, and to adopt a priority rule to define the initial priorities. This model will be used in the research along with the key representation of *Hartmann & Kolisch (1999)*, where the sorted orders of the algorithm's outputs are to be mapped to the corresponding activity keys.

7.5.2. Levelling Schedule Generation Scheme (LSGS)

The Dynamic Multi-Constrained Project Scheduling Model (DMCPSM) was formulated for solving almost all static scheduling problem types (problems with different single / multi-objectives), as well as extending its formulation with additional variables, constraints and objectives which will support dynamic scheduling analysis.

The two SGSs available in literature (SSGS & PSGS) are oriented for the RCPSP and cannot be used for TCPSP category where no resource constraints exist. So, the *Levelling SGS (LSGS)* is a new SGS proposed in this research for generating schedules for the TCPSP problems.

The idea beyond the LSGS is to generate a schedule with resource profiles as levelled as possible; so, the LSGS can be considered as resource level oriented. The main concept of the LSGS, that the resource profiles are used as open-top containers and the resource requests are placed (or stacked) based on the predefined priority rule or random keys.

The LSGS consists of two main stages, first all critical activities are stacked, because there is no alternative for their location other than their early start dates. Then the second stage involves stacking the rest of activities one at a time according to their priority at the best location where their resource requests are at the lowest possible level.

7.5.3. Stacking Justification

Stacking Justification (SJ) is another simple and efficient justification technique which leads to further improvement to solutions quality; but before going through its concept and process, the reason for proposing another

justification technique needs to be clarified. *Double Justification (DJ)* was proven by *Valls (2005)* to be efficient with several algorithms. The key behind its success is that *DJ* improves solutions quality by changing the solution itself (i.e. the activities priorities list) to a better neighboring solution, if a better neighbor exists. And since the same result will occur if the original priorities list was selected for analysis in next generations, then this original list is somehow eliminated from the search space, which makes *DJ's* effect to appear as minimizing the search space rather than improving solutions quality. This observation is further clarified within this section's examples.

If we considered that the *SGS* minimizes the original search space by eliminating priorities lists which does not respect precedence, and that the *DJ* further minimizes the search space by directing few neighboring solutions to their local optimum, then another justification technique which can further minimize the search space (beyond *SGS*/*DJ* effect) will definitely be efficient.

DJ works on justifying the solution by scheduling activities based on the order of their start/finish times (i.e. their priorities), then respecting the resources limits; while the concept of *SJ* is to respect first the resources limits by scheduling activities which will give more efficient stacking (minimal gaps in resources profiles), then will respect the activities priorities (if more than one activity are having the same stacking efficiency).

SJ also consists of two justification cycles (right & left). The justification process can be detailed as follows:

1. In the right (left) cycle, activities are prioritized in ascending (descending) order based on their latest finish time (earliest start time), so the higher (lower) the *LFT* (*EST*) the more priority the activity gets and the earlier it will be scheduled.
2. Activities will then be scheduled in successive iterations, each corresponding to a time period *t* in the project time frame, starting from time period 0 (*T*) for right (left) cycle.
3. During each iteration, a list of activities eligible for scheduling is prepared. An activity is considered as eligible for scheduling if it can or start (finish) in the current time period *t* without violating resources constraints throughout its total duration. Activities are sorted in the list based on their initial priority order, but if there exists an activity which must be scheduled in this time period (i.e. the activity's *LFT = t (EST = t)*) or otherwise it will impact the project duration, it will be given the highest priority.

4. The highest priority activity to be scheduled, and step 3 to be repeated.
5. If there is no eligible activities within this iteration, the current time period is advanced to the next (previous) time period *t+1 (t-1)* until all activities are scheduled.

Example 1:

To illustrate how *SJ* works and compare it to the original *DJ*, let's consider the simple example shown in figure 7.3. The network consists of 4 activities (+ 2 dummies), and one renewable resource with 2 available units.

ID	D	r	Succ.
1	0	-	2, 3
2	1	1	5
3	1	2	4
4	1	1	6
5	1	2	6
6	0	-	-
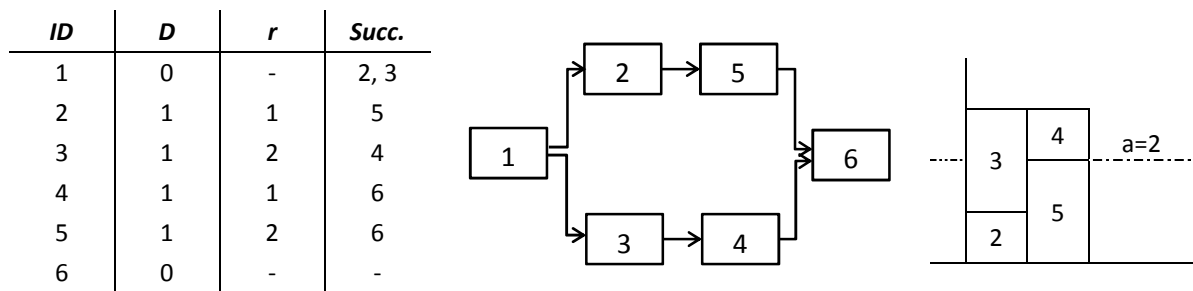
Figure 7.3: Example 1 - Activities list, network and original resource profile

Table 7.2 was prepared for assessing the effect of the *SGS*, *DJ* and *SJ* on the search space size. Since the number of activities to be optimized is four, then the number of possibilities for priorities list is ⌊4 = 24 options (*2345, 2354* … etc.). The serial schedule generation scheme (*SSGS*) eliminates all options which do not respect precedence. For example, the priorities list *"2435"* will be automatically converted to *"2345"* during *SGS*, as scheduling of activity 4 will have to wait until activity 3 is scheduled. And accordingly, as shown in table 1, *SGS* will reduce the search space from 24 options down to only 6 options.

Original	2354	2453	2534	2543	4253	4523	5234	5243	5423	2345	2435	4235	3425	3452	3542	4325	4352	4532	5342	5432	3245	3254	3524	5324
SGS	2354			2534							2345				3425							3245	3254		
DJ	2354			2534											3425							3245	3254		
SJ										3425												3245	3254		

Table 7.2: Effect of applying SGS, DJ and SJ on the search space of example 1

As shown in figure 7.4, after the application of SGS, priorities list options were reduced to six options: *2354, 2534, 2345, 3425, 3245 & 3254*;

out of which, three options *(3425, 3245 & 3524)* are achieving the optimum make-span of 3 time units.

When the *SSGS* is followed by a *DJ*, solution *"2345"* will be optimized and converted to *"3425"* during the right justification cycle. So, the search space was reduced into 5 options after *DJ*, 2 of which are non-optimum & 3 are optimum. On the other hand, when the *SGS* is followed by a *SJ*, solutions *"2354"*, *"2534"*, & *"2345"* and converted to *"3425"* during the right justification cycle; which leads to a reduction of the search space down to 3 options, all are optimum.
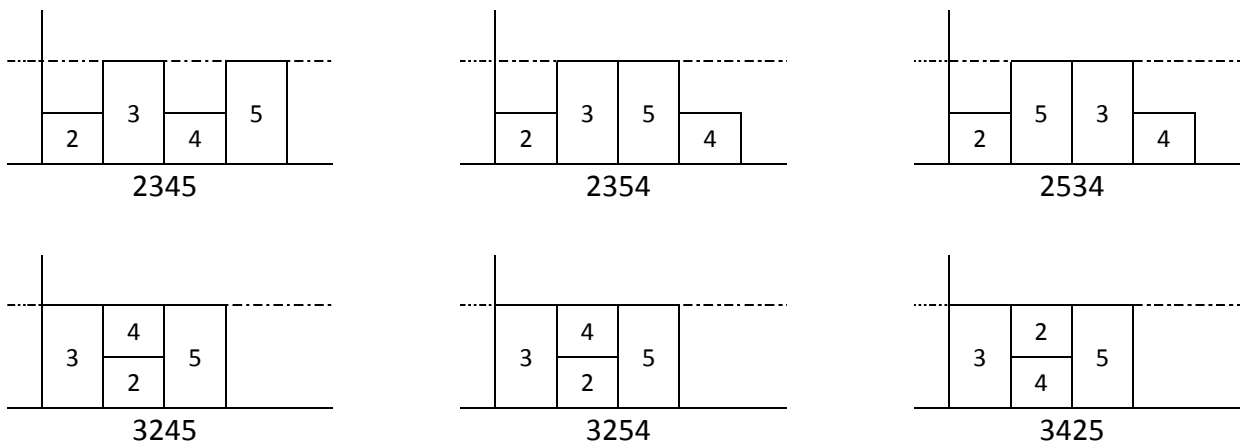
Figure 7.4: Example 1 - Resource profiles for available options after SSGS

Example 2:

To elaborate the observations of example 1, another larger example was considered as shown in figures 7.5 & 7.6. The network consists of 7 activities (+ 2 dummies), and one renewable resource with 4 available units.

ID	d	r	Succ.
1	0	-	2,5,6
2	3	3	3,8
3	2	2	4
4	2	1	9
5	4	2	9
6	1	1	7
7	1	3	9
8	2	4	9
9	0	-	-
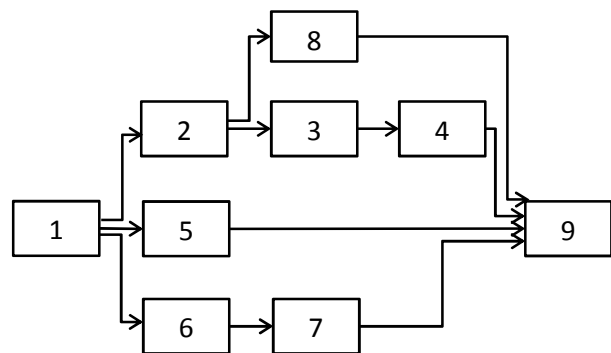
Figure 7.5: Example 2 - Activities list & network

The activities to be optimized are seven, so the number of possibilities for priorities list is ⌞7 = 5040 options. *SGS* eliminated 4725 options which do not respect precedence, leaving only 315 valid options. A detailed analysis

was performed to determine how much options were eliminated by each of *SJ & DJ*, as well as both together (*Stacking & Double Justification*, abbreviated as *SDJ* through the rest of the research); and the results were listed in table 7.3. The reduction in search space was higher for *DJ* than *SJ* in forward scheduling, while the reverse for backward scheduling; and finally for *SDJ*, the reduction was higher than both *DJ & SJ*. The extra search space reduced for *SDJ* above *DJ* is completely dependent on the problem's network structure and resources requirements, in example 2 this extra reduction is 1%, while it was more than 33% in example 1.
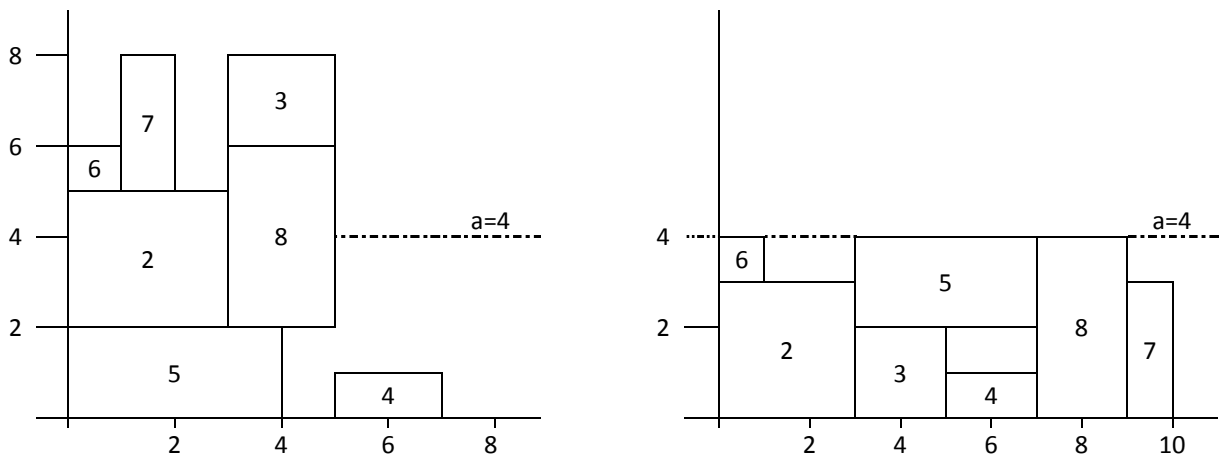
Figure 7.6: Example 2 - Original resource profile and optimum resource profile

	Search Space Size				Reduction in Search Space Size from SGS		
	Original	SSGS	DJ	SJ	SDJ	DJ	SJ	SDJ
Forward Scheduling	5040	315	215	225	215	31.7%	28.6%	31.7%
Backward Scheduling	5040	315	163	157	155	48.3%	50.2%	50.8%
Forward / Backward	5040	630	378	382	370	40.0%	39.4%	41.3%

Table 7.3: Example 2- Search space size under different justification schemes

The effect of this reduction will appear clearly in the verification results (presented in Chapter 8) that it significantly improves the final solutions. But for the current example, table 7.4 shows this impact on the amount of optima reached with only 1 iteration (note: *LFT* priority rule was used); where the results show that *SDJ* introduced consistent reduction to the search space.

	Optima reached				Solution rate (from 315 options)			
	SSGS	DJ	SJ	SDJ	SSGS	DJ	SJ	SDJ
Forward Scheduling	165	242	247	256	52.4%	76.8%	78.4%	81.3%
Backward Scheduling	76	139	203	208	24.1%	44.1%	64.4%	66.0%
Forward / Backward	197	244	247	256	62.5%	77.5%	78.4%	81.3%

Table 7.4: Example 2 - Optima reached under different justification schemes

7.5.4. The Differential Density PSO (DDPSO) algorithm

The *Differential-Density PSO (or DDPSO)* proposed under this research is a variation to the original PSO model; it was developed to improve the search capabilities of the PSO algorithm. One of the main downfalls of PSO is the early convergence (refer to section 7.4.2); the *DDPSO* proposed overcoming this downfall by introducing a new characteristic to the swarm particles, the *Density* δ_i, to be generated either randomly during the initialization of each particle, or to be a predefined value per particle which can be obtained through detailed testing of most suitable values. So, the final formulation of the *DDPSO* is as follows:

$$P = No. of\ generated\ schedules\ /\ Schedules\ limit \qquad (7.5)$$

$$V_{ij}^t = \left(w \times V_{ij}^{t-1} + r_1 c_1 \left(L_{ij}^{t-1} - X_{ij}^{t-1}\right) + r_2 c_2 \left(G_j^{t-1} - X_{ij}^{t-1}\right)\right) / \delta_i \qquad (7.6)$$

$$X_{ij}^t = X_{ij}^{t-1} + V_{ij}^t \qquad (7.7)$$

The concept behind the proposed model modification is that a high density swarm particle should move slower than a low density particle, and accordingly explore the search space in a higher intensity; so, δ_i (or the *density* of particle *i*) is inversely proportional to the particles velocity; and thus, introduced as a denominator to the velocity update formula (equation 7.6). This will also lead to different convergence speed between the swarm particles. Generally, this is different than the *Constriction Factor (CF)*, which applies to all particles in *Standard PSO*; while in *DDPSO*, each particle will accordingly have different *CF* by applying different densities.

Conceptually, the *DDPSO* should improve the PSO performance for any optimization problem. But since this research is scheduling oriented, the *DDPSO* will be tested with different scheduling problems. In addition, *DDJPSO* algorithm includes implementation of *FBI*, *SDJ* (with mapping) and *CPR* (refer to next section). And accordingly, the pseudo code for the *DDPSO* can be summarized as shown in table 7.5.

While total generated schedules < schedules limit
   t = 1
   For each particle i in forward & backward swarms
      If t = 1 Initialize DD swarm particles using CPR
      Update V_i^t & X_i^t
      Generate schedule using RSGS
      Apply selected justification scheme
      Map justified solution into X_i^t
      Calculate particle's fitness
      Update local best L_i^t & global best G^t
   End for
   t = t + 1
  End while

Table 7.5: *DDPSO* pseudo code

The selected priority can be either a single priority rule, or the *CPR*; and the justification scheme can be original justification, stacking justification, or a combination of both. The total generated schedules can be calculated using equation (7.8); where for each particle, each justification cycle (whether original or stacking, left or right) is considered as a generated schedule, in addition to the original schedule generated with selected *SGS*.

$$Total\ generated\ schedules =$$
$$(\text{No. of swarm particles}) \times (1 + \text{No. justification cycles}) \qquad (7.8)$$

7.5.5. Combined Priority Rules (CPR)

In meta-heuristics, the use of priority rules mostly involves the initialization of the first population; and in particle swarm specifically, initializing the swarm particles with an ineffective priority rule will lead to placing the particles in a bad side of the search space, and accordingly will require large computational effort to reach the optimum solution, if not trapped to any local optimum away from it.

The most commonly used priority rules in literature are listed in table 7.1; each of them is having a different performance with difference problem types and sizes (for comparison of priority rules performance refer to *Kolisch (1996b)*). Regardless of which rule is having the highest performance, the facts that each rule is having a different behaviour and producing different moderate to good quality solutions are the basis of the proposed *combined priority rules (CPR)* approach.

The concept of *CPR* is to make use of the differential behaviour of priority rules in order to achieve wide & proper spread of initial population on the good areas of the search space. If we assumed that the search space consists of several good areas, each with a local optimum, and that each priority rule directs to one of these areas. Then, initializing each individual (or particle for PSO) in the initial population with a different priority rule will lead to proper diversity of population over several areas of the search space with high prospects of being close to the overall optimum, which consequently will lead to reaching the optimum quicker than normal initialization process. This assumption will be proven to be correct in the experimental test results within static verification chapter. And since applying priority rules involves very small computational effort and the particles were going to be initialized in all cases, then this process involves almost no additional computational burden.

7.5.6. Rectified Schedule Generation Scheme (RSGS)

In example 1, table 7.2, it can be easily observed that the distribution resulting from eliminating priorities lists which does not respect precedence is not fairly distributed among other lists which do respect precedence; this might cause difficulties in finding the optimum solution if it received less probability share from the eliminated options.

In this research, the *Rectified Schedule Generation Scheme (RSGS)* is proposed to overcome the above mentioned problem by manipulating the priorities lists in order to generate fairly distributed search space after the schedule generation.

The concept of *RSGS* is that the unfair distribution of priorities lists after eliminating lists which do not respect precedence is mainly caused by incorrect order of activities within the lists. For example, if activity 2 is a predecessor of activity 5, as in example 1, then any priority list with activity 5 having higher priority than activity 2 needs to be rectified first before applying the *SGS*.

This concept can be achieved by checking all schedule relations first and correcting the related activities sequence in all priority lists by simply switching the incorrect sequence. So, if we applied this to example 1, there are two relations to be rectified: 2-5 and 3-4; and accordingly applying two rectification cycles on the priorities lists will result in changing the rectified lists as shown in the third row of table 7.6. The rectification process resulted in a fairly distributed solution space which can support any optimization algorithm in finding the optimum solution quicker.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Original	2345	5342	2435	5432	2354	5324	2453	5423	2534	5234	2543	5243	4235	4532	3542	3245	3425	3452	4325	4352	4253	4523	3254	3524
Rectifying 2-5	2345		2435		2354		2453		2534		2543		4235		3245		3425		4325		4253		3254	
Rectifying 3-4	2345				2354				2534				3245				3425				3254			
SSGS	2345				2354				2534				3245				3425				3254			
PSGS	2345						2354						3245						3254					

Table 7.6: Applying Rectified Schedule Generation Scheme (RSGS)

After priorities lists rectification, applying *Serial SGS (SSGS)* will result in generating exactly the same priorities lists; however, applying *Parallel SGS (PSGS)* will result in eliminating some valid possibilities (for the current example 2534 & 3425) which will result in some problems in not reaching the optimum solution. Accordingly, only *SSGS* should be used after the rectification process. It was also verified in literature, that *PSGS* can only find non-delay schedules, and the set of non-delay schedules is only a subset of all schedules *[Chen, 2011]*.

Finally, it was noticed that for larger schedules, where schedule paths are intersecting, the distribution of solutions space becomes disrupted because all priorities lists are rectified with the same sequence of schedule logic every time. This can be corrected by ordering the schedule logic before rectification according to the appearance of related activities in the priorities list. For example, for a priority list 2354, the logic 2-5 will have higher priority (i.e. rectified first) than logic 3-4; and the case is reversed for priorities list 3245.

7.6. Summary

This chapter was intended to develop an optimization algorithm should be developed with the ability to explore the search space generated by the formulated *DMCPS* model for finding the optimum solution as per the model's objectives.

The *Differential Density PSO (DDPSO)* algorithm was developed including several contributions proposed under this research:

a) The *Stacking Justification (SJ)*, a heuristic technique to improve solutions quality for resource-constrained problems.

b) The *Float Justification (FJ)*, a heuristic technique to improve solutions quality for time-constrained problems.

c) The *Rectified Schedule Generation Scheme (RSGS)*, an improved version of the original SGS, which improves the distribution of the search space

d) The *Combined Priority Rules (CPR)*, a technique to initialize particle swarm initialization for proper spreading of swarm particles among good quality areas of the search space.

e) The *Differential Density Particle Swarm Optimization (DDPSO)*, a modified PSO with the introduction of density parameters to swarm particles to overcome the algorithm's early convergence.

Chapter 8: DS model & DDPSO algorithm static verification

The *Dynamic Multi-constrained Construction Project Scheduling Model (DMCPSM)* was formulated for solving almost all static scheduling problem types (problems with different single / multi-objectives), as well as extending its formulation with additional variables, constraints and objectives which will support dynamic scheduling analysis.

So, in order to verify the *DMCPSM*, the model was tested in this Chapter with different static scheduling problem sets; this will confirm the multi-objective solution capabilities of the model from an operational research perspective. Second, the model was tested in Chapter 10 with real projects data to verify its solution capabilities under dynamic environment and from Construction industry perspective.

The first section of this chapter will define the selected static problem sets which will be used for the verification process; then, the computational results for the selected problem sets will be presented along with performance analysis for the *DMCPSM* using the developed *DDPSO* algorithm. The verification of the model & the algorithm, as well as the DS software tool, for dynamic scheduling environment will be presented in the chapter 10.

8.1. Static problem sets selection

During the last decade, most of the researches submitted in the scheduling context have used benchmarks problem sets generated by two well-known libraries: the PSPLib, and the PSPLib/max. These libraries were generated using the problems generators PROGEN *(Kolisch & Sprecher, 1997)* & PROGEN/max *(Kolisch et al., 1998)* respectively.

The optimal values are not known for all these instances, thus the best known solutions were used for performance comparison of the calculated lower bounds. The best known solutions are collected in the online libraries of PSPLIB and website http://129.187.106.231/psplib/ and the PSPLIB/max website www.wior.uni-karlsruhe.de/RCPSPmax/progenmax/ respectively.

8.2. DDPSO Computational results & performance analysis

Results were obtained using a personal laptop with Intel core processor i7 2.4GHz (only single core was utilized for the analysis). The computer was operated by Microsoft Windows 7, and the algorithm was programmed in Visual C#.Net 4.0.

The PSPLIB's *(Kolisch & Sprecher, 1997)* SRCPSP j-30 (480 instances), j-60 (480 instances), j-90 (480 instances) & j-120 (600 instances) were used

for testing the RCPSP category; this is mainly because these problem sets were extensively used in literature which will enable proper comparability for the algorithms performance. While for the TCPSP category, the SRIP/max j-10 (270 instances), j-20 (270 instances) & j-30 (270 instances) were used.

For j-60, j-90 & j-120, not all optimum values are known; so, the comparison was made using equation 8.2, where the *Average Deviation from Critical Path (AD$_{CP}$)* is the time increase due to the consideration of resources constraints between the best solution reached and the original problems' critical path; while for the j-30 instances, all optimum values are well known, so another measure is commonly used in literature as shown in equation 8.1, where the *Average Deviation from Optimum (AD$_O$)* represents the variance between the analysis results and the instances optima. For j-30, results comparison was prepared using AD_{CP} for parameter testing, and using AD_O for comparison to other algorithms in literature. During the analysis, if a comparison is to be made between different problem sizes, the performance of the j-30 instances will be also measured using AD_{CP}. And finally, for the SRIP/max equation 8.3 was used for performance measurement, where the *Average Cost Saving (ACS)* is the cost reduction in the best solution from the initial problems' cost.

$$AD_O = \frac{\left(\sum_{i=1}^{N} \frac{(BT_i - OT_i)}{OT_i}\right)}{N} \tag{8.1}$$

$$AD_{CP} = \frac{\left(\sum_{i=1}^{N} \frac{(BT_i - CP_i)}{CP_i}\right)}{N} \tag{8.2}$$

$$ACS = \frac{\left(\sum_{i=1}^{N} \frac{(IC_i - BC_i)}{IC_i}\right)}{N} \tag{8.3}$$

Where BT_i is the best project time found for instance i, and OT_i is the optimum project time for instance i, N is the total number of instances, CP_i is the total time of the critical path for instance i, BC_i is the best cost achieved for instance i, and IC_i is the initial cost for instance i.

Finally, the algorithm's stopping criteria was set to the number of schedules generated during the analysis, which enables fair comparison among algorithms regardless of the efficiency of the hardware or programming technique implemented. Taking into consideration that the number of schedules generated per particle in each iteration increases according to the adopted justification scheme; and accordingly, the total number of generated schedules should be calculated as explained in the previous chapter (refer to equation 7.6).

8.2.1. Testing the performance of different elements of scheduling optimization algorithms

Prior to testing the *DDPSO*, few scheduling algorithm's architectural elements and parameters should undergo performance testing. Detailed experimental analysis was performed on different *Priority Rules, Forward/Backward Scheduling*, *Double Justification*, *Mapping*, *Constriction Factor* values; as well as the number of *PSO* particles. The full results of this simulation were included in Appendix B; and best performing elements and parametric values were adopted within further *DDPSO* testing.

8.2.2. Computational results for testing CPR

For testing the implementation of *Combined Priority Rules (CPR)*, *Base (or original) PSO* was used, with 20 single density forward particles, *DJ* was applied, and the stopping condition was set to 1000, 5000 & 10000 schedules. In this section, as well as the rest of testing in this chapter, analysis was performed using *CPR* as well as the 3 high performance priority rules: *LST, LFT & MTS* for *RCPSPs* and *EST, LST & GRWC* for *TCPSPs* (refer to appendix B section B.1 for performance comparison of priority rules).

N_{Sch}	Priority Rule	AD_O	AD_{CP}				Problems Solved to Optimality				
		j-30	j-60	j-90	j-120	Average	j-30	j-60	j-90	j-120	Average
1,000	LST	1.25%	14.0%	13.7%	41.3%	**23.0%**	71.3	69.2	70.0	25.0	**58.9%**
	LFT	1.22%	14.0%	13.7%	41.3%	**23.0%**	71.0	69.6	69.4	25.0	**58.8%**
	MTS	2.06%	13.9%	13.4%	40.2%	**22.5%**	61.5	65.2	68.8	22.7	**54.5%**
	CPR	0.78%	13.6%	13.3%	40.4%	**22.4%**	76.7	70.6	71.5	26.0	**61.2%**
5,000	LST	0.55%	13.1%	13.0%	39.7%	**21.9%**	80.2	72.1	72.5	28.3	**63.3%**
	LFT	0.53%	13.0%	13.0%	39.7%	**21.9%**	81.7	71.9	72.9	28.2	**63.7%**
	MTS	1.20%	12.9%	12.7%	38.8%	**21.5%**	69.8	70.4	72.3	28.0	**60.1%**
	CPR	0.39%	13.0%	12.9%	39.5%	**21.8%**	84.4	72.7	72.9	28.0	**64.5%**
10,000	LST	0.40%	12.8%	12.7%	39.3%	**21.6%**	85.0	72.9	72.3	28.5	**64.7%**
	LFT	0.42%	12.8%	12.7%	39.4%	**21.6%**	83.5	72.7	73.5	28.5	**64.6%**
	MTS	1.20%	12.6%	12.6%	38.4%	**21.2%**	73.5	72.1	73.3	29.0	**62.0%**
	CPR	0.27%	12.7%	12.7%	39.2%	**21.6%**	88.3	73.3	72.9	29.2	**65.9%**

Table 8.1: Combined Priority Rules (CPR) performance comparison for SRCPSP

The computational results showed in tables 8.1 & 8.2 shows that the implementation of *CPR* during swarm particles initialization is having a considerable improvement for *RCPSPs* results and a significant improvement for *TCPSPs* optimization results. An average improvement to optimal solutions reached of 3-7% for *RCPSPs* and 31-40% for *TCPSPs* with respect to results of using a single priority rule; taking into consideration that the priority rules used were the ones having the best results (as per appendix B). The *CPR* improvement was high for lower number of generated schedules,

and it decreases gradually with the increase in the number of generated schedules.

Accordingly, CPR can be considered ideal when quick solution is needed; and most probably efficient (as shown in the rest of DDPSO testing) for detailed (long time) analysis.

N_{Sch}	Priority Rule	Average Cost Saving (ACS)				Problems Solved to Optimality			
		j-10	j-20	j-30	Average	j-10	j-20	j-30	Average
1,000	EST	27.1%	34.5%	31.3%	**31.0%**	51.1%	31.5%	24.1%	**35.6%**
	LST	30.8%	35.8%	31.1%	**32.6%**	55.9%	30.0%	23.7%	**36.5%**
	GRWC	24.5%	28.0%	29.0%	**27.2%**	43.7%	24.1%	24.8%	**30.9%**
	CPR	35.2%	40.2%	36.2%	**37.2%**	74.8%	39.3%	30.0%	**48.0%**
5,000	EST	29.0%	36.9%	34.1%	**33.3%**	52.6%	35.2%	28.1%	**38.6%**
	LST	31.2%	37.6%	35.0%	**34.6%**	58.1%	33.7%	27.0%	**39.6%**
	GRWC	25.1%	31.3%	32.0%	**29.5%**	43.3%	25.9%	26.3%	**31.9%**
	CPR	34.7%	41.6%	38.6%	**38.3%**	72.2%	43.3%	33.3%	**49.6%**
10,000	EST	29.6%	36.3%	34.5%	**33.5%**	55.6%	33.7%	26.7%	**38.6%**
	LST	31.1%	38.4%	37.9%	**35.8%**	57.4%	32.6%	28.1%	**39.4%**
	GRWC	26.2%	32.1%	34.2%	**30.8%**	45.2%	27.4%	26.7%	**33.1%**
	CPR	34.9%	41.3%	36.5%	**37.6%**	72.6%	41.9%	30.7%	**48.4%**

Table 8.2: Combined Priority Rules (CPR) performance comparison for SRIP/max

8.2.3. Testing Stacking Justification (SJ)

Standard PSO and *gbest* communication topology were adopted through the rest of the testing process (except where indicated that neighbouring topology is used). *FBI* was also implemented, with the number of forward and backward particles as indicated in headers of results tables.

For testing the new justification technique, five justification schemes were implemented: *NJ* (no justification), *DJ* (original *double justification* as per *Valls, 2005*), *SJ* (*stacking justification* as proposed in this research), *SDJ* (*SJ & DJ*, where both techniques are applied to all particles during each iteration), and *ASDJ* (alternating *SJ & DJ*, where both techniques are used alternatively between iterations). The constriction factor value was set to 0.73 (as suggested by *Bratton & Kennedy, 2007*).

Justification Scheme	Priority Rule	1,000 Schedules (SSGS - 10F/10B Particles)				5,000 Schedules (PSGS - 10F/10B Particles)				50,000 Schedules (PSGS - 20F/20B Particles)			
		AD_O	AD_{CP}			AD_O	AD_{CP}			AD_O	AD_{CP}		
		j-30	j-60	j-90	j-120	j-30	j-60	j-90	j-120	j-30	j-60	j-90	j-120
NJ	LST	1.34	14.81	14.95	45.02	0.70	13.79	14.25	43.59	0.36	12.77	13.16	41.00
	LFT	1.33	14.98	15.11	45.62	0.66	13.90	14.21	43.87	0.26	12.57	12.91	40.63
	MTS	1.18	14.41	14.46	44.03	0.57	13.65	13.95	42.75	0.21	12.50	12.79	39.74
	CPR	0.90	14.54	14.65	44.03	0.63	13.57	13.98	43.22	0.30	12.49	12.78	39.92

DJ	LST	0.63	12.98	12.60	38.66	0.21	12.06	11.97	37.13	0.07	11.40	11.40	35.57
	LFT	0.66	12.97	12.66	38.63	0.20	12.05	12.00	37.19	0.08	11.43	11.44	35.65
	MTS	0.73	13.01	12.62	38.56	0.18	12.06	11.93	37.07	0.06	11.44	11.40	35.68
	CPR	0.50	12.91	12.58	38.58	0.16	11.98	11.93	36.95	0.06	11.40	11.37	35.61
SJ	LST	0.57	12.92	12.89	39.40	0.13	12.13	12.26	38.07	0.04	11.53	11.70	36.71
	LFT	0.46	12.92	12.85	39.33	0.14	12.12	12.27	38.22	0.06	11.52	11.71	36.67
	MTS	0.55	12.92	12.87	39.19	0.13	12.15	12.26	38.07	0.06	11.62	11.66	36.63
	CPR	0.39	12.90	12.72	38.77	0.13	12.15	12.19	37.96	0.06	11.59	11.68	36.62
SDJ	LST	0.51	12.46	12.13	37.23	0.11	11.73	11.60	36.13	0.03	*11.17*	11.15	*34.89*
	LFT	0.49	12.52	12.16	37.30	0.09	11.64	*11.57*	36.04	*0.02*	11.19	11.14	34.93
	MTS	0.54	12.50	12.11	37.22	0.09	11.68	11.60	36.04	0.03	11.19	*11.11*	34.94
	CPR	0.38	*12.39*	*12.08*	*37.04*	*0.08*	*11.63*	11.59	*36.02*	0.03	11.21	11.13	34.90
ASDJ	LST	0.40	12.76	12.51	38.59	0.14	12.04	12.13	37.37	0.06	11.49	11.52	35.99
	LFT	0.46	12.71	12.59	38.55	0.14	12.07	12.07	37.38	0.05	11.48	11.53	36.00
	MTS	0.47	12.76	12.61	38.56	0.09	12.10	12.09	37.39	0.05	11.51	11.57	36.00
	CPR	*0.36*	12.73	12.52	38.58	0.13	12.05	12.06	37.29	0.03	11.50	11.50	35.92

Table 8.3: Test results for different RCPSP justification schemes

Generally, the results in table 8.3 showed that *SJ* outperformed *DJ* for small sized problems, while the case became gradually reversed with the increase in problem size. However, using combined justifications (or *SDJ*) was always showing better performance than both techniques separately. While the test results for *ASDJ* showed an unsteady good results for the 1000 schedules (mainly due to the reduction in number of justification cycles), but the performance was definitely lower than *SDJ* for larger sized problems and larger number of schedules. And accordingly, *SDJ* will be used for further detailed analysis in the following sections.

The summary of RCPSP justification schemes testing were shown in table 8.3; for full detailed testing of RCPSP justification refer to appendix C section C.1.

8.2.4. TCPSP Justifications

For testing TCPSP justification schemes, Standard PSO and *gbest* communication topology were also adopted through the rest of the testing process (except where indicated that neighbouring topology is used). *FBI* was implemented, with the number of forward and backward particles as indicated in headers of results tables.

Five justification schemes were proposed in this research: *NJ* (no justification), *FJ* (*free-float justification*), *TJ* (*total-float justification*), *FTJ* (*FJ & TJ*, where both techniques are applied to all particles during each iteration), and *AFTJ* (alternating *FJ & TJ*, where both techniques are used alternatively between iterations). The constriction factor value was set to 0.73 (as suggested by *Bratton & Kennedy, 2007*).

N$_{Sch}$	Justification Scheme	Priority Rule	Average Cost Saving (ACS)				Problems Solved to Optimality			
			j-10	j-20	j-30	Aver.	j-10	j-20	j-30	Aver.
Summary 1,000 Sched. (10F/10B)	NJ	Best of EST, LST, GRWC & CPR	36.12	44.57	49.24	**43.31**	75.56	40.37	28.52	**48.15**
	FJ		36.74	46.61	52.00	**45.12**	84.81	53.33	47.04	**61.73**
	TJ		36.98	46.42	51.09	**44.83**	85.56	51.48	36.30	**57.78**
	FTJ		37.13	*47.31*	*52.46*	**45.64**	*88.89*	*61.48*	*52.22*	*67.53*
	AFTJ		*37.19*	46.87	51.76	**45.27**	89.63	56.30	44.81	63.58
Summary 5,000 Sched. (10F/10B)	NJ	Best of EST, LST, GRWC & CPR	35.96	44.64	49.42	**43.34**	75.19	41.11	30.74	**49.01**
	FJ		36.58	46.55	52.17	**45.10**	82.96	54.81	*51.11*	**62.96**
	TJ		36.90	46.43	51.04	**44.79**	85.19	51.48	35.93	**57.53**
	FTJ		*37.16*	*47.38*	*52.44*	**45.66**	*88.89*	*60.74*	*52.22*	*67.28*
	AFTJ		37.07	46.93	51.94	**45.31**	88.89	57.78	46.30	**64.32**
Summary 50,000 Sched. (20F/20B)	NJ	Best of EST, LST, GRWC & CPR	36.32	44.99	49.85	**43.72**	76.30	40.37	29.63	**48.77**
	FJ		37.02	47.40	52.57	**45.66**	88.52	65.56	55.56	**69.88**
	TJ		37.06	46.47	51.27	**44.93**	87.04	51.48	38.15	**58.89**
	FTJ		*37.26*	*47.30*	*52.56*	**45.70**	*91.11*	61.48	54.44	**69.01**
	AFTJ		37.15	47.04	52.13	**45.44**	90.37	59.63	46.67	**65.56**

Table 8.4: Test results for different TCPSP justification schemes

Generally, the results in table 8.3 showed that the *FTJ* is having the the best performance in most cases; but for large analysis (50,000 schedules) *FJ* was a bit better for j-20 and j-30 instances. While the test results for *AFTJ* showed an unsteady good results for the 1000 schedules (mainly due to the reduction in number of justification cycles), but the performance was lower than *FTJ* for larger sized problems and larger number of schedules. And accordingly, *FJ & FTJ* will be used for further detailed analysis in the following sections.

The summary of TCPSP justification schemes testing were shown in table 8.4; for full detailed testing of TCPSP justification refer to appendix C section C.2.

8.2.5. Computational results for testing differential density approaches

The *DDPSO* involves applying various density values to swarm particles resembling different material particles. Density values can either be randomly generated or predefined values. The performances of both approaches were tested in this section with three different value ranges.

Three different ranges were used to test both *DDPSO* approaches (*Random DD* & *Predefined DD*): High (from 1.0 to 5.0), Medium (0.5 to 2.0) & Low (0.1 to 1.0). For *Predefined DD*, values were selected uniformly within each range.

A detailed testing was performed on these six differential density ranges (three random and three predefined) for both RCPSPs & TCPSPs. The summary of the results are included in table 8.4; the full results are tabulated in appendix B section C.3.1. The tests were performed using original PSO with only one change related to the additional density parameter (δ_i). FBI was implemented with different number of particles as indicated in the left column of summary table; and finally DJ was used. The results included in table 8.5 are the best achieved for the selected priority rules.

N_{Sch}	Differential Densities Range	Priority Rule	AD_O	AD_{CP}					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
Summary 1000	DJ only	Best of LST, LFT, MTS & CPR	0.73	14.43	13.26	13.08	39.79	**20.14**	77.29	72.71	71.04	27.33	**62.09**
	Random High		0.58	14.21	12.54	12.13	37.31	**19.05**	79.58	72.08	73.54	29.33	**63.64**
	Random Med.		0.73	14.42	13.12	12.88	39.43	**19.96**	77.71	72.08	71.88	28.00	**62.42**
	Random Low		1.12	14.97	13.70	13.42	40.56	**20.66**	71.67	71.04	69.79	25.50	**59.50**
	Predefined High		0.54	14.16	12.49	12.10	37.33	**19.02**	81.67	73.13	73.75	30.67	**64.59**
	Predef. Med.		0.62	14.27	13.05	12.75	38.98	**19.76**	80.42	72.50	72.29	28.67	**63.42**
	Predefined Low		0.98	14.78	13.69	13.31	40.26	**20.51**	73.33	71.04	70.63	26.00	**60.25**
Summary 5000 (10/10)	DJ only	Best of LST, LFT, MTS & CPR	0.26	13.76	12.35	12.40	38.18	**19.17**	89.38	74.17	75.00	31.50	**67.51**
	Random High		0.47	14.07	12.02	11.35	35.20	**18.16**	82.71	73.54	75.42	31.50	**65.79**
	Random Med.		0.37	13.92	12.25	12.19	37.32	**18.92**	86.04	73.33	73.96	31.00	**66.08**
	Random Low		0.93	14.70	13.33	13.08	39.93	**20.26**	76.88	71.04	71.67	27.83	**61.85**
	Predefined High		0.42	13.98	11.92	11.43	35.17	**18.13**	83.75	74.38	73.96	33.00	**66.11**
	Predef. Med.		0.28	13.79	11.96	11.84	36.55	**18.54**	86.88	73.75	74.58	31.67	**66.57**
	Predefined Low		0.48	14.09	12.79	12.73	38.95	**19.64**	82.71	72.71	73.54	29.00	**64.49**
Summary 5000 (20/20)	DJ only	Best of LST, LFT, MTS & CPR	0.23	13.73	12.40	12.42	38.33	**19.22**	89.58	74.17	74.79	31.17	**67.05**
	Random High		0.31	13.85	11.86	11.34	35.26	**18.08**	87.08	73.96	75.21	32.67	**67.23**
	Random Med.		0.32	13.86	12.30	12.04	37.35	**18.88**	87.71	73.75	75.21	31.50	**66.89**
	Random Low		0.79	14.51	13.27	13.03	39.91	**20.18**	77.08	71.88	70.83	26.67	**61.61**
	Predefined High		0.28	13.79	11.78	11.31	35.16	**18.01**	86.88	74.58	74.79	33.50	**67.44**
	Predef. Med.		0.21	13.70	12.05	11.83	36.66	**18.56**	90.00	74.17	74.79	32.00	**67.70**
	Predefined Low		0.51	14.13	12.78	12.75	39.02	**19.67**	83.13	73.75	72.71	28.83	**64.60**
Overall Summary	DJ only	Best of LST, LFT, MTS & CPR	0.23	13.73	12.35	12.40	38.18	**19.17**	89.58	74.17	75.00	31.50	**67.51**
	Random High		0.31	13.85	11.86	11.34	35.20	**18.08**	87.08	73.96	75.42	32.67	**67.23**
	Random Med.		0.32	13.86	12.25	12.04	37.32	**18.88**	87.71	73.75	75.21	31.50	**66.89**
	Random Low		0.79	14.51	13.27	13.03	39.91	**20.18**	77.08	71.88	71.67	27.83	**61.85**
	Predefined High		0.28	13.79	11.78	11.31	35.16	**18.01**	86.88	74.58	74.79	33.50	**67.44**
	Predef. Med.		0.21	13.70	11.96	11.83	36.55	**18.54**	90.00	74.17	74.79	32.00	**67.70**
	Predefined Low		0.48	14.09	12.78	12.73	38.95	**19.64**	83.13	73.75	73.54	29.00	**64.60**

Table 8.5: Summary of test results for RCPSPs under different DD approaches

The first observation from the test results of different PSO particles densities is that there is no definite range which can guarantee the best results for all problem types and sizes. For RCPSPs, there was a clear trend that the medium density range (0.5-2.0) is the most suitable for j-30, while the high density range (1.0-5.0) was clearly suitable for the larger sized problems. So, both ranges will be used for further *DDPSO* detailed ranges analysis.

The second observation is that random ranges did not have steady performance, whether good or bad; however, for predefined ranges, there was some sort of consistency for their results whether each range is suitable or not. Accordingly, the *Random DD* approach will be eliminated from further analysis.

8.2.6. Testing Rectified SGS (RSGS)

Before commencing with the detailed DD ranges testing, the effect of applying the *Rectified SGS (RSGS)* modification was checked. A comparison between the performances of *DDPSO* for few density ranges was checked with and without the application of *RSGS*; and results were presented in table 8.6 (Note: values of DD ranges will be mentioned in the next section).

N_{Sch}	Rectification	DD Range	AD_O j-30	AD_{CP} j-30	j-60	j-90	j-120	Average
1,000 Schedules (10F/10B Particles)	Yes	1	0.65%	14.34%	12.79%	12.41%	37.66%	**19.30%**
		2	0.47%	14.07%	12.52%	12.24%	37.35%	**19.05%**
		3	0.25%	13.75%	12.21%	11.99%	36.86%	**18.70%**
		4	0.24%	13.74%	11.97%	11.75%	36.23%	**18.42%**
		5	0.22%	13.72%	11.84%	11.62%	35.71%	**18.22%**
	No	1	0.68%	14.38%	12.93%	12.50%	37.84%	**19.42%**
		2	0.53%	14.18%	12.58%	12.38%	37.62%	**19.19%**
		3	0.32%	13.85%	12.46%	12.11%	37.09%	**18.88%**
		4	0.23%	13.73%	12.10%	11.86%	36.57%	**18.56%**
		5	0.25%	13.76%	11.89%	11.59%	35.92%	**18.29%**
	Improvement variance for using Rectification	1	0.03%	0.05%	0.14%	0.09%	0.18%	**0.11%**
		2	0.06%	0.11%	0.06%	0.13%	0.28%	**0.14%**
		3	0.07%	0.10%	0.25%	0.12%	0.23%	**0.18%**
		4	-0.01%	0.00%	0.13%	0.11%	0.34%	**0.14%**
		5	0.03%	0.04%	0.04%	-0.03%	0.21%	**0.07%**
5,000 Schedules (10F/10B Particles)	Yes	1	0.67%	14.38%	12.77%	12.39%	37.69%	**19.31%**
		2	0.19%	13.66%	11.97%	11.83%	36.33%	**18.45%**
		3	0.08%	13.50%	11.48%	11.40%	35.39%	**17.94%**
		4	0.08%	13.50%	11.23%	11.04%	34.49%	**17.56%**
		5	0.18%	13.64%	11.24%	10.83%	33.88%	**17.40%**
	No	1	0.72%	14.45%	12.89%	12.50%	37.91%	**19.44%**
		2	0.20%	13.67%	12.03%	11.85%	36.72%	**18.57%**
		3	0.07%	13.48%	11.54%	11.49%	35.71%	**18.05%**
		4	0.14%	13.59%	11.28%	11.07%	34.61%	**17.64%**
		5	0.17%	13.64%	11.29%	10.85%	34.00%	**17.44%**
	Improvement variance for using Rectification	1	0.05%	0.07%	0.12%	0.12%	0.21%	**0.13%**
		2	0.01%	0.01%	0.07%	0.02%	0.39%	**0.12%**
		3	-0.01%	-0.02%	0.06%	0.09%	0.32%	**0.11%**
		4	0.06%	0.09%	0.05%	0.03%	0.13%	**0.07%**
		5	-0.01%	0.00%	0.04%	0.01%	0.12%	**0.05%**

50,000 Schedules (20F/20B Particles)	Yes	1	0.54%	14.20%	12.66%	12.26%	37.37%	**19.12%**
		2	0.04%	13.44%	11.50%	11.36%	35.38%	**17.92%**
		3	0.02%	13.41%	11.03%	10.94%	34.46%	**17.46%**
		4	0.02%	13.40%	10.86%	10.55%	33.46%	**17.07%**
		5	0.08%	13.50%	10.97%	10.36%	32.69%	**16.88%**
	No	1	0.61%	14.30%	12.77%	12.37%	37.56%	**19.25%**
		2	0.06%	13.47%	11.41%	11.33%	35.45%	**17.92%**
		3	0.04%	13.43%	11.06%	11.02%	34.62%	**17.53%**
		4	0.03%	13.43%	10.89%	10.61%	33.61%	**17.14%**
		5	0.06%	13.47%	10.93%	10.40%	32.77%	**16.89%**
	Improvement variance for using Rectification	1	0.07%	0.10%	0.11%	0.11%	0.20%	**0.13%**
		2	0.02%	0.03%	-0.09%	-0.03%	0.08%	**0.00%**
		3	0.02%	0.02%	0.02%	0.09%	0.16%	**0.07%**
		4	0.01%	0.02%	0.03%	0.06%	0.15%	**0.07%**
		5	-0.02%	-0.03%	-0.04%	0.04%	0.08%	**0.01%**

Table 8.6: Comparison for performance of DDPSO with & without RSGS

As shown in table 8.6, the results using *RSGS* were better in most cases than the original *SSGS* without rectification, especially for large sized problems and large sized analysis. And the average results for all problem sizes were always better when *RSGS* was used. Accordingly, all following analysis for *DDPSO* will be adopting *RSGS* for schedules generation.

8.2.7. *Computational results for detailed DD ranges testing*

According to the initial *Density Ranges (DD)* testing in section 8.2.5, the medium density range (0.5-2.0) and the high density range (1.0-5.0) were dominating the best achieved results; so, these ranges were broken down further to ten *DD* ranges (as shown in table 8.7) which will be used for the rest of *DDPSO* testing.

	Density Range									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Low	0.1	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
High	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0

Table 8.7: DDPSO density ranges limits

An Intensive analysis was performed for these *DD* ranges as well as different inertia (*w*) values; *CPR, SDJ (FTJ) & RSGS (LSGS)* were used for all RCPSP (TCPSP) testing. Experimental test results were summarized in tables 8.7 & 8.8, while full analysis details were included in appendix C section C.3.2.

For RCPSP, summarized results shown in table 8.8 shows that the more the schedules generated and the larger the schedule size, the more the need for larger density range to achieve best results; this is mainly because large

density ranges will allow larger solutions space exploration, and accordingly the results become better with larger exploration for large size problems and large numbers of schedules generated. Comparison of *DDPSO* results and *MJPSO*, as well as other literature algorithms will be performed in section 8.2.9; but in general, the use of detailed density ranges was in most cases achieving better results than original *PSO* algorithm.

N_{Sch}	w	DD Range	AD_O	AD_{CP}					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
1,000 Schedules (10F/10B Particles)	Best Inertia (w)	1	0.25	13.75	12.18	11.88	36.49	18.58	89.58	73.75	73.96	31.00	66.67
		2	0.21	13.70	11.94	11.63	35.81	18.27	89.79	75.42	74.79	33.00	68.25
		3	0.19	13.67	11.63	11.33	35.12	17.96	91.46	76.88	76.04	33.50	68.90
		4	0.18	13.64	11.63	11.25	34.85	17.87	91.46	76.04	75.83	34.00	68.68
		5	0.22	13.72	11.69	11.23	34.87	17.92	89.79	76.67	76.25	34.17	68.91
		6	0.26	13.77	11.71	11.33	35.05	17.98	88.13	76.04	76.46	33.83	68.21
		7	0.27	13.80	11.75	11.33	35.11	18.03	88.75	76.25	75.83	34.00	68.27
		8	0.29	13.82	11.79	11.37	35.14	18.05	87.92	75.83	75.83	33.50	67.96
		9	0.28	13.80	11.84	11.41	35.23	18.07	88.13	75.21	75.63	33.33	67.83
		10	0.27	13.77	11.85	11.43	35.27	18.12	87.50	75.63	76.04	33.67	67.72
	Aver. for all Inertia (w)	1	0.45	14.04	12.51	12.21	37.28	19.01	83.31	72.84	72.97	30.00	64.69
		2	0.30	13.82	12.23	11.95	36.71	18.68	87.37	74.22	74.06	31.23	66.72
		3	0.23	13.72	11.88	11.67	36.02	18.32	89.35	75.42	75.21	32.44	68.10
		4	0.22	13.71	11.77	11.46	35.49	18.11	89.69	75.36	75.39	33.23	68.42
		5	0.25	13.75	11.74	11.39	35.28	18.04	88.88	75.57	75.68	33.44	68.39
		6	0.29	13.81	11.75	11.40	35.26	18.06	87.40	75.47	75.55	33.27	67.92
		7	0.30	13.84	11.79	11.40	35.26	18.07	87.37	75.44	75.49	33.27	67.89
		8	0.32	13.86	11.84	11.41	35.26	18.09	86.35	74.90	75.44	32.96	67.41
		9	0.31	13.84	11.87	11.45	35.34	18.12	87.19	74.87	75.18	32.81	67.51
		10	0.32	13.87	11.90	11.47	35.32	18.14	86.28	75.10	75.52	33.10	67.50
5,000 Schedules (10F/10B Particles)	Best Inertia (w)	1	0.10	13.54	11.88	11.62	35.80	18.21	94.79	75.83	75.42	32.67	69.09
		2	0.06	13.47	11.50	11.38	35.17	17.91	96.46	78.13	76.88	34.33	71.22
		3	0.06	13.47	11.22	10.99	34.29	17.52	96.04	80.83	77.71	36.50	72.46
		4	0.08	13.50	11.19	10.80	33.82	17.40	95.00	79.79	77.71	36.83	72.17
		5	0.17	13.63	11.24	10.73	33.66	17.34	91.25	77.50	77.29	36.83	70.43
		6	0.19	13.66	11.27	10.74	33.57	17.34	89.58	77.50	76.46	36.67	69.74
		7	0.21	13.69	11.31	10.71	33.56	17.33	90.42	77.29	76.88	36.67	70.07
		8	0.25	13.75	11.31	10.73	33.65	17.40	88.33	78.13	77.08	36.17	69.41
		9	0.21	13.69	11.34	10.77	33.67	17.37	89.79	77.71	76.67	36.33	69.92
		10	0.24	13.74	11.32	10.83	33.80	17.44	89.58	77.71	77.08	36.67	69.74
	Aver. for all Inertia (w)	1	0.33	13.88	12.26	11.97	36.75	18.72	87.34	73.88	73.83	30.90	66.06
		2	0.09	13.52	11.67	11.51	35.70	18.10	94.79	77.21	76.09	33.25	70.34
		3	0.08	13.49	11.37	11.18	34.92	17.74	95.42	79.11	76.77	35.40	71.67
		4	0.14	13.59	11.26	10.88	34.06	17.45	92.34	77.86	76.98	36.44	70.91
		5	0.21	13.69	11.31	10.78	33.74	17.38	89.61	77.08	76.48	36.31	69.87
		6	0.25	13.73	11.31	10.77	33.66	17.37	88.67	76.69	76.20	36.17	69.43
		7	0.25	13.75	11.33	10.76	33.65	17.37	88.93	76.77	76.59	36.08	69.59
		8	0.28	13.80	11.36	10.77	33.73	17.41	87.45	76.77	76.35	35.65	69.05
		9	0.27	13.78	11.35	10.83	33.77	17.43	88.31	77.06	76.51	35.75	69.41
		10	0.26	13.77	11.38	10.85	33.84	17.46	87.97	76.85	76.43	35.90	69.29

		#										
50,000 Schedules (20F/20B Particles)	Best Inertia (w)	1	0.04	13.45	11.48	11.26	35.04	**17.81**	97.29	79.17	77.08	34.83	**72.01**
		2	0.01	13.39	11.13	11.00	34.35	**17.47**	99.17	82.71	77.92	38.17	**74.44**
		3	0.01	13.39	10.85	10.58	33.46	**17.09**	99.17	85.42	78.96	40.50	**75.44**
		4	0.02	13.40	10.84	10.39	32.77	**16.90**	98.33	83.75	79.17	40.50	**75.28**
		5	0.07	13.47	10.97	10.34	32.54	**16.86**	95.83	81.04	79.17	40.00	**73.85**
		6	0.11	13.54	11.00	10.36	32.42	**16.87**	94.58	80.42	78.13	39.17	**73.07**
		7	0.09	13.51	11.04	10.35	32.39	**16.84**	95.00	79.79	78.13	40.00	**72.59**
		8	0.11	13.54	11.05	10.36	32.36	**16.85**	93.75	80.00	78.13	39.33	**72.33**
		9	0.12	13.56	10.98	10.34	32.31	**16.84**	93.33	81.25	78.13	40.33	**72.66**
		10	0.11	13.54	11.01	10.31	32.35	**16.82**	94.17	81.04	78.33	40.17	**72.91**
	Aver. for all Inertia (w)	1	0.22	13.70	11.92	11.68	36.06	**18.34**	90.96	75.94	75.36	32.21	**67.91**
		2	0.03	13.41	11.24	11.14	34.83	**17.66**	98.20	80.94	77.37	36.33	**73.21**
		3	0.02	13.40	10.90	10.73	33.85	**17.22**	98.70	83.75	78.52	39.10	**75.02**
		4	0.06	13.47	10.93	10.45	33.01	**16.96**	96.46	82.24	78.28	39.60	**74.15**
		5	0.11	13.55	11.03	10.38	32.60	**16.89**	93.75	79.48	77.94	38.94	**72.53**
		6	0.14	13.59	11.06	10.40	32.46	**16.88**	92.63	79.04	77.50	38.73	**71.97**
		7	0.16	13.61	11.08	10.39	32.43	**16.88**	91.95	78.98	77.66	38.27	**71.72**
		8	0.15	13.60	11.10	10.38	32.42	**16.87**	92.45	78.80	77.37	38.65	**71.82**
		9	0.15	13.61	11.08	10.37	32.42	**16.87**	92.21	79.19	77.40	38.88	**71.92**
		10	0.14	13.60	11.04	10.36	32.42	**16.85**	92.50	79.24	77.71	39.06	**72.13**

Table 8.8: Summary of test results for RCPSPs under different PSO particles densities

For TCPSP, summarized results shown in table 8.9 do not show a general trend for certain density ranges or inertia values achieving best results; however, for the average results, density range R02 was achieving in most cases the best average, especially for large number of schedules generated; and similarly inertia value of 0.5 was also achieving best averages in many cases. These scattered best results is believed to be due to the nature of RIP/max problems, where the maximum lag relations affect the shape of solutions space causing spiky hills rather than smoothly distributed hills.

N_{Sch}		Inertia (w)	Density Range	Average Cost Saving (ACS)				Problems Solved to Optimality			
				j-10	j-20	j-30	Aver.	j-10	j-20	j-30	Aver.
1,000 Schedules (10F/10B Particles)	Best Results	0.73	Best DD Range	37.21	47.33	52.50	**45.64**	90.74	62.22	52.22	**67.53**
		0.6		37.20	47.35	52.48	**45.62**	90.00	60.74	51.48	**67.04**
		0.5		37.24	47.34	52.49	**45.69**	90.74	62.22	51.85	**68.27**
		0.4		37.22	47.39	52.52	**45.68**	90.00	61.48	52.59	**67.78**
		0.3		37.21	47.33	52.47	**45.64**	90.00	60.37	52.59	**67.28**
		0.2		37.24	47.33	52.48	**45.68**	89.63	61.85	52.59	**68.02**
		0.1		37.22	47.27	52.44	**45.60**	89.63	60.74	50.74	**66.67**
		0.0		37.24	47.25	52.45	**45.60**	90.37	60.00	51.11	**66.91**
		SPSO	Best w	37.24	47.34	52.49	**45.69**	90.74	62.22	52.22	**68.27**
		R01		37.21	47.28	52.52	**45.64**	90.00	61.85	52.59	**67.53**
		R02		37.24	47.35	52.48	**45.68**	90.00	62.22	52.59	**66.91**
		R03		37.24	47.36	52.47	**45.68**	90.00	61.48	52.22	**67.04**
		R04		37.23	47.33	52.50	**45.63**	90.74	60.37	51.85	**67.16**
		R05		37.21	47.39	52.52	**45.67**	90.37	61.85	52.59	**67.28**

Schedules	Result type	w	Metric								
	Average Results	0.73	Average for all DD Ranges	37.16	47.25	52.43	**45.62**	89.26	60.12	50.99	**66.79**
		0.6		37.16	47.21	52.41	**45.59**	89.07	59.44	50.25	**66.26**
		0.5		37.17	47.26	52.40	**45.61**	89.32	60.31	50.80	**66.81**
		0.4		37.17	47.26	52.47	**45.64**	89.44	60.49	51.54	**67.16**
		0.3		37.19	47.16	52.42	**45.59**	89.57	59.44	50.93	**66.65**
		0.2		37.18	47.24	52.43	**45.62**	89.20	60.19	50.99	**66.79**
		0.1		37.16	47.19	52.36	**45.57**	89.01	59.20	50.12	**66.11**
		0.0		37.15	47.16	52.36	**45.56**	89.38	58.89	50.25	**66.17**
		SPSO	Average for all Inertia (w) values	37.17	47.20	52.41	**45.60**	89.58	59.95	50.88	**66.81**
		R01		37.15	47.20	52.41	**45.59**	89.17	59.54	50.60	**66.44**
		R02		37.16	47.27	52.41	**45.61**	89.07	60.23	50.83	**66.71**
		R03		37.20	47.21	52.41	**45.61**	89.40	59.81	50.97	**66.73**
		R04		37.17	47.19	52.42	**45.59**	89.44	59.03	50.51	**66.33**
		R05		37.16	47.22	52.40	**45.59**	89.03	60.00	50.60	**66.54**
5,000 Schedules (10F/10B Particles)	Best Results	0.73	Best DD Range	37.19	47.27	52.48	**45.65**	89.44	60.06	51.85	**67.12**
		0.6		37.16	47.23	52.44	**45.61**	89.32	60.31	51.23	**66.95**
		0.5		37.17	47.26	52.42	**45.62**	89.32	60.25	50.99	**66.85**
		0.4		37.19	47.27	52.41	**45.62**	89.81	60.25	50.99	**67.02**
		0.3		37.19	47.22	52.42	**45.61**	89.57	59.51	50.62	**66.56**
		0.2		37.14	47.21	52.43	**45.59**	88.64	59.14	50.80	**66.19**
		0.1		37.14	47.18	52.43	**45.58**	89.01	59.32	51.23	**66.52**
		0.0		37.17	47.13	52.35	**45.55**	89.88	58.40	49.94	**66.07**
		SPSO	Best w	37.16	47.22	52.42	**45.60**	89.26	59.81	51.39	**66.82**
		R01		37.17	47.19	52.45	**45.60**	89.26	59.81	51.44	**66.84**
		R02		37.17	47.28	52.46	**45.64**	89.40	60.09	51.85	**67.11**
		R03		37.20	47.20	52.41	**45.60**	89.77	59.12	50.14	**66.34**
		R04		37.16	47.22	52.41	**45.60**	89.31	59.17	51.11	**66.53**
		R05		37.15	47.21	52.37	**45.58**	89.26	59.91	49.81	**66.33**
	Average Results	0.73	Average for all DD Ranges	37.13	47.02	52.31	**45.49**	89.26	57.04	50.37	**65.56**
		0.6		37.13	47.22	52.39	**45.58**	89.26	59.26	50.00	**66.17**
		0.5		37.25	47.17	52.39	**45.60**	90.74	58.52	49.63	**66.30**
		0.4		37.26	47.13	52.36	**45.58**	90.74	59.26	50.37	**66.79**
		0.3		37.17	47.09	52.31	**45.52**	90.00	57.78	49.63	**65.80**
		0.2		37.11	47.15	52.32	**45.53**	89.26	58.52	49.63	**65.80**
		0.1		37.23	47.38	52.56	**45.71**	90.00	61.85	53.70	**68.40**
		0.0		37.24	47.30	52.48	**45.64**	90.00	61.48	52.59	**68.02**
		SPSO	Average for all Inertia (w) values	37.20	47.36	52.50	**45.66**	90.00	61.11	53.33	**67.65**
		R01		37.23	47.36	52.51	**45.69**	90.74	61.48	53.33	**68.02**
		R02		37.27	47.33	52.46	**45.64**	91.11	60.37	52.22	**67.16**
		R03		37.21	47.35	52.49	**45.64**	89.26	60.37	52.96	**66.79**
		R04		37.19	47.34	52.50	**45.63**	89.26	61.11	52.59	**67.16**
		R05		37.26	47.22	52.39	**45.60**	90.74	59.26	50.37	**66.79**
50,000 Schedules (20F/20B Particles)	Best Results	0.73	Best DD Range	37.26	47.43	52.56	**45.70**	91.11	62.22	54.44	**69.01**
		0.6		37.31	47.33	52.52	**45.70**	92.59	62.96	54.07	**69.63**
		0.5		37.28	47.49	52.50	**45.76**	91.85	63.70	53.70	**69.75**
		0.4		37.30	47.33	52.44	**45.68**	91.11	63.33	51.85	**68.52**
		0.3		37.25	47.42	52.55	**45.74**	91.48	62.96	52.59	**68.64**
		0.2		37.28	47.41	52.52	**45.70**	91.85	63.33	51.85	**68.40**
		SPSO	Best w	37.28	47.37	52.56	**45.70**	91.48	62.59	54.44	**69.01**
		R01		37.31	47.41	52.49	**45.70**	92.59	63.33	52.96	**68.52**

Average Results											
		R02	37.28	47.49	52.55	**45.76**	91.85	63.70	54.07	**69.75**
		R03	37.26	47.36	52.52	**45.68**	91.11	62.59	52.96	**68.40**
		R04	37.30	47.36	52.52	**45.68**	91.11	63.33	51.85	**68.15**
		R05	37.27	47.40	52.48	**45.72**	91.48	62.22	51.48	**68.40**
	0.73	Average for all DD Ranges	37.22	47.29	52.47	**45.66**	90.25	61.54	52.22	**68.00**
	0.6		37.25	47.27	52.45	**45.65**	91.17	61.23	51.79	**68.07**
	0.5		37.23	47.33	52.44	**45.67**	90.56	61.73	51.17	**67.82**
	0.4		37.24	47.22	52.42	**45.62**	90.80	61.17	50.86	**67.61**
	0.3		37.23	47.25	52.47	**45.65**	90.99	61.05	51.73	**67.92**
	0.2		37.25	47.32	52.44	**45.67**	91.17	61.79	50.56	**67.84**
	SPSO	Average for all Inertia (w) values	37.24	47.28	52.48	**45.66**	90.74	61.42	51.60	**67.92**
	R01		37.25	47.27	52.43	**45.65**	91.11	61.36	51.42	**67.96**
	R02		37.26	47.34	52.48	**45.69**	91.17	62.16	52.35	**68.56**
	R03		37.22	47.26	52.44	**45.64**	90.49	61.54	51.36	**67.80**
	R04		37.23	47.27	52.41	**45.64**	90.56	61.11	50.80	**67.49**
	R05		37.22	47.27	52.45	**45.64**	90.86	60.93	50.80	**67.53**

Table 8.9: Summary of test results for TCPSPs under different PSO particles densities

8.2.8. Results for DDPSO under different communication topologies

For the purpose of improving the test results of the DDPSO, detailed testing was performed using different values of inertia (w) & different PSO communication topologies. For RCPSPs, best and average test results were grouped in tables 8.10a-8.10c, and summarized in table 8.10d; while table 8.11 shows the summary results of TCPSPs. Full analysis details were included in appendix C section C.3.3.

N_{Sch}	w	DD Range	AD_O	AD_{CP}					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
1,000 Schedules (10F/10B Particles) (GR=0.75)	Best Inertia (w)	1	0.27	13.79	12.28	11.94	36.60	**18.65**	88.54	74.58	73.75	31.17	**66.83**
		2	0.20	13.67	11.95	11.73	35.91	**18.32**	90.63	75.63	75.00	32.50	**68.35**
		3	0.17	13.65	11.71	11.37	35.23	**17.99**	92.08	76.46	76.04	33.83	**69.22**
		4	0.18	13.65	11.67	11.29	34.94	**17.91**	90.42	76.46	76.25	34.33	**68.79**
		5	0.20	13.69	11.68	11.29	34.96	**17.95**	90.42	76.46	75.83	34.33	**69.21**
		6	0.21	13.69	11.67	11.29	35.10	**17.96**	90.63	76.67	76.04	33.83	**69.00**
		7	0.21	13.69	11.71	11.38	35.17	**18.02**	89.79	76.46	76.04	33.83	**68.44**
		8	0.24	13.74	11.76	11.36	35.16	**18.04**	88.75	75.63	75.83	33.33	**68.19**
		9	0.26	13.78	11.81	11.42	35.23	**18.07**	88.75	75.63	75.83	33.33	**68.18**
		10	0.25	13.76	11.79	11.41	35.22	**18.09**	89.17	76.04	76.25	33.83	**67.93**
	Aver. for all Inertia (w)	1	0.45	14.04	12.52	12.24	37.33	**19.03**	82.92	72.99	72.95	29.75	**64.65**
		2	0.28	13.80	12.22	11.99	36.74	**18.69**	87.71	74.58	73.99	31.00	**66.82**
		3	0.22	13.71	11.93	11.68	36.06	**18.34**	89.86	75.38	74.83	32.47	**68.14**
		4	0.21	13.69	11.76	11.49	35.54	**18.12**	89.86	75.56	75.17	33.33	**68.48**
		5	0.22	13.71	11.72	11.42	35.34	**18.05**	89.76	76.08	75.49	33.36	**68.67**
		6	0.25	13.76	11.77	11.41	35.31	**18.06**	88.92	75.90	75.28	33.44	**68.39**
		7	0.25	13.76	11.77	11.43	35.30	**18.07**	88.96	75.38	75.31	33.17	**68.20**
		8	0.27	13.79	11.81	11.42	35.33	**18.09**	87.92	75.00	75.63	32.89	**67.86**
		9	0.28	13.80	11.84	11.45	35.37	**18.11**	87.53	75.10	75.24	32.97	**67.71**
		10	0.29	13.82	11.87	11.48	35.35	**18.13**	87.64	74.93	75.17	32.78	**67.63**

		#											
1,000 Schedules (10F/10B Particles) (GR=0.5)	Best Inertia (w)	1	0.27	13.79	12.27	11.99	36.77	**18.70**	88.54	74.58	74.17	31.00	**67.07**
		2	0.21	13.70	11.96	11.70	36.09	**18.36**	90.42	75.21	75.42	32.33	**68.24**
		3	0.18	13.64	11.74	11.42	35.38	**18.05**	92.08	76.04	76.25	34.17	**69.58**
		4	0.18	13.66	11.69	11.30	35.05	**17.94**	90.63	76.25	76.25	34.00	**69.10**
		5	0.19	13.67	11.71	11.36	35.03	**17.96**	90.63	77.29	75.83	34.33	**69.28**
		6	0.23	13.73	11.70	11.33	35.13	**17.99**	89.79	76.25	76.04	34.17	**68.54**
		7	0.23	13.73	11.75	11.41	35.18	**18.05**	90.63	75.42	75.63	33.67	**68.69**
		8	0.23	13.74	11.81	11.32	35.25	**18.05**	89.79	75.42	76.04	34.17	**68.44**
		9	0.25	13.76	11.83	11.44	35.28	**18.10**	88.54	75.63	76.04	33.33	**68.01**
		10	0.24	13.75	11.82	11.42	35.35	**18.11**	88.54	75.63	75.63	33.00	**68.16**
	Aver. for all Inertia (w)	1	0.42	14.01	12.51	12.18	37.25	**18.99**	83.84	73.13	73.24	30.02	**65.06**
		2	0.28	13.80	12.20	11.95	36.72	**18.67**	88.13	74.38	74.26	31.19	**66.99**
		3	0.20	13.68	11.95	11.68	36.00	**18.33**	90.39	75.39	75.12	32.64	**68.38**
		4	0.21	13.70	11.78	11.48	35.54	**18.12**	89.76	75.57	75.63	33.29	**68.56**
		5	0.23	13.72	11.75	11.42	35.38	**18.07**	89.43	75.98	75.42	33.48	**68.58**
		6	0.25	13.76	11.77	11.41	35.33	**18.07**	88.84	75.27	75.51	33.60	**68.30**
		7	0.25	13.77	11.81	11.45	35.37	**18.10**	88.54	75.18	75.42	33.31	**68.11**
		8	0.27	13.78	11.84	11.45	35.40	**18.12**	88.24	74.91	75.63	33.10	**67.97**
		9	0.27	13.79	11.86	11.48	35.41	**18.14**	87.89	75.03	75.48	32.93	**67.83**
		10	0.28	13.80	11.88	11.47	35.45	**18.15**	87.44	75.06	75.36	32.64	**67.63**
1,000 Schedules (10F/10B Particles) (GR=0.25)	Best Inertia (w)	1	0.28	13.81	12.33	12.04	36.94	**18.78**	88.54	74.38	73.96	31.00	**66.78**
		2	0.18	13.66	12.08	11.77	36.21	**18.44**	90.63	75.21	74.38	31.67	**67.82**
		3	0.16	13.62	11.75	11.47	35.45	**18.08**	91.46	76.04	76.46	33.17	**69.07**
		4	0.19	13.66	11.70	11.34	35.17	**17.97**	91.67	77.08	75.83	34.00	**69.28**
		5	0.17	13.64	11.70	11.33	35.20	**18.01**	90.83	76.04	76.25	34.00	**68.76**
		6	0.18	13.66	11.76	11.37	35.18	**18.02**	90.83	75.83	76.04	34.00	**68.60**
		7	0.23	13.72	11.79	11.42	35.24	**18.07**	89.17	76.04	76.04	33.83	**68.32**
		8	0.27	13.78	11.82	11.42	35.32	**18.09**	88.33	75.83	75.83	33.33	**68.18**
		9	0.26	13.79	11.84	11.42	35.39	**18.14**	88.33	75.63	76.04	33.50	**68.06**
		10	0.27	13.78	11.84	11.47	35.43	**18.16**	87.92	75.63	75.63	33.17	**67.81**
	Aver. for all Inertia (w)	1	0.42	14.01	12.50	12.22	37.29	**19.00**	84.08	73.27	73.10	29.88	**65.08**
		2	0.27	13.79	12.23	11.98	36.74	**18.68**	87.89	74.52	73.93	31.05	**66.85**
		3	0.20	13.69	11.95	11.67	36.06	**18.34**	90.09	75.27	75.12	32.14	**68.15**
		4	0.20	13.68	11.78	11.50	35.59	**18.14**	90.36	75.95	75.48	33.02	**68.70**
		5	0.23	13.72	11.76	11.44	35.46	**18.10**	89.20	75.65	75.33	33.71	**68.47**
		6	0.23	13.75	11.81	11.45	35.43	**18.11**	89.35	75.39	75.48	32.93	**68.28**
		7	0.26	13.78	11.84	11.47	35.44	**18.13**	88.18	75.36	75.48	33.05	**68.02**
		8	0.28	13.81	11.86	11.48	35.48	**18.16**	87.77	75.06	75.33	32.88	**67.76**
		9	0.30	13.83	11.90	11.48	35.49	**18.18**	87.41	74.91	75.60	32.81	**67.68**
		10	0.30	13.84	11.90	11.50	35.53	**18.19**	87.53	74.97	75.24	32.71	**67.61**
1,000 Schedules (10F/10B Particles) (GR=0.0)	Best Inertia (w)	1	0.29	13.82	12.35	12.09	37.12	**18.85**	88.96	75.00	74.17	30.67	**66.99**
		2	0.22	13.72	12.10	11.78	36.32	**18.49**	90.21	75.63	75.00	32.17	**68.13**
		3	0.21	13.70	11.75	11.52	35.53	**18.13**	90.21	76.04	75.21	33.00	**68.33**
		4	0.19	13.65	11.75	11.38	35.24	**18.03**	91.46	76.25	75.83	34.17	**69.27**
		5	0.19	13.68	11.73	11.35	35.24	**18.03**	90.83	76.67	75.83	33.83	**68.82**
		6	0.24	13.74	11.81	11.42	35.34	**18.10**	89.58	75.63	76.04	33.83	**68.56**
		7	0.23	13.74	11.83	11.46	35.40	**18.15**	89.79	76.04	75.63	33.67	**68.33**
		8	0.25	13.75	11.85	11.48	35.49	**18.17**	88.96	75.42	75.42	33.17	**68.10**
		9	0.27	13.79	11.90	11.48	35.51	**18.21**	87.92	75.83	75.63	35.66	**67.78**
		10	0.29	13.82	11.91	11.50	35.58	**18.23**	88.54	75.21	75.63	33.00	**67.56**

	DD Range	AD_O j-30	AD_CP j-30	j-60	j-90	j-120	Aver.	Problems Solved j-30	j-60	j-90	j-120	Aver.
Aver. for all Inertia (w)	1	0.43	14.02	12.51	12.21	37.32	**19.02**	83.72	73.30	73.07	29.90	**65.00**
	2	0.28	13.80	12.23	11.99	36.76	**18.70**	88.04	74.35	74.05	31.02	**66.86**
	3	0.24	13.73	11.95	11.70	36.10	**18.37**	89.20	75.00	74.85	32.19	**67.81**
	4	0.22	13.72	11.83	11.53	35.66	**18.19**	89.79	75.39	75.09	33.00	**68.32**
	5	0.23	13.72	11.80	11.45	35.53	**18.13**	89.49	75.60	75.45	33.12	**68.41**
	6	0.27	13.78	11.84	11.48	35.51	**18.15**	87.71	75.12	75.60	33.21	**67.91**
	7	0.28	13.81	11.85	11.49	35.57	**18.18**	87.89	75.27	75.30	32.69	**67.79**
	8	0.29	13.81	11.89	11.53	35.58	**18.20**	87.62	75.00	75.12	32.71	**67.61**
	9	0.32	13.87	11.92	11.53	35.63	**18.23**	76.46	66.02	66.32	33.29	**60.52**
	10	0.32	13.86	11.95	11.54	35.64	**18.25**	86.96	74.55	75.18	32.67	**67.34**

Table 8.10a: Best & average test results for RCPSPs under different PSO topologies
(1,000 schedules – 10F/10B particles)

N_Sch	w	DD Range	AD_O j-30	AD_CP j-30	j-60	j-90	j-120	Aver.	Problems Solved to Optimality j-30	j-60	j-90	j-120	Aver.
5,000 Schedules (10F/10B Particles) (GR=0.75)	Best Inertia (w)	1	0.10	13.53	11.87	11.68	35.92	**18.25**	94.17	77.08	75.42	32.67	**69.48**
		2	0.06	13.47	11.54	11.34	35.23	**17.90**	96.46	78.33	76.67	34.67	**71.48**
		3	0.06	13.45	11.21	10.98	34.44	**17.55**	96.67	80.42	77.50	36.67	**72.36**
		4	0.08	13.49	11.11	10.78	33.86	**17.36**	95.21	80.00	77.71	37.33	**72.00**
		5	0.13	13.57	11.17	10.71	33.62	**17.30**	93.13	79.17	77.29	37.67	**71.49**
		6	0.14	13.59	11.20	10.68	33.58	**17.29**	92.08	79.17	77.71	37.33	**71.13**
		7	0.17	13.63	11.23	10.72	33.59	**17.31**	92.08	78.54	77.08	37.00	**70.96**
		8	0.16	13.63	11.25	10.75	33.67	**17.34**	91.88	77.71	77.29	36.83	**70.57**
		9	0.18	13.65	11.24	10.78	33.74	**17.38**	91.25	78.33	77.08	37.00	**70.64**
		10	0.18	13.65	11.29	10.81	33.73	**17.37**	90.42	78.33	77.29	37.17	**70.49**
	Aver. for all Inertia (w)	1	0.29	13.81	12.17	11.93	36.64	**18.64**	88.51	74.52	74.02	31.05	**67.03**
		2	0.08	13.50	11.67	11.52	35.71	**18.10**	95.42	77.47	76.10	33.60	**70.65**
		3	0.07	13.47	11.30	11.13	34.82	**17.68**	96.13	79.32	76.85	35.86	**72.04**
		4	0.11	13.55	11.18	10.84	34.10	**17.42**	93.75	79.23	77.26	36.52	**71.69**
		5	0.14	13.59	11.21	10.75	33.71	**17.32**	92.50	77.98	76.82	37.00	**71.07**
		6	0.17	13.64	11.24	10.72	33.64	**17.31**	91.13	77.98	77.05	36.69	**70.71**
		7	0.18	13.65	11.27	10.77	33.67	**17.34**	90.83	77.80	76.58	36.29	**70.37**
		8	0.20	13.67	11.29	10.77	33.72	**17.36**	90.65	77.08	76.88	36.21	**70.21**
		9	0.20	13.67	11.30	10.81	33.81	**17.40**	90.33	77.65	76.82	36.45	**70.31**
		10	0.21	13.70	11.33	10.84	33.83	**17.42**	89.58	77.59	76.61	36.29	**70.02**
5,000 Schedules (10F/10B Particles) (GR=0.5)	Best Inertia (w)	1	0.11	13.54	11.89	11.66	36.00	**18.30**	94.38	76.04	75.42	32.83	**69.35**
		2	0.06	13.47	11.55	11.39	35.33	**17.95**	96.46	79.17	76.46	34.83	**71.69**
		3	0.05	13.45	11.28	11.05	34.50	**17.58**	96.67	80.42	77.29	36.33	**72.31**
		4	0.08	13.49	11.15	10.82	33.91	**17.37**	95.42	80.00	77.71	37.00	**72.23**
		5	0.10	13.53	11.13	10.74	33.68	**17.30**	94.38	79.38	77.29	37.33	**71.76**
		6	0.11	13.54	11.19	10.71	33.63	**17.30**	93.54	78.96	77.50	37.17	**71.50**
		7	0.16	13.62	11.24	10.74	33.59	**17.33**	92.71	78.54	77.08	37.17	**70.91**
		8	0.15	13.61	11.24	10.74	33.72	**17.34**	92.71	78.75	77.29	37.00	**71.26**
		9	0.16	13.61	11.27	10.80	33.76	**17.39**	91.88	77.92	77.08	37.17	**70.73**
		10	0.16	13.62	11.27	10.84	33.84	**17.40**	92.50	78.75	76.88	37.17	**71.10**
	Aver. for all Inertia (w)	1	0.28	13.80	12.16	11.93	36.65	**18.63**	88.18	74.73	74.14	31.24	**67.07**
		2	0.09	13.51	11.68	11.53	35.72	**18.11**	95.18	77.35	76.07	33.71	**70.58**
		3	0.07	13.48	11.32	11.17	34.85	**17.70**	95.80	79.35	76.70	35.83	**71.92**
		4	0.10	13.53	11.18	10.88	34.16	**17.44**	94.49	79.14	77.08	36.74	**71.86**
		5	0.13	13.57	11.18	10.77	33.80	**17.33**	93.15	78.54	76.85	36.67	**71.30**

Group	Sub	#											
		6	0.15	13.60	11.23	10.73	33.69	**17.32**	92.11	78.24	76.99	36.69	**71.01**
		7	0.18	13.64	11.25	10.77	33.70	**17.34**	91.22	77.80	76.82	36.48	**70.58**
		8	0.16	13.63	11.28	10.77	33.76	**17.36**	91.28	78.01	76.73	36.50	**70.63**
		9	0.19	13.67	11.31	10.82	33.83	**17.41**	90.57	77.59	76.82	36.43	**70.35**
		10	0.19	13.67	11.32	10.86	33.92	**17.44**	90.89	77.83	76.70	36.17	**70.40**
5,000 Schedules (10F/10B Particles) (GR=0.25)	Best Inertia (w)	1	0.12	13.57	11.87	11.69	36.11	**18.32**	93.54	76.46	75.21	32.17	**69.34**
		2	0.06	13.47	11.60	11.38	35.49	**17.99**	96.25	77.92	76.46	34.33	**70.91**
		3	0.05	13.45	11.28	11.04	34.55	**17.60**	96.67	80.42	77.50	37.00	**72.52**
		4	0.06	13.48	11.14	10.83	33.96	**17.39**	96.25	80.21	77.71	37.50	**72.71**
		5	0.08	13.50	11.17	10.77	33.77	**17.32**	95.00	79.17	77.08	38.00	**71.91**
		6	0.13	13.57	11.21	10.77	33.74	**17.34**	93.13	79.38	77.50	36.83	**71.40**
		7	0.12	13.57	11.22	10.76	33.69	**17.33**	93.54	79.38	77.29	37.00	**71.33**
		8	0.16	13.62	11.28	10.79	33.82	**17.39**	92.08	78.54	77.29	37.50	**70.90**
		9	0.15	13.61	11.27	10.81	33.88	**17.42**	92.08	78.54	77.50	36.83	**70.92**
		10	0.15	13.60	11.28	10.83	33.94	**17.42**	92.50	78.96	77.08	36.50	**71.05**
	Aver. for all Inertia (w)	1	0.27	13.79	12.15	11.93	36.70	**18.64**	88.57	74.55	74.02	31.14	**67.07**
		2	0.08	13.50	11.68	11.53	35.77	**18.12**	95.30	77.05	76.04	33.29	**70.42**
		3	0.06	13.47	11.34	11.18	34.87	**17.71**	96.22	78.81	76.79	35.79	**71.90**
		4	0.09	13.50	11.19	10.90	34.20	**17.45**	95.03	79.17	77.11	36.76	**72.02**
		5	0.12	13.56	11.19	10.79	33.86	**17.35**	93.72	78.69	76.70	36.83	**71.49**
		6	0.14	13.59	11.23	10.79	33.78	**17.35**	92.32	78.51	76.96	36.50	**71.07**
		7	0.17	13.63	11.27	10.78	33.78	**17.37**	91.73	78.13	77.14	36.48	**70.87**
		8	0.18	13.65	11.29	10.83	33.86	**17.41**	91.37	77.74	76.85	36.55	**70.63**
		9	0.18	13.66	11.31	10.85	33.92	**17.43**	90.77	77.95	76.88	36.26	**70.46**
		10	0.18	13.65	11.33	10.87	33.99	**17.46**	91.22	77.80	76.85	35.98	**70.46**
5,000 Schedules (10F/10B Particles) (GR=0.0)	Best Inertia (w)	1	0.12	13.56	11.91	11.74	36.23	**18.36**	93.54	75.83	75.00	32.17	**69.14**
		2	0.05	13.45	11.62	11.46	35.57	**18.04**	96.88	78.13	76.46	33.67	**70.89**
		3	0.07	13.47	11.29	11.02	34.61	**17.61**	96.04	79.58	77.29	36.33	**71.97**
		4	0.07	13.48	11.20	10.87	34.02	**17.42**	95.42	78.96	77.50	37.50	**71.93**
		5	0.09	13.52	11.20	10.80	33.87	**17.35**	95.00	79.58	77.08	37.33	**72.07**
		6	0.14	13.58	11.23	10.78	33.80	**17.36**	92.71	78.75	77.29	37.00	**71.28**
		7	0.17	13.64	11.27	10.78	33.80	**17.37**	91.88	79.17	77.29	36.83	**70.82**
		8	0.18	13.65	11.31	10.84	33.88	**17.43**	91.46	78.54	77.08	36.50	**70.50**
		9	0.18	13.65	11.32	10.84	33.93	**17.44**	91.25	78.54	77.29	36.50	**70.53**
		10	0.18	13.66	11.34	10.87	34.04	**17.48**	91.25	78.54	76.88	36.33	**70.49**
	Aver. for all Inertia (w)	1	0.28	13.80	12.18	11.97	36.73	**18.67**	88.81	74.23	73.99	30.81	**66.96**
		2	0.08	13.50	11.70	11.55	35.78	**18.13**	95.12	76.85	75.89	33.24	**70.27**
		3	0.07	13.49	11.35	11.17	34.90	**17.73**	95.74	78.90	76.85	35.57	**71.76**
		4	0.09	13.51	11.26	10.93	34.22	**17.48**	94.82	78.36	77.05	36.43	**71.67**
		5	0.13	13.57	11.26	10.82	33.94	**17.40**	93.33	78.15	76.76	36.43	**71.17**
		6	0.17	13.63	11.28	10.82	33.86	**17.40**	91.37	78.15	76.99	36.45	**70.74**
		7	0.18	13.65	11.31	10.82	33.87	**17.41**	91.07	78.04	76.93	36.26	**70.58**
		8	0.20	13.68	11.35	10.87	33.93	**17.46**	90.48	77.68	76.73	36.10	**70.24**
		9	0.21	13.70	11.36	10.88	34.02	**17.49**	89.88	77.50	76.88	35.86	**70.03**
		10	0.21	13.70	11.38	10.90	34.08	**17.52**	90.09	77.74	76.31	35.74	**69.97**

Table 8.10b: Best & average test results for RCPSPs under different PSO topologies (5,000 schedules – 10F/10B particles)

N_Sch	w	DD Range	AD_O	AD_CP					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
50,000 Schedules (20F/20B Particles) (GR=0.75)	Best Inertia (w)	1	0.04	13.44	11.50	11.28	35.07	**17.83**	97.50	78.33	76.88	35.17	**71.66**
		2	0.01	13.39	11.16	10.99	34.40	**17.49**	98.96	82.29	77.92	37.50	**74.01**
		3	0.01	13.39	10.85	10.65	33.55	**17.12**	99.17	84.79	78.75	40.17	**75.35**
		4	0.02	13.40	10.84	10.35	32.78	**16.88**	98.54	83.54	78.75	41.33	**75.28**
		5	0.05	13.45	10.90	10.31	32.44	**16.80**	96.67	81.88	78.75	40.50	**74.16**
		6	0.05	13.46	10.92	10.31	32.37	**16.79**	96.88	81.67	78.54	39.83	**73.64**
		7	0.07	13.48	10.98	10.28	32.30	**16.78**	95.83	80.63	78.54	39.83	**73.33**
		8	0.08	13.49	10.98	10.31	32.30	**16.78**	96.04	80.83	78.13	39.67	**73.61**
		9	0.08	13.50	10.96	10.32	32.31	**16.79**	95.21	81.46	78.33	39.83	**73.55**
		10	0.07	13.48	10.92	10.32	32.39	**16.80**	95.63	81.46	78.33	39.50	**73.47**
	Aver. for all Inertia (w)	1	0.15	13.60	11.79	11.58	35.85	**18.20**	93.15	76.31	75.54	33.07	**69.52**
		2	0.02	13.41	11.24	11.14	34.76	**17.64**	98.27	81.10	77.32	36.33	**73.26**
		3	0.02	13.40	10.91	10.74	33.85	**17.23**	98.54	83.72	78.18	39.26	**74.93**
		4	0.04	13.43	10.90	10.41	32.99	**16.93**	97.35	82.47	78.42	40.26	**74.63**
		5	0.07	13.49	10.99	10.40	32.72	**16.90**	95.68	80.89	77.98	39.26	**73.45**
		6	0.07	13.49	10.98	10.33	32.41	**16.80**	95.45	80.39	78.13	39.19	**73.29**
		7	0.09	13.51	11.01	10.32	32.33	**16.79**	94.88	80.18	78.13	39.19	**73.09**
		8	0.10	13.52	11.01	10.33	32.35	**16.80**	94.73	80.18	77.92	39.17	**73.00**
		9	0.10	13.53	11.00	10.34	32.39	**16.81**	94.26	80.42	77.92	39.26	**72.96**
		10	0.10	13.53	10.98	10.34	32.45	**16.83**	94.29	80.65	77.77	38.95	**72.92**
50,000 Schedules (20F/20B Particles) (GR=0.5)	Best Inertia (w)	1	0.04	13.43	11.45	11.31	35.20	**17.87**	97.71	78.75	76.88	35.17	**72.02**
		2	0.01	13.39	11.17	11.01	34.46	**17.51**	99.17	81.88	77.71	37.33	**73.86**
		3	0.01	13.39	10.84	10.62	33.58	**17.13**	98.96	84.38	78.96	40.17	**75.25**
		4	0.01	13.39	10.80	10.35	32.78	**16.86**	98.96	85.00	78.75	40.50	**75.55**
		5	0.04	13.43	10.85	10.29	32.35	**16.76**	97.50	83.33	79.17	40.83	**75.11**
		6	0.05	13.46	10.89	10.28	32.31	**16.77**	96.67	82.92	78.96	40.00	**74.48**
		7	0.06	13.47	10.93	10.28	32.33	**16.76**	96.67	82.29	78.54	40.67	**73.76**
		8	0.07	13.47	10.93	10.30	32.33	**16.77**	96.25	81.25	78.75	40.00	**73.57**
		9	0.10	13.52	10.95	10.30	32.40	**16.81**	94.58	80.83	78.54	40.00	**73.15**
		10	0.09	13.51	10.93	10.30	32.45	**16.81**	95.00	81.46	78.75	40.33	**73.23**
	Aver. for all Inertia (w)	1	0.17	13.63	11.78	11.60	35.87	**18.22**	92.23	76.49	75.57	32.88	**69.29**
		2	0.02	13.40	11.24	11.13	34.80	**17.64**	98.72	80.92	77.26	36.14	**73.26**
		3	0.02	13.40	10.92	10.73	33.90	**17.24**	98.63	83.36	78.45	39.36	**74.95**
		4	0.03	13.41	10.84	10.42	33.03	**16.93**	98.24	83.33	78.39	40.10	**75.02**
		5	0.06	13.47	10.90	10.31	32.50	**16.79**	96.40	82.23	78.54	40.17	**74.33**
		6	0.08	13.49	10.94	10.31	32.39	**16.78**	95.51	81.40	78.60	39.62	**73.78**
		7	0.08	13.50	10.95	10.30	32.37	**16.78**	95.36	80.98	77.95	39.64	**73.48**
		8	0.09	13.51	10.96	10.32	32.40	**16.80**	94.94	80.65	78.04	39.43	**73.26**
		9	0.11	13.53	10.98	10.33	32.45	**16.82**	94.20	80.36	77.83	39.52	**72.98**
		10	0.10	13.53	10.96	10.33	32.50	**16.83**	94.23	80.77	77.98	39.45	**73.11**
50,000 Schedules (20F/20B Particles) (GR=0.25)	Best Inertia (w)	1	0.04	13.43	11.49	11.36	35.32	**17.91**	97.29	78.54	76.88	34.00	**71.47**
		2	0.01	13.39	11.18	11.07	34.61	**17.57**	99.17	81.67	77.71	37.50	**73.78**
		3	0.01	13.39	10.88	10.63	33.63	**17.15**	98.96	84.79	78.33	40.17	**75.56**
		4	0.01	13.39	10.77	10.37	32.79	**16.87**	98.96	85.83	79.58	41.17	**75.80**
		5	0.03	13.41	10.80	10.26	32.45	**16.76**	98.13	83.75	78.96	40.83	**75.21**
		6	0.04	13.43	10.82	10.27	32.36	**16.75**	97.71	84.79	78.96	40.50	**75.09**
		7	0.06	13.46	10.86	10.26	32.37	**16.74**	96.46	82.71	79.17	40.67	**74.55**
		8	0.04	13.44	10.90	10.30	32.39	**16.76**	97.29	82.92	78.13	40.33	**74.42**

		9	0.06	13.46	10.91	10.31	32.45	**16.79**	96.46	82.08	78.54	40.50	**74.08**
		10	0.06	13.47	10.91	10.31	32.48	**16.81**	96.04	82.29	78.75	40.83	**74.33**
	Aver. for all Inertia (w)	1	0.15	13.60	11.77	11.60	35.89	**18.21**	93.07	76.55	75.54	32.60	**69.44**
		2	0.02	13.41	11.25	11.16	34.83	**17.66**	98.36	80.77	77.23	36.12	**73.12**
		3	0.02	13.40	10.91	10.74	33.91	**17.24**	98.75	84.26	78.24	39.36	**75.15**
		4	0.03	13.42	10.83	10.40	33.02	**16.92**	98.01	83.63	78.93	40.74	**75.33**
		5	0.05	13.44	10.84	10.31	32.52	**16.78**	97.08	82.92	78.39	40.40	**74.70**
		6	0.05	13.46	10.87	10.30	32.46	**16.77**	96.70	82.38	78.66	39.86	**74.40**
		7	0.06	13.47	10.90	10.30	32.43	**16.77**	96.16	81.76	78.33	40.19	**74.11**
		8	0.06	13.47	10.92	10.33	32.43	**16.79**	96.04	81.73	77.95	39.83	**73.89**
		9	0.08	13.49	10.93	10.34	32.49	**16.81**	95.36	81.52	78.15	39.86	**73.72**
		10	0.07	13.49	10.94	10.34	32.54	**16.83**	95.42	81.25	78.24	39.67	**73.64**
50,000 Schedules (20F/20B Particles) (GR=0.0)	Best Inertia (w)	1	0.03	13.42	11.51	11.40	35.39	**17.93**	97.92	78.75	76.88	34.00	**71.74**
		2	0.02	13.40	11.18	11.09	34.70	**17.59**	98.75	81.67	77.50	37.67	**73.79**
		3	0.01	13.39	10.92	10.66	33.69	**17.18**	99.17	83.75	78.54	39.67	**75.02**
		4	0.01	13.39	10.84	10.45	32.94	**16.94**	99.17	83.75	78.54	40.17	**75.16**
		5	0.03	13.41	10.90	10.36	32.60	**16.85**	98.33	83.96	78.54	40.17	**74.83**
		6	0.05	13.46	10.93	10.38	32.52	**16.85**	97.08	82.71	78.33	39.83	**74.13**
		7	0.07	13.49	10.97	10.37	32.54	**16.86**	95.21	82.29	78.33	39.50	**73.51**
		8	0.10	13.53	10.99	10.37	32.52	**16.86**	94.58	81.25	77.92	39.67	**73.25**
		9	0.10	13.53	10.97	10.37	32.57	**16.88**	94.38	81.04	78.13	39.50	**72.95**
		10	0.12	13.56	11.03	10.37	32.58	**16.90**	93.75	81.04	78.33	39.33	**72.59**
	Aver. for all Inertia (w)	1	0.16	13.62	11.82	11.64	35.95	**18.26**	92.50	76.34	75.42	32.45	**69.18**
		2	0.02	13.41	11.25	11.16	34.86	**17.67**	98.24	80.77	77.11	36.40	**73.13**
		3	0.02	13.39	10.95	10.76	33.94	**17.26**	98.90	83.33	78.21	39.05	**74.87**
		4	0.03	13.42	10.91	10.48	33.10	**16.98**	98.07	82.62	78.33	39.64	**74.67**
		5	0.05	13.45	10.94	10.39	32.71	**16.87**	96.76	82.41	78.13	39.57	**74.22**
		6	0.08	13.50	10.97	10.40	32.59	**16.86**	95.21	81.31	77.92	39.14	**73.39**
		7	0.10	13.53	10.99	10.40	32.56	**16.87**	94.23	81.28	77.83	38.83	**73.04**
		8	0.12	13.56	11.01	10.40	32.58	**16.89**	93.48	80.57	77.71	38.79	**72.64**
		9	0.12	13.56	11.02	10.40	32.61	**16.90**	93.60	80.36	77.77	38.79	**72.63**
		10	0.13	13.58	11.04	10.41	32.64	**16.92**	92.77	80.15	77.65	38.69	**72.31**

Table 8.10c: Best & average test results for RCPSPs under different PSO topologies
(50,000 schedules – 20F/20B particles)

No. of Schedules	PSO Topology	j-30				j-60				j-120			
		GR	w	DD Range	AD_O	GR	w	DD Range	AD_{CP}	GR	w	DD Range	AD_{CP}
1,000	gBest	1.0	0.5	4	0.18	*1.0*	*0.0*	*3*	*11.63*	*1.0*	*0.0*	*4*	*34.85*
	GR<1.0	*0.25*	*0.3*	*3*	*0.16*	0.75	0.0	6	11.67	0.75	0.0	4	34.94
5,000	gBest	1.0	0.1	2	0.06	1.0	0.6	4	11.19	*1.0*	*0.6*	*7*	*33.56*
	GR<1.0	*0.5*	*0.4*	*3*	*0.05*	*0.75*	*0.5*	*4*	*11.11*	0.75	0.5	6	33.58
50,000	gBest	*1.0*	*0.0*	*2*	*0.01*	1.0	0.6	4	10.84	1.0	0.2	9	32.31
	GR<1.0	*0.8*	*0.1*	*3*	*0.01*	*0.3*	*0.6*	*4*	*10.77*	*0.8*	*0.4*	*7*	*32.30*

Table 8.10d: Summary of test results for RCPSPs under different PSO topologies

Table 8.10d shows that implementing the neighbouring topology was generally achieving better results than the *gBest* topology; except for small number of generated schedules, where global best conceptually should perform better due to the small number of iterations involved.

N_Sch	Topology	Density Range	Average Cost Saving (ACS)				Problems Solved to Optimality			
			j-10	j-20	j-30	Aver.	j-10	j-20	j-30	Aver.
1,000 Schedules (10F/10B Particles)	Best DD Range	GR=1.0	37.21	47.33	52.50	**45.64**	90.74	62.22	52.22	**67.53**
		GR=0.75	37.22	47.22	52.51	**45.63**	89.63	60.00	52.22	**66.91**
		GR=0.50	37.22	47.36	52.48	**45.66**	90.00	62.22	51.85	**68.02**
		GR=0.25	37.23	47.27	52.46	**45.65**	90.00	60.74	51.85	**67.04**
		GR=0.0	37.16	47.29	52.47	**45.62**	90.00	60.74	51.48	**67.16**
	Best Topology	SPSO	37.19	47.31	52.46	**45.64**	90.00	61.48	52.22	**67.53**
		R01	37.22	47.24	52.46	**45.61**	89.63	61.85	52.22	**66.91**
		R02	37.23	47.33	52.48	**45.66**	90.00	62.22	51.85	**68.02**
		R03	37.21	47.36	52.51	**45.66**	90.00	62.22	51.85	**67.65**
		R04	37.19	47.26	52.50	**45.63**	90.74	60.74	51.85	**67.16**
		R05	37.20	47.30	52.50	**45.61**	90.00	60.00	51.85	**66.54**
5,000 Schedules (10F/10B Particles)	Best DD Range	GR=1.0	37.23	47.38	52.56	**45.70**	90.00	61.85	53.70	**68.40**
		GR=0.75	37.26	47.37	52.46	**45.66**	90.37	61.11	52.96	**67.78**
		GR=0.50	37.25	47.40	52.54	**45.70**	91.48	61.85	53.33	**68.77**
		GR=0.25	37.26	47.32	52.55	**45.70**	90.37	61.85	52.59	**67.78**
		GR=0.0	37.18	47.36	52.49	**45.65**	89.63	60.74	52.22	**66.91**
	Best Topology	SPSO	37.26	47.38	52.55	**45.70**	91.48	61.85	53.33	**68.77**
		R01	37.26	47.40	52.56	**45.70**	90.37	61.85	53.70	**68.40**
		R02	37.21	47.29	52.55	**45.66**	89.63	61.11	52.22	**66.91**
		R03	37.19	47.33	52.44	**45.66**	90.37	60.74	52.96	**67.78**
		R04	37.26	47.36	52.46	**45.66**	90.00	60.74	51.85	**67.04**
		R05	37.17	47.37	52.45	**45.64**	90.00	61.11	52.22	**67.28**
50,000 Schedules (20F/20B Particles)	Best DD Range	GR=1.0	37.26	47.43	52.56	**45.71**	91.11	62.22	54.44	**69.01**
		GR=0.75	37.25	47.28	52.49	**45.65**	91.85	62.59	51.48	**68.52**
		GR=0.50	37.30	47.31	52.48	**45.66**	91.85	63.33	52.22	**68.52**
		GR=0.25	37.28	47.43	52.50	**45.71**	91.48	65.19	52.59	**68.77**
		GR=0.0	37.27	47.35	52.48	**45.69**	91.85	63.33	52.96	**68.64**
	Best Topology	SPSO	37.27	47.35	52.56	**45.71**	91.85	63.33	54.44	**69.01**
		R01	37.25	47.31	52.49	**45.67**	91.85	62.59	52.96	**68.52**
		R02	37.24	47.43	52.47	**45.71**	91.11	65.19	51.48	**68.77**
		R03	37.26	47.33	52.50	**45.71**	91.11	62.96	51.85	**68.15**
		R04	37.30	47.34	52.52	**45.69**	91.85	62.22	52.22	**68.64**
		R05	37.28	47.34	52.49	**45.68**	91.48	63.33	51.48	**68.40**

Table 8.11: Summary of test results for TCPSPs under different PSO topologies

While for TCPSP, the results show the same scattered best results as shown earlier in test results with *gBest* topology (table 8.9); finally, using neighboring topology with *DDPSO* showed slight improvement for small number of schedules generated, but in general it was either the same or lower than original results.

8.3. DDPSO algorithm rating

Since *Justification PSO* (or *JPSO*) presented by *Chen (2011)* is currently the best performing *PSO* algorithm for single mode RCPSP in literature, then for the sake of rating the *DDPSO* (developed under this research) on the *PSO* level, a comparison was performed between the best results of both proposed algorithms *JPSO & MJPSO*, and results were tabulated as follows:

PSO Topology	Priority Rule	Algorithm	1,000 Schedules			5,000 Schedules			50,000 Schedules		
			AD_O	AD_{CP}		AD_O	AD_{CP}		AD_O	AD_{CP}	
			j-30	j-60	j-120	j-30	j-60	j-120	j-30	j-60	j-120
gBest	LFT	JPSO	0.29	12.03	35.71	0.14	11.43	33.88	0.07	11.41	33.72
		MJPSO	0.32	11.97	35.80	0.05	11.31	*33.82*	*0.02*	*10.85*	*32.43*
	CPR	MJPSO	*0.25*	*11.88*	*35.65*	*0.08*	*11.19*	33.84	*0.02*	10.89	32.44
Neighboring (incl. lBest)	LFT	JPSO	0.29	12.03	35.71	0.14	11.43	33.88	0.04	11.00	32.89
		MJPSO	0.31	11.96	35.80	0.06	*11.19*	33.86	*0.02*	*10.78*	*32.40*
	CPR	MJPSO	*0.22*	*11.86*	*35.69*	*0.05*	11.21	*33.78*	*0.02*	10.83	32.43

Table 8.12: Performance comparison between *JPSO & MJPSO* algorithms

This comparison was performed on the *gBest & neighboring PSO* topologies, and on the same priority rule, while adding the *CPR* for *MJPSO* for best results listing. Results show clearly that the implementation of *SDJ & CPR* lead to a significant improvement than *JPSO*.

Table 8.13 shows a summarized comparison between the algorithms developed under this research, the *MJPSO* and *DDPSO*, with and without neighboring topology implementation. Results show that *DDPSO* outperformed *MJPSO* in almost all cases, which concludes the successful and steady improvement caused by the *DDPSO* algorithm to solutions quality for RCPSPs. These improvements will ensure obtaining high quality solutions when the proposed dynamic solution is tested with real projects data under Chapter 10.

PSO Topology	Algorithm	Schedules 1,000			Schedules 5,000			Schedules 50,000		
		AD_O	AD_{CP}		AD_O	AD_{CP}		AD_O	AD_{CP}	
		j-30	j-60	j-120	j-30	j-60	j-120	j-30	j-60	j-120
gBest	MJPSO	0.25	11.88	35.65	0.08	11.19	33.84	0.02	10.89	32.44
	DDPSO	0.18	*11.63*	*34.85*	0.06	11.19	33.56	*0.01*	10.84	32.31
Neighboring (incl. lBest)	MJPSO	0.22	11.86	35.69	*0.05*	11.21	33.78	0.02	10.83	32.43
	DDPSO	*0.16*	11.67	34.94	*0.05*	*11.11*	33.58	*0.01*	*10.77*	*32.30*

Table 8.13: Performance comparison between *MJPSO & DDPSO* algorithms

Kolisch & Hartmann (2006) have performed a detailed survey on the best performing algorithms for solving RCPSPs. The results of this survey were amended with both experimental results of the *MJPSO* and *DDPSO*

proposed in this research, as well as the *JPSO* (*Chen, 20*11) for being the best performing *PSO* algorithm in literature for SRCPSPs. Results of *Tchomté & Gourgand (2009)* were not considered in this comparison as best *PSO* results because the value which was presented in their paper for critical path average deviation AD_{CP} for j-60 problem (9.01) is actually lower than that of the j-60's lower bounds (9.42), which is not feasible if their calculation method for the AD_{CP} is similar to the common method used in literature (equation 8.3).

The performance comparison presented in tables 8.14 to 8.16 corresponding to SRCPSP j-30, j-60 & j-120, shows that both *MJPSO* and *DDPSO* are highly ranked between state-of-the-art algorithms for solving single mode RCPSPs; and *DDPSO* also outperformed other *PSO* algorithms.

Both algorithms, *MJPSO & DDPSO*, outperformed all other PSO algorithms in literature, and showed very high performance with other optimization techniques under all problem sizes and stopping conditions.

Algorithm	SGS	Reference	Max. # of schedules		
			1,000	5,000	50,000
GA, TS—path relinking	Both	Kochetov & Stolyar (2003)	0.10	0.04	0.00
PSO—DD, MJ, RSGS	*Serial*	*This research*	*0.16*	*0.05*	*0.01*
Scatter Search—FBI	Serial	Debels et al (2006)	0.27	0.11	0.01
PSO—SDJ, FBI (MJPSO)	*Both*	*This research*	*0.22*	*0.05*	*0.02*
GA—hybrid, FBI	Serial	Valls et al (2008)	0.27	0.06	0.02
GA—FBI	Serial	Valls et al (2005)	0.34	0.20	0.02
GA—forw.–backw., FBI	Both	Alcaraz et al (2004)	0.25	0.06	0.03
GA—forw.–backw.	Serial	Alcaraz & Maroto (2001)	0.33	0.12	–
PSO—DJ, FBI (JPSO)	Serial	Chen (2011)	0.29	0.14	0.04
Sampling—LFT, FBI	Both	Tormos & Lova (2003b)	0.25	0.13	0.05
TS—activity list	Serial	Nonobe & Ibaraki (2002)	0.46	0.16	0.05
Sampling—LFT, FBI	Both	Tormos & Lova (2001)	0.30	0.16	0.07
GA—self-adapting	Both	Hartmann (2002)	0.38	0.22	0.08
GA—activity list	Serial	Hartmann (1998)	0.54	0.25	0.08
Sampling—LFT, FBI	Both	Tormos & Lova (2003a)	0.30	0.17	0.09
TS—activity list	Serial	Klein (2000)	0.42	0.17	–
Sampling—random, FBI	Serial	Valls et al (2005)	0.46	0.28	0.11
SA—activity list	Serial	Bouleimen & Lecocq (2003)	0.38	0.23	–
GA—late join	Serial	Coelho & Tavares (2003)	0.74	0.33	0.16
Sampling—adaptive	Both	Schirmer (2000)	0.65	0.44	–
TS—schedule scheme	Related	Baar et al (1998)	0.86	0.44	–
Sampling—adaptive	Both	Kolisch & Drexl (1996)	0.74	0.52	–
GA—random key	Serial	Hartmann (1998)	1.03	0.56	0.23
Sampling—LFT	Serial	Kolisch (1996)	0.83	0.53	0.27
Sampling—global	Serial	Coelho & Tavares (2003)	0.81	0.54	0.28
Sampling—random	Serial	Kolisch (1995)	1.44	1.00	0.51
GA—priority rule	Serial	Hartmann (1998)	1.38	1.12	0.88
Sampling—WCS	Parallel	Kolisch (1996a, 1996b)	1.40	1.28	–
Sampling—LFT	Parallel	Kolisch (1996)	1.40	1.29	1.13
Sampling—random	Parallel	Kolisch (1995)	1.77	1.48	1.22
GA—problem space	Mod. par.	Leon & Ramamoorthy (1995)	2.08	1.59	–

Table 8.14: *Algorithms comparison for AD_O of ProGen SRCPSP j-30*

Algorithm	SGS	Reference	Max. # of schedules		
			1,000	5,000	50,000
Scatter search—FBI	Serial	Debels et al (2006)	11.73	11.10	10.71
GA—hybrid, FBI	Serial	Valls et al (2008)	11.56	11.10	10.73
GA, TS—path relinking	Both	Kochetov & Stolyar (2003)	11.71	11.17	10.74
GA—FBI	Serial	Valls et al (2005)	12.21	11.27	10.74
PSO—DD, MJ, RSGS	*Serial*	*This research*	*11.63*	*11.11*	*10.77*
GA—forw.–backw., FBI	Both	Alcaraz et al (2004)	11.89	11.19	10.84
PSO—SDJ, FBI (MJPSO)	*Both*	*This research*	*11.86*	*11.19*	*10.85*
PSO—DJ, FBI (JPSO)	Serial	Chen (2011)	12.03	11.43	11.00
GA—self-adapting	Both	Hartmann (2002)	12.21	11.70	11.21
GA—activity list	Serial	Hartmann (1998)	12.68	11.89	11.23
Sampling—LFT, FBI	Both	Tormos & Lova (2003b)	11.88	11.62	11.36
Sampling—LFT, FBI	Both	Tormos & Lova (2003a)	12.14	11.82	11.47
GA—forw.–backw.	Serial	Alcaraz & Maroto (2001)	12.57	11.86	–
Sampling—LFT, FBI	Both	Tormos & Lova (2001)	12.18	11.87	11.54
SA—activity list	Serial	Bouleimen & Lecocq (2003)	12.75	11.90	–
TS—activity list	Serial	Klein (2000)	12.77	12.03	–
TS—activity list	Serial	Nonobe & Ibaraki (2002)	12.97	12.18	11.58
Sampling—random, FBI	Serial	Valls et al (2005)	12.73	12.35	11.94
Sampling—adaptive	Both	Schirmer (2000)	12.94	12.58	–
GA—late join	Serial	Coelho & Tavares (2003)	13.28	12.63	11.94
GA—random key	Serial	Hartmann (1998)	14.68	13.32	12.25
GA—priority rule	Serial	Hartmann (1998)	13.30	12.74	12.26
Sampling—adaptive	Both	Kolisch & Drexl (1996)	13.51	13.06	–
Sampling—WCS	Parallel	Kolisch (1996a, 1996b)	13.66	13.21	–
Sampling—global	Serial	Coelho & Tavares (2003)	13.80	13.31	12.83
Sampling—LFT	Parallel	Kolisch (1996)	13.59	13.23	12.85
TS—schedule scheme	Related	Baar et al (1998)	13.80	13.48	–
GA—problem space	Mod. par.	Leon & Ramamoorthy (1995)	14.33	13.49	–
Sampling—LFT	Serial	Kolisch (1996)	13.96	13.53	12.97
Sampling—random	Parallel	Kolisch (1995)	14.89	14.30	13.66
Sampling—random	Serial	Kolisch (1995)	15.94	15.17	14.22

Table 8.15: *Algorithms comparison for AD_{CP} of ProGen SRCPSP j-60*

Algorithm	SGS	Reference	Max. # of schedules		
			1,000	5,000	50,000
GA—hybrid, FBI	Serial	Valls et al (2008)	34.07	32.54	31.24
GA—forw.–backw., FBI	Both	Alcaraz et al (2004)	36.53	33.91	31.49
Scatter Search—FBI	Serial	Debels et al (2006)	35.22	33.10	31.57
GA—FBI	Serial	Valls et al (2005)	35.39	33.24	31.58
GA, TS—path relinking	Both	Kochetov & Stolyar (2003)	34.74	33.36	32.06
PSO—DD, MJ, RSGS	*Serial*	*This research*	*34.85*	*33.56*	*32.30*
PSO—SDJ, FBI (MJPSO)	*Both*	*This research*	*35.60*	*33.78*	*32.40*
Population-based—FBI	Serial	Valls et al (2005)	35.18	34.02	32.81
PSO—DJ, FBI (JPSO)	Serial	Chen (2011)	35.71	33.88	32.89
GA—self-adapting	Both	Hartmann (2002)	37.19	35.39	33.21
Sampling—LFT, FBI	Both	Tormos & Lova (2003b)	35.01	34.41	33.71
Ant system	Serial	Merkle et al (2002)	–	35.43	–
GA—activity list	Serial	Hartmann (1998)	39.37	36.74	34.03
Sampling—LFT, FBI	Both	Tormos & Lova (2003a)	36.24	35.56	34.77
Sampling—LFT, FBI	Both	Tormos & Lova (2001)	36.49	35.81	35.01
GA—forw.–backw.	Serial	Alcaraz & Maroto (2001)	39.36	36.57	–
TS—activity list	Serial	Nonobe & Ibaraki (2002)	40.86	37.88	35.85
GA—late join	Serial	Coelho & Tavares (2003)	39.97	38.41	36.44
Sampling—random, FBI	Serial	Valls et al (2005)	38.21	37.47	36.46

SA—activity list	Serial	Bouleimen & Lecocq (2003)	42.81	37.68	–
GA—priority rule	Serial	Hartmann (1998)	39.93	38.49	36.51
Sampling—adaptive	Both	Schirmer (2000)	39.85	38.70	–
Sampling—LFT	Parallel	Kolisch (1996)	39.60	38.75	37.74
Sampling—WCS	Parallel	Kolisch (1996a, 1996b)	39.65	38.77	–
GA—random key	Serial	Hartmann (1998)	45.82	42.25	38.83
Sampling—adaptive	Both	Kolisch & Drexl (1996)	41.37	40.45	–
Sampling—global	Serial	Coelho & Tavares (2003)	41.36	40.46	39.41
GA—problem space	Mod. par.	Leon & Ramamoorthy (1995)	42.91	40.69	–
Sampling—LFT	Serial	Kolisch (1996)	42.84	41.84	40.63
Sampling—random	Parallel	Kolisch (1995)	44.46	43.05	41.44

Table 8.16: *Algorithms comparison for AD$_{CP}$ of ProGen SRCPSP j-120*

8.4. DDPSO static verification conclusions

This Chapter verified the performance of the developed model from a static operational research perspective; while dynamic aspects and construction related features of the model will be verified in Chapter 10.

Experimental results illustrated that the combination of *Stacking Justification (SJ)* with the original *Double Justification (DJ)* technique achieved a considerable improvement to solutions quality. Accordingly the combined *SDJ* technique will be implemented in all dynamic verification process (presented in next chapter).

Additionally, the use of the proposed CPR approach was proven to have significant improvement to results, especially for small number of generated schedules; while the improvement decreased (but still existed) with the amount of generated schedules. This behaviour is suitable for practical applications where achieving quick good-to-high quality solutions is necessary. CPR involves no additional computational burden, which makes its use also a free quality improvement approach. Similarly, *CPR* will be implemented in the dynamic verification.

And finally, the best values of density ranges were subjective to size & complexity of problems; so, several values between 0.5-4.0 (which achieved best results in this section) will be adopted during the dynamic verification process.

Chapter 9: The Dynamic Scheduling Software Tool (Dynamic Scheduler)

In chapter 4, the project management practitioners' opinions about the scheduling problems' extents and the proposed tool's functionality have been reviewed in the questionnaire survey; and the participants' responses & opinions were converted into a group of functional specifications & main features for the proposed solution. The proposed solution's general architecture was developed in chapter 5, in which the dynamic scheduling software tool was identified as the focal point between the end user of the proposed solution, the developed dynamic scheduling model, and the current project management practices.

This chapter will review the software tool development process, the software's functionality, and will present at the end a simple comparison for its optimization capabilities in comparison with current available project management software packages.

9.1. The Dynamic Scheduler Development

9.1.1. Functional specifications & software main features

The specs & features defined earlier in chapter 4 can be organized into three main categories:

a) *Architectural:*

- Fully integrated solution, where solutions are prepared and stored outside the main scheduling software, before users review and confirm the transfer.

- A user interface for manipulating optimization parameters, review of optimized solutions, and confirmation of changes before the transfer to main database.

b) *Main functionalities:*

- Optimization should be multi-objective, and results should include the best achieved solutions with minimum amount of schedule changes.

- Clear presentational capability for viewing the benefits of the proposed schedule changes in each of the optimized solutions (additional users requested features).

- Changes made must be summarized in a *"Changes Report"*, and stored for user reference and for the optimization algorithm's

reference in future optimization cycles (additional users requested features).

c) *Optional features:*

- Optimization can be done on project level and/or enterprise level (spec 6).

- Cost optimization can be done on cost level, cash flow level, or both (spec 7).

- Schedule indices (activities/resources flexibility & criticality) can be introduced as part of the optimization objectives (spec 8).

d) *Default features, alterable by users:*

- Optimization to work on critical/sub critical activities & scarce resources only (spec 3).

- Modes considered within optimization belong only to critical activities (spec 4).

- *Re-sequencing, resources leveling & lags manipulation* are all acceptable tactics for optimization (spec 5).

9.1.2. The Dynamic Scheduler Architecture

The general architecture of the dynamic scheduling model was initially defined in section 5.5.1, where the data to be communicated between the planning software, the dynamic scheduling software tool (or the *Dynamic Scheduler*), and their databases were preliminary identified. In addition, in chapter 6, the data required for the DS model's functionality were detailed. Accordingly, the *Dynamic Scheduler*'s general architecture was defined in figure 5.5.

The architecture of the *Dynamic Scheduler* was designed to ensure a fully integrated solution with the main planning & scheduling software package; where the software was developed with full interface capabilities with the database of *Primavera Project Management*®.

As mentioned earlier in chapter 4, this software tool will be a prototype for the proof of concept, so it does have to be integrated with all commonly used planning software packages. So, it was designed to be integral with the most commonly used package, which is *Primavera Project Management*® software (as defined in the functional specs).

This full integrity avoids the need for double entries of project data and progress updates, as well as there is no extra work to be done for the transfer of optimized solutions back to the planning software. The *Dynamic Scheduler* contains a user interface which allows the manipulation of optimization parameters, viewing optimized solutions, confirming changes, as well as

storing to and retrieving from the *Dynamic Scheduler Database (DSDB)* required optimization data and achieved optimization results.

As shown in figure 9.1, this full integrity was achieved by developing the *Dynamic Scheduler* with two main integration functionalities: to read project data and progress update data directly from the planning software database, and to write back selected optimized solutions to the planning software database. The structure and details of data stored in the *Dynamic Scheduler Database (DSDB)* will be explained in the next section

9.1.3. The Dynamic Scheduler Database (DSDB) structure

The *DSDB* contains four main data categories: *integration data*, *additional data*, *optimization inputs*, and *optimization results*. The *integration data* is basically the data required to identify the location of the main project and the several project schedule versions (revisions & progress update) within the planning software database. The *additional data* represent any project information which cannot be stored in the planning software, such as activity modes details, identification of soft logic, total availability resource constraints, indirect costs, contractual payment terms, invoice payment delay period …etc.

For *optimization inputs*, the *Dynamic Scheduler* user is required to define the optimization objectives and their weightages, the optimization settings (stopping condition and optimization algorithm parameters), a breakdown (if needed) for the activities and resources sets into optimizable and non-optimizable, and the soft logic originally existing in schedule.

Finally, the *optimization results* represent the output Pareto Front and the solution details for each of the optimized Pareto Front alternatives (i.e. selected activity modes and resource logic).

Figure 9.1 shows the *DSDB's* table structure and a simplified marking for the four data categories mentioned above.

9.2. Main software functionalities

The main function of the *Dynamic Scheduler* is to optimize construction schedules with full integration with general scheduling practices. Accordingly, the main functionalities of this software tool is: importing schedules, addition of extra project data, definition of optimization objectives & settings, optimization process, viewing optimized solutions, and exporting selected solutions back to source planning software.

This section starts with a brief description for the *Dynamic Scheduler's* user interface, and then each of the software's functionalities is reviewed explaining how it can be achieved through the developed user interface.
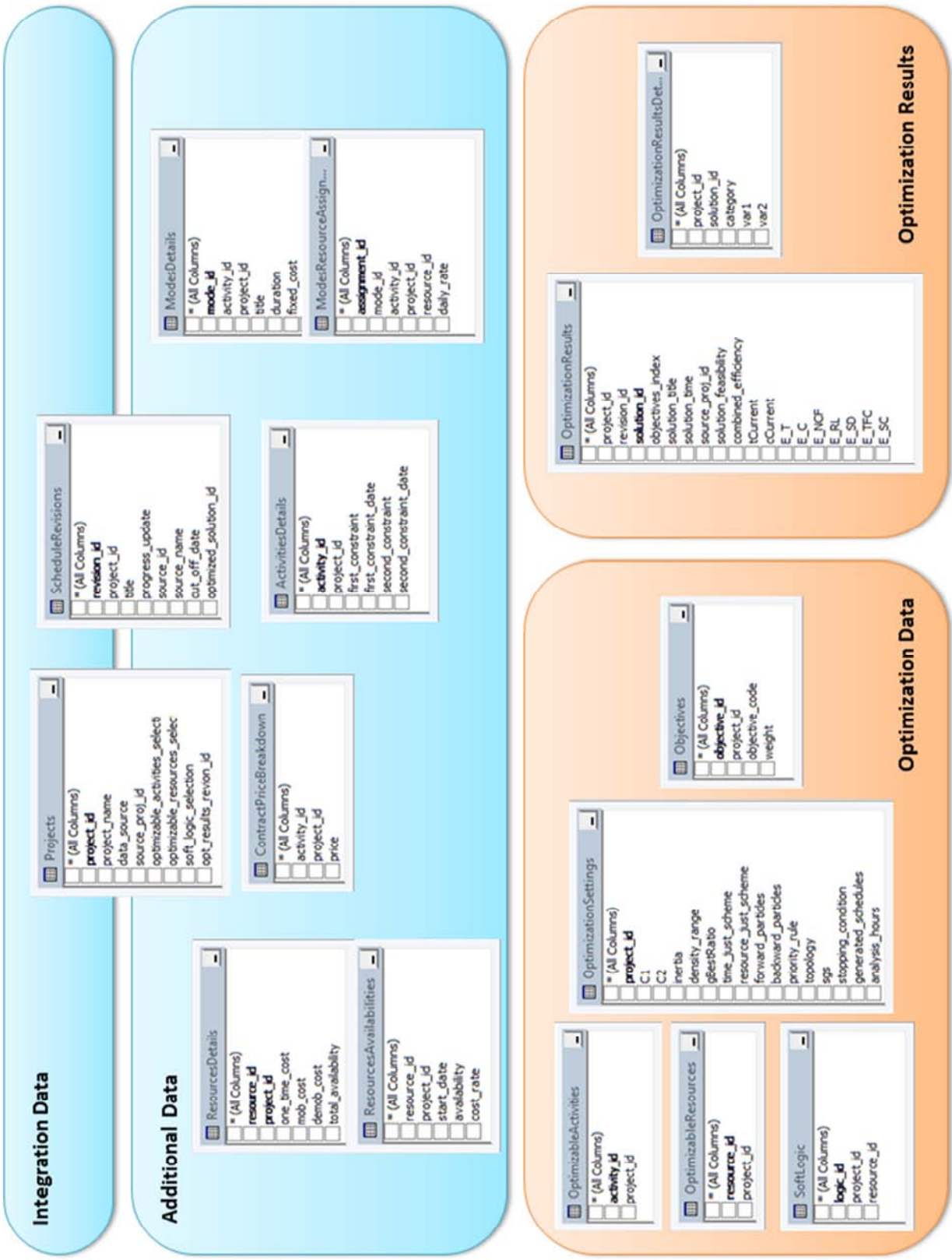
Figure 9.1: Dynamic Scheduler Database's (DSDB) table structure

9.2.1. The Dynamic Scheduler main user interface

The main user interface (as shown in figure 9.2) is simply a dashboard to view and alter the imported schedule data, to define optimization data and to view the optimization results.
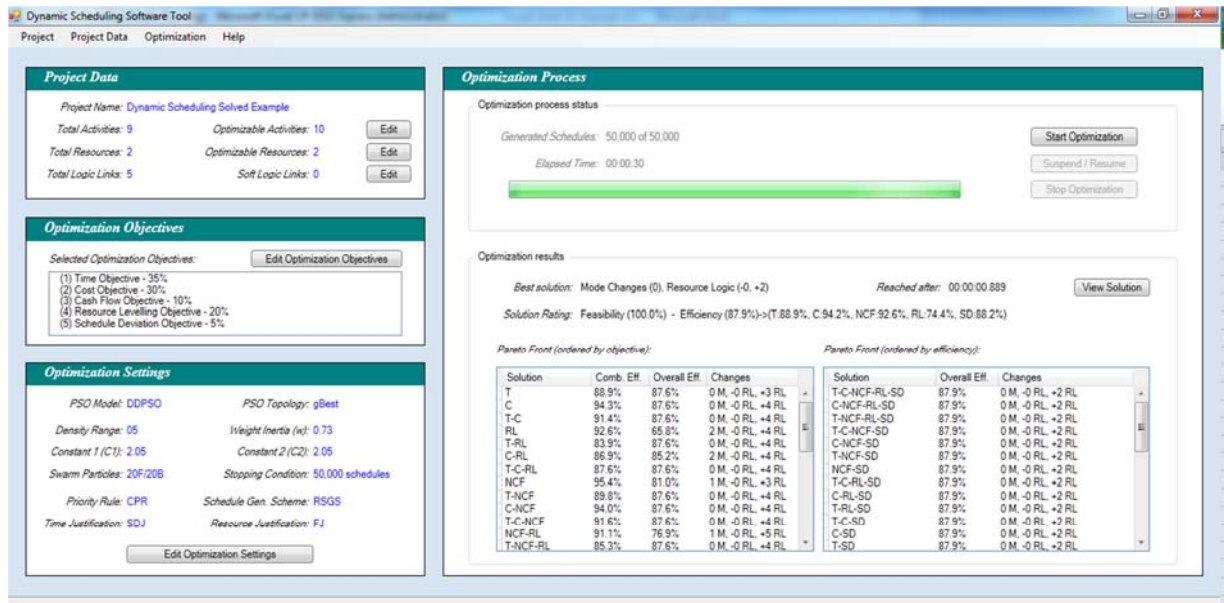
Figure 9.2: The Dynamic Scheduler's main user interface

The top left panel in the main user interface summarizes the imported schedule's data and enables (along with the *Project Data* menu as shown in figure 9.3a) the manipulation of the schedule's data and the additional data defined in the *Dynamic Scheduler*.

Similarly, the middle & bottom left panels in the main user interface summarize the defined optimization objectives & settings and also enables (along with the *Optimization* menu as shown in figure 9.3b) the manipulation of these optimization inputs data.

And finally, the right panel of the main interface shows the status of optimization during the optimization process, and details the optimization results during and after optimization completion.
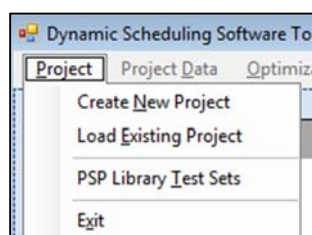
(a) Project menu
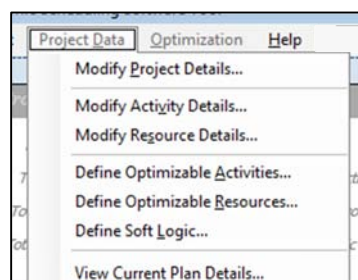
(b) Project Data menu
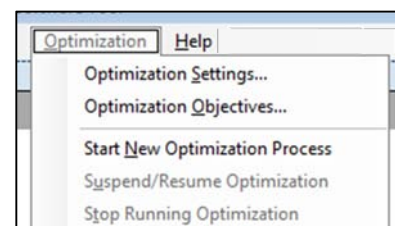
(c) Optimization menu

Figure 9.3: The Dynamic Scheduler's main menus

9.2.2. Importing construction schedules

Schedules are managed in the software within projects. Each *Dynamic Scheduler Project (DSP)* contains several version of the project schedule: baseline, updates, revisions, and optimized versions for the latest schedule. The dynamic scheduling process starts with creating a project and importing a baseline schedule to it. Through the *Project* menu (figure 9.3c), the user can create a new *DSP*, load an existing project, or start testing PSP problem sets (as detailed in section 9.2.6).

The *Data Source Form*, shown in figure 9.4, contains the corresponding options for creating and loading a *DSP* project, as well as working with PSP problem sets. For creating a new project, has to select the source database & project; then he has to define a title for the *DSP*. As mentioned above the *DSP* can contain more than one schedule revision and progress updates; so, the selected source project during *DSP* creation will be dealt as the "baseline" project, and the user can change this or add more versions as described later.
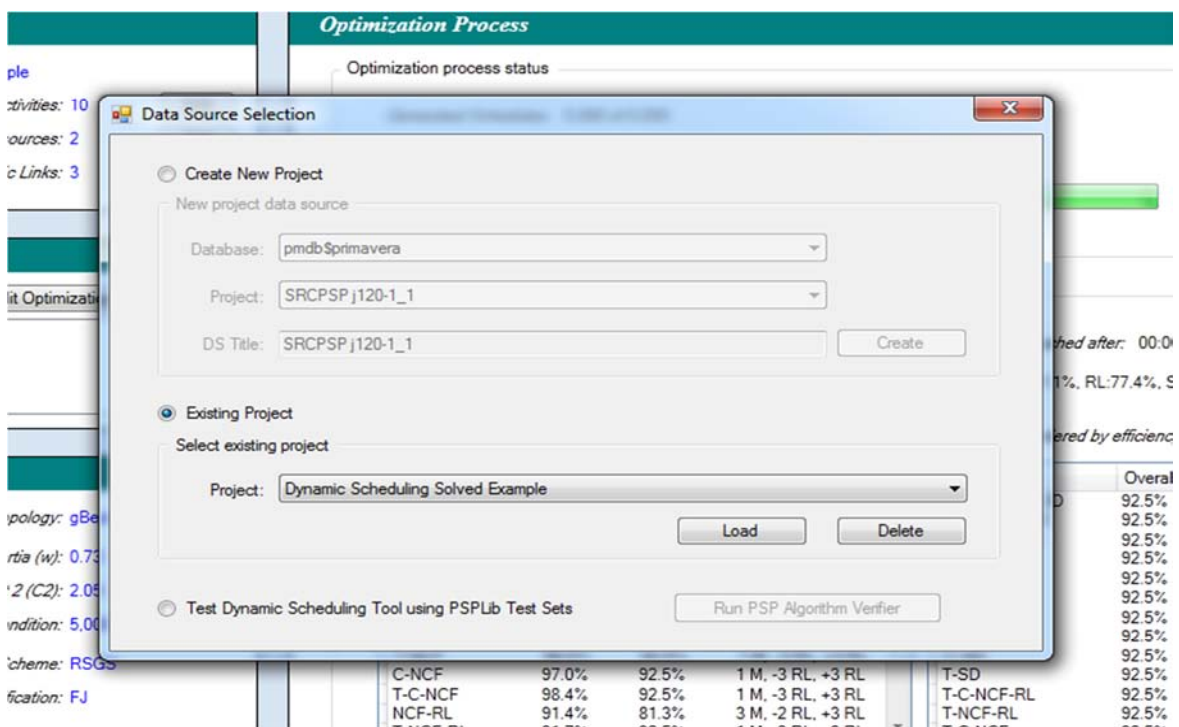
Figure 9.4: Dynamic Scheduler – Data Source Form

9.2.3. Definition of extra project data

There are few additional project data which cannot be defined in the planning software, *Primavera P6*, but are needed for the optimization project, such as: Project indirect cost, contractual price breakdown, payment terms, schedule revisions & update, activity modes, resources total constraints (not per period constraints), custom activities/resource costs …etc. This section reviews the user interface developed under *Dynamic Scheduler* to define/alter these data.

These data can be defined under three main forms within the software: *Project Details Form, Activities Details Form & Resources Details Form.*; all can be accessed from the *Project Data* menu.

The *Project Details Form* consists of four tabs as shown in figure 9.5. In the *General* tab, the *Periodical Indirect Cost (PIC), Contract Value Breakdown & Project Constraints* can be defined; while in the *Contractuals* tab, the user can add the contractual payments terms, the invoicing periods, the expected delay in payment, and the contract's price breakdown through the *Contract Breakdown Form* (as shown in figure 9.6). Through the last two tabs, *Schedule Revisions & Progress Updates*, the different schedule versions can be added, deleted or altered (as shown in figure 9.7).

(a) General tab

(b) Contractuals tab

(c) Schedule Revisions tab

(d) Progress Updates tab

Figure 9.5: Dynamic Scheduler – Project Details Form

Figure 9.6: Dynamic Scheduler – Contract Breakdown Form
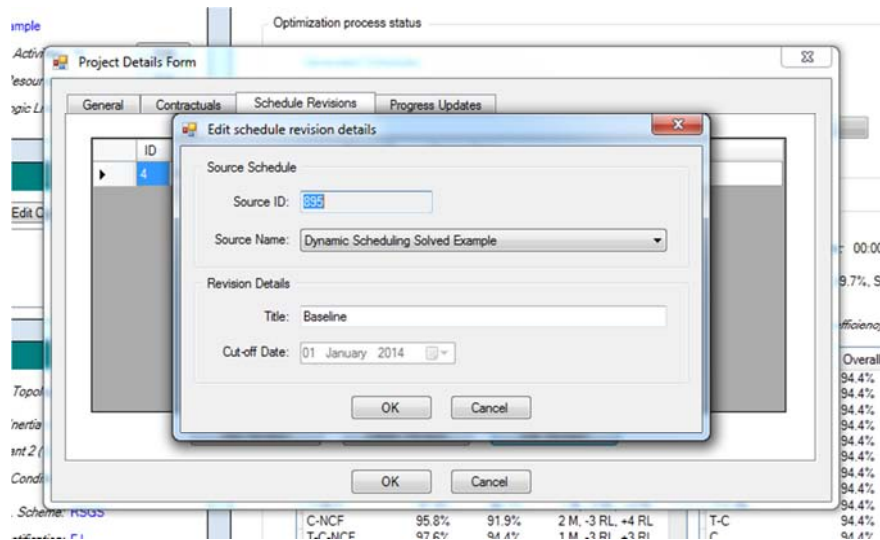
Figure 9.7: Dynamic Scheduler – Edit Schedule Revision/Update Form

The main purpose of the *Activity Details Form* is the definition of different activities' execution modes. As shown in figure 9.8, the form consists of two tabs, the *General* tab, where the activity can be selected either by ID or name, and the *Activity Modes* tab, where modes can be added, deleted and modified. The mode details include the mode's duration, fixed cost and resource details. In addition, the form enables and the ability to access and modify activities' time constraints.
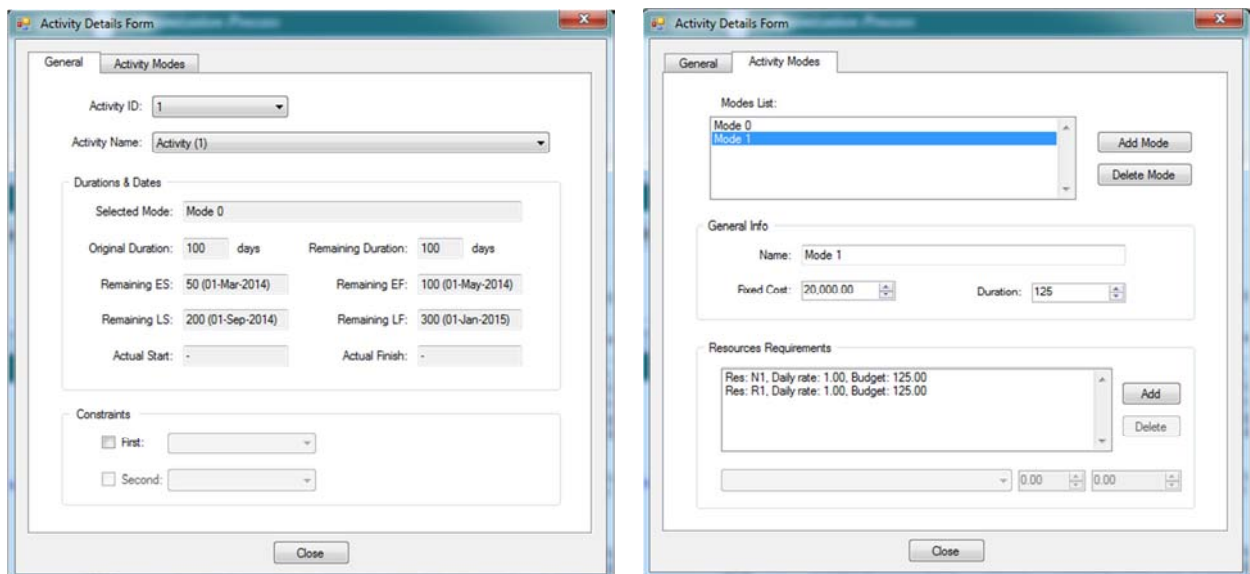
(a) General tab	(b) Activity Modes tab

Figure 9.8: Dynamic Scheduler – Activity Details Form

The last form in this section is the *Resource Details Form* which is used to define the resources cost details & availability constraints (figure 9.9). The resource can be selected either by ID or name, and the form is basically used to define/alter resource details imported from *P6* (resource daily costs and availabilities), and to define resource details which cannot be defined in P6

(one-time cost, mobilization/de-mobilization costs, and overall resource availability).

Figure 9.9: Dynamic Scheduler – Resource Details Form

9.2.4. *Definition of optimization inputs*

There are two groups of inputs required for starting the optimization process: project related and algorithm related. The project related optimization inputs represent breakdown of project main sets (activities, resources & logic) into optimizable (or will be modified within the optimization process) and non-optimizable (or will be ignored during optimization to minimize the computational burden). For schedule logic, this breakdown is titled as soft and hard logic; where soft logic can be removed by the optimization algorithm if this is needed for improving optimization results.

Figure 9.10: Dynamic Scheduler – Optimizable Activities Form

Figure 9.11: Dynamic Scheduler – Optimizable Resources Form

These three breakdowns can be performed through *Optimizable Activities Form* (figure 9.10), *Optimizable Resources Form* (figure 9.11), and *Soft Logic Form* (figure 9.12). These forms can be accessed from the main user interface or from the *Project Data* menu.
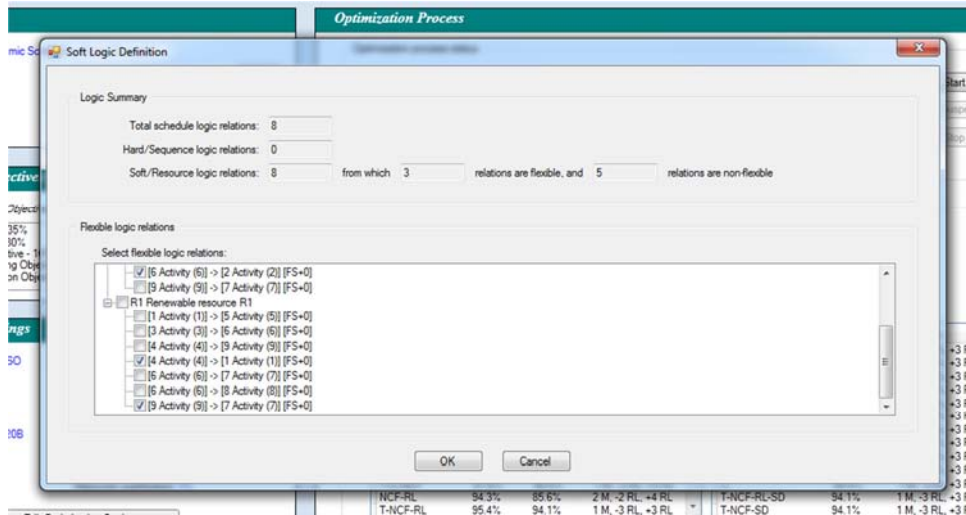
Figure 9.12: Dynamic Scheduler – Soft Logic Form

The second group of optimization inputs includes the optimization objectives & their weights, and the optimization settings. These data can be defined through the *Optimization Objectives Form* (figure 9.13), and the *Optimization Settings Form* (figure 9.14). These forms can also be accessed from the main user interface or from the *Project Data* menu. The optimization objectives are necessary to start the optimization process; and the objectives to be added and their weights are purely dependent on the project and/or organization requirements. While the optimization settings definition require some experience to properly identify the most suitable values; but the default values in the software will work fine in most cases. The defined optimization inputs are always displayed in the main user interface.
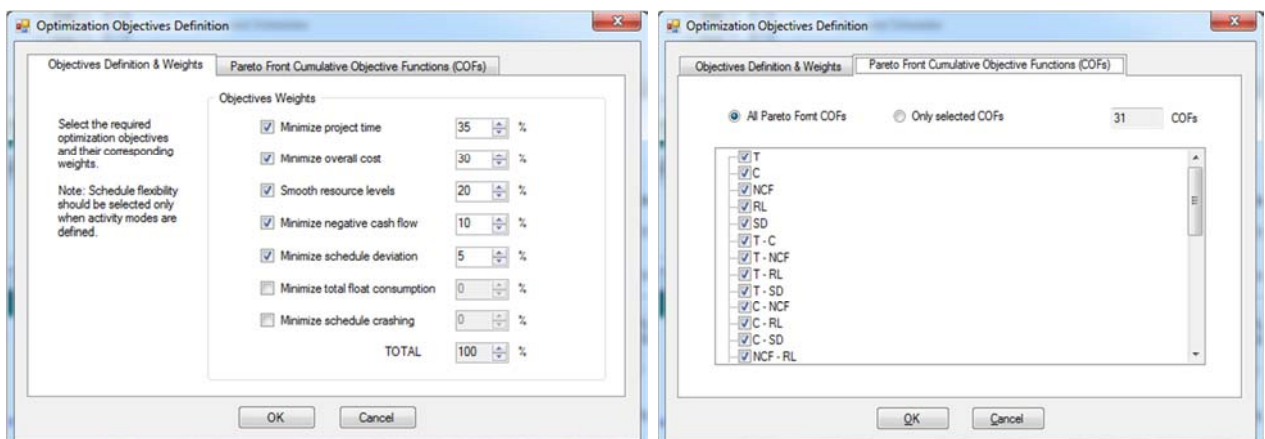
(a) Objectives Definition & Weights tab   (b) Pareto Front COFs tab

Figure 9.13: Dynamic Scheduler – Optimization Objectives Form
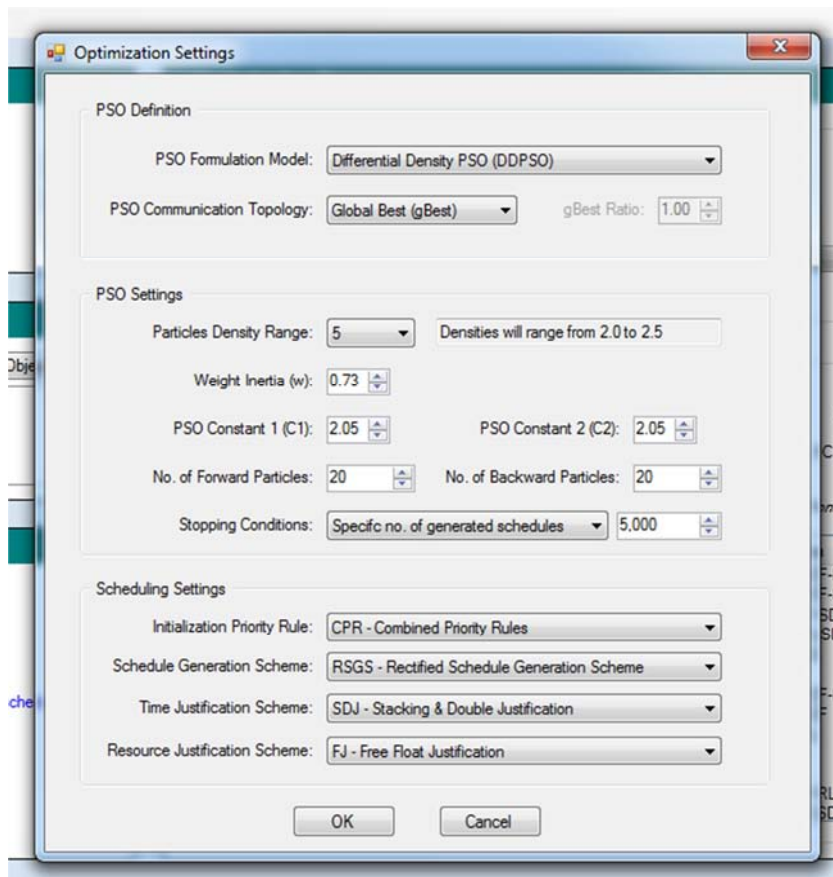
Figure 9.14: Dynamic Scheduler – Optimization Settings Form

9.2.5. *Viewing optimized solutions and exporting to source database*

There are to levels for viewing the optimization results in the *Dynamic Scheduler*, the first level is through the main user interface form (as shown in figure 9.15, where the rating and summary of the best achieved solution (or for simplicity, titled as the optimum solution) is displayed, and the Pareto Front solutions are all listed in two lists, one ordered by objectives combinations and another ordered by the overall efficiency.
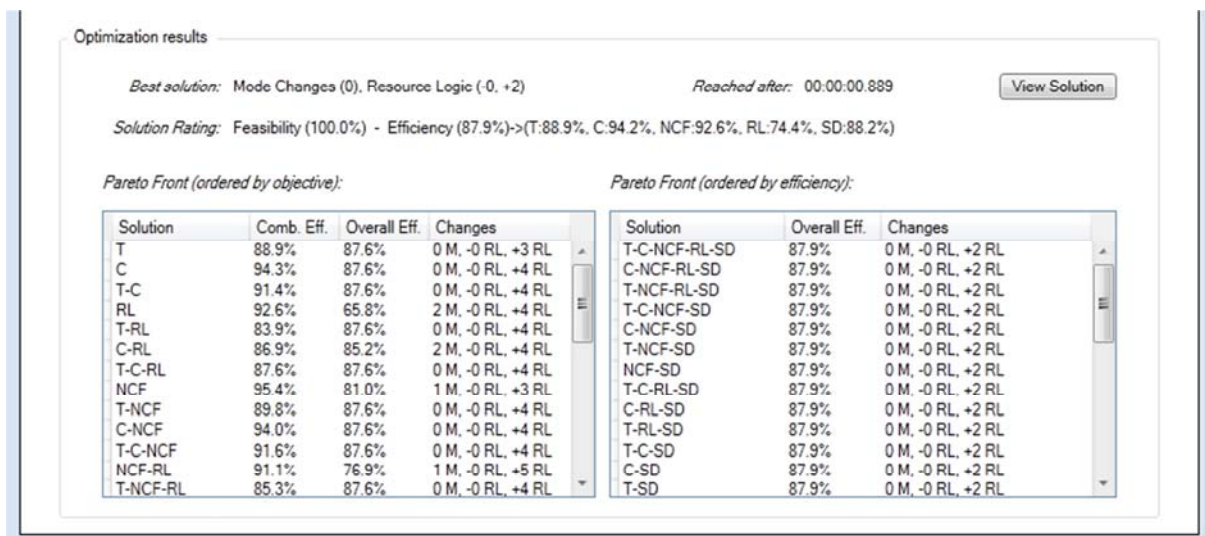
Figure 9.15: Dynamic Scheduler – Optimization Settings Form

The second level for displaying optimized solutions is through the *View Solution Form*. This form can be access by clicking the *View Solution* button in the optimization results panel or by double clicking any of the solutions displayed in the Pareto Front lists. As shown in figures 9.16 & 9.17, the form consists of four tabs: *Optimized Solution General Data, Solution Changes, Resources Details*, and *Cash Flow Details*. The first tab displays the solution's efficiency ratings and the details of their calculations with respect to solutions space limits. The second tab displays the changes made to the schedule to reach the solution (activity mode changed & resource logic added/deleted).
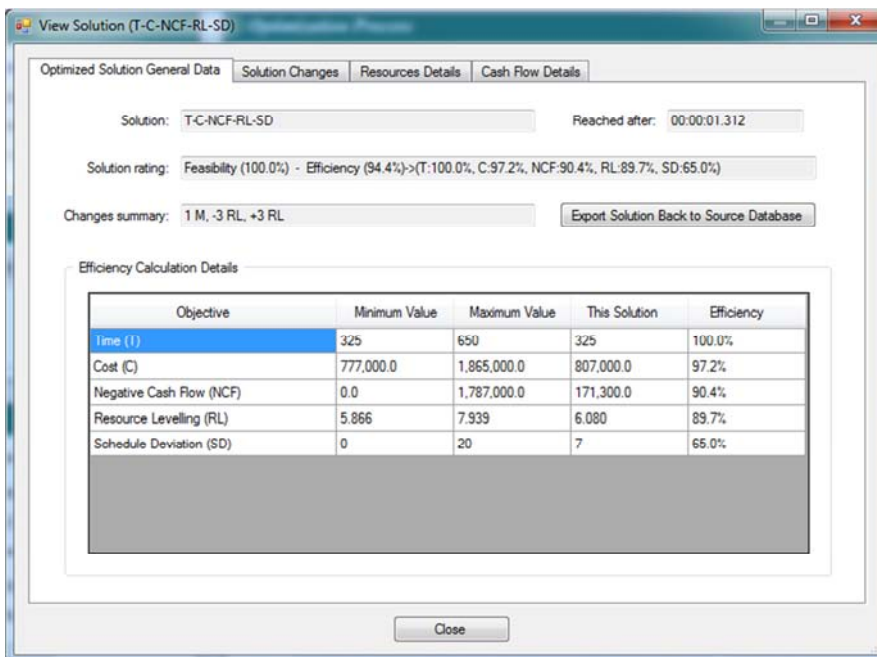
(a) Optimized Solution General Data tab
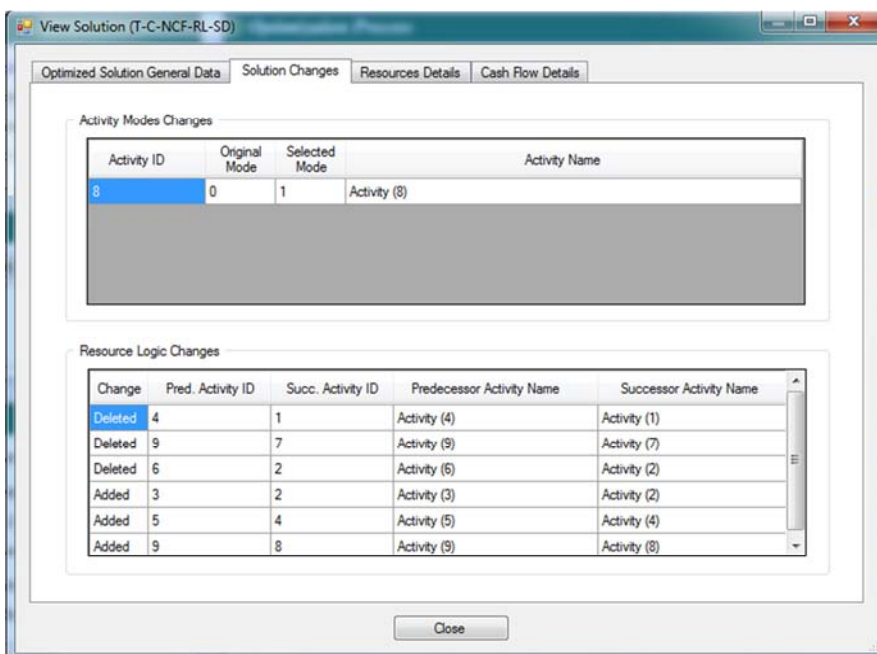
(b) Solution changes tab

Figure 9.16: Dynamic Scheduler – View Solution Details Form – Solution summary tabs

The third and fourth tabs display the details of the proposed solution: resources histograms and project cash flow. In the *Resources Details* tab, the resource histograms are shown with reference to both the original and maximum levels; while in the *Cash Flow Details* tab, the details of cash-out, cash-in and cash-flow calculations are shown on major cash-flow elements.
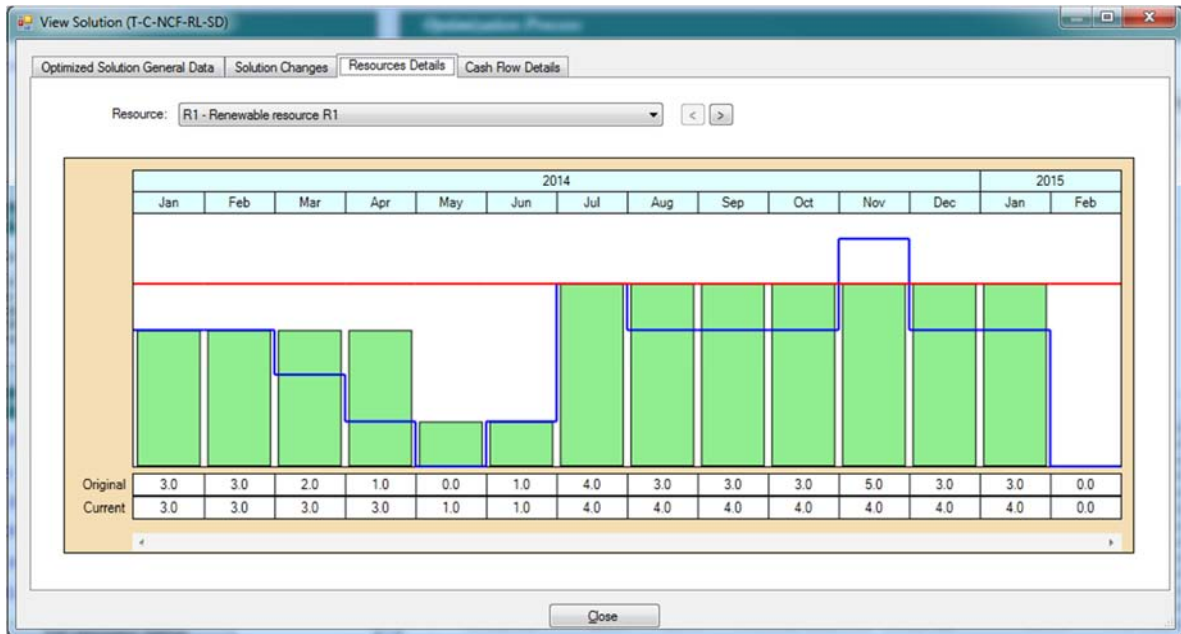
(a) Resources Details tab
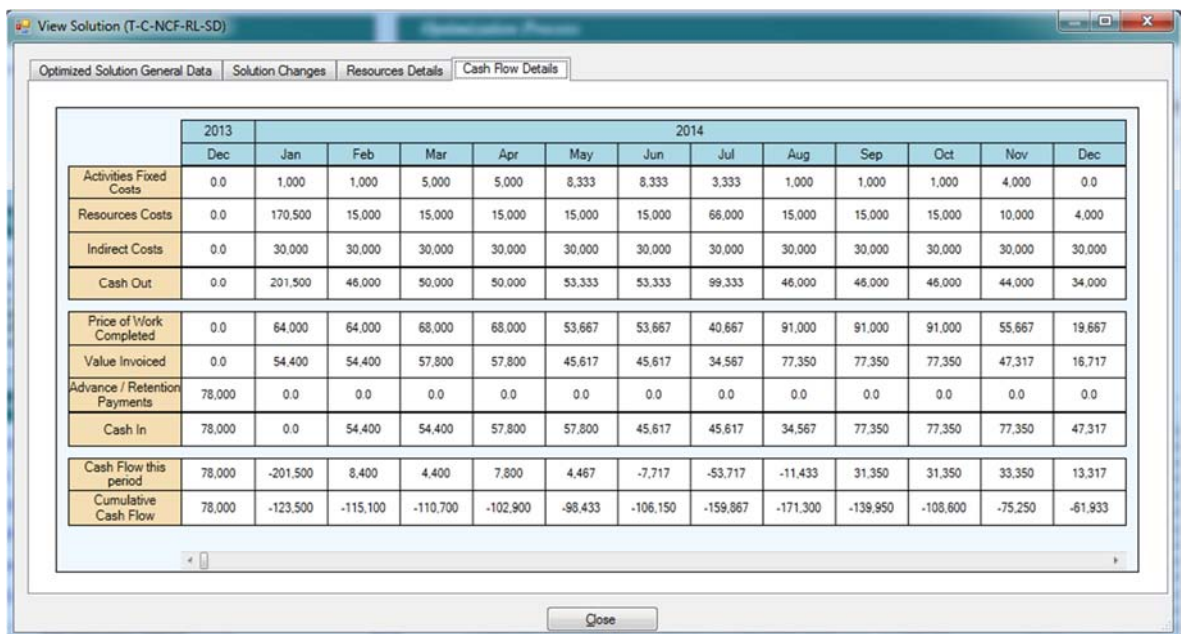
(b) Cash Flow Details tab

Figure 9.17: Dynamic Scheduler – View Solution Details Form – Solution details tabs

The same form can be initially accessed from the *Project Data* menu to display the original schedule's efficiency ratings, resources histograms, and cash flow details.

9.2.6. PSP libraries testing

The *Dynamic Scheduler* contains an additional functionality for mass analysis of problem sets. This functionality is located in the *Project* menu and in the *Data Source Form*, and it is performed by the *PSP Algorithm Verifier (PSPAV)* form which was used for the detailed testing of the *CDS* model and the optimization algorithm in Chapter 7.

In the first tab of the *PSPAV* form (as shown in figure 9.18), the user can select a folder which contains the problem sets to be tested. The *PSPAV* is integrated with most text formats of problem sets in literature; so, any problem files within the selected folder will be identified and loaded into the left pan of the form. Then, the user can select either few problems or a large set to analyze
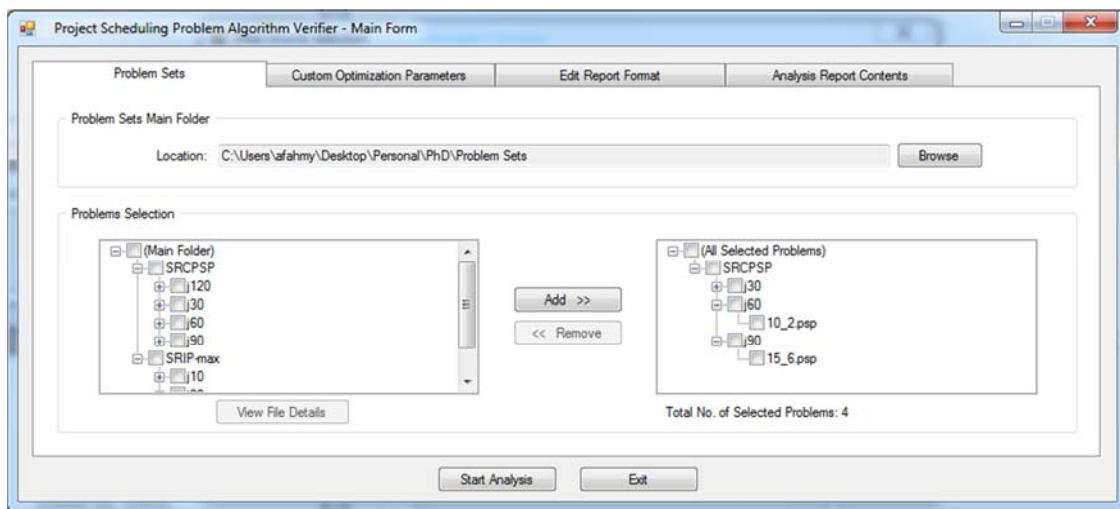
Figure 9.18: Dynamic Scheduler – *PSPAV* form – Problems selection

Before starting the analysis, the user should define the optimization algorithm's parameters in the second *PSPAV* tab (figure 9.19), and define the format and contents of the report which will be saved and displayed after the analysis completion (figure 9.20).
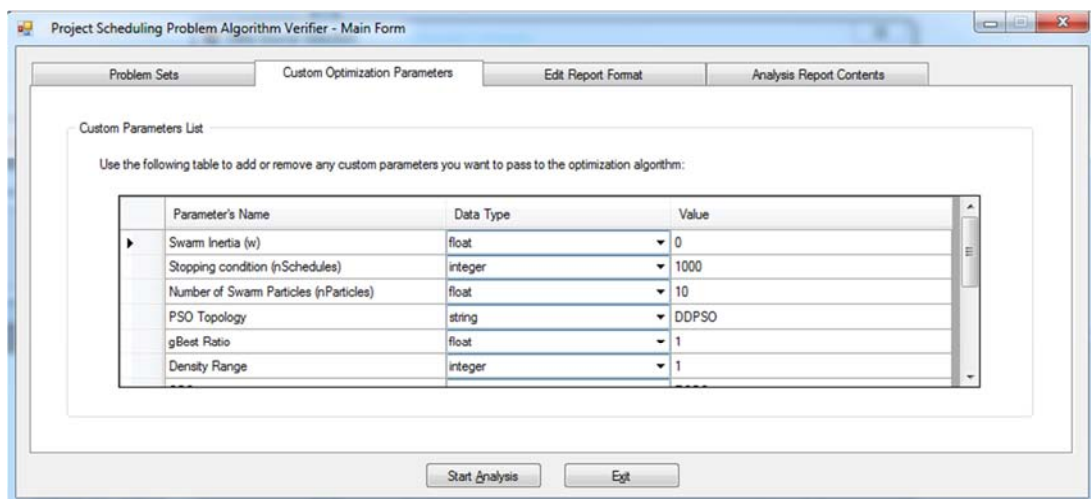
Figure 9.19: Dynamic Scheduler – *PSPAV* form – Parameters definition
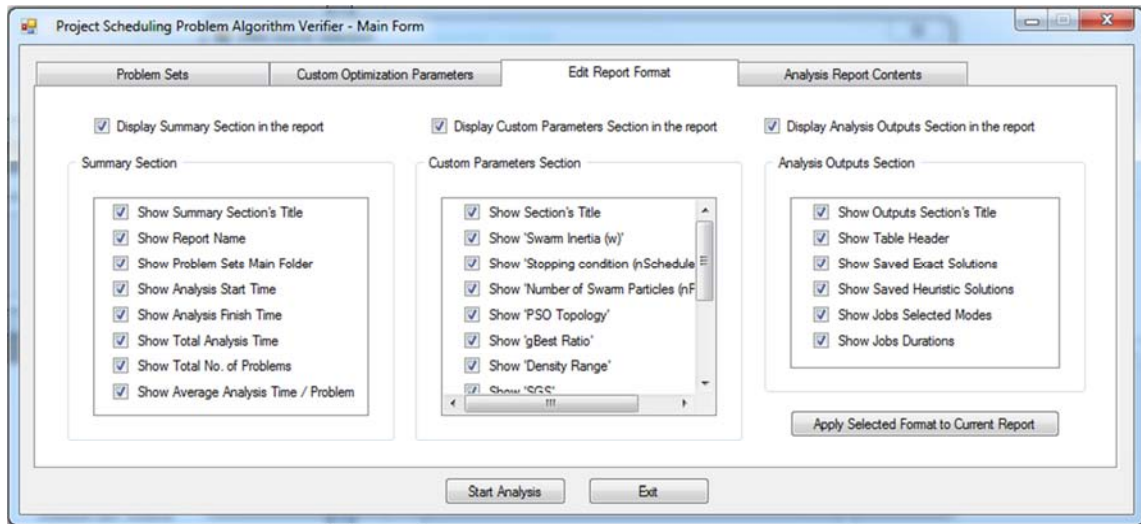
Figure 9.20: Dynamic Scheduler – *PSPAV* form – Report format definition

When the analysis starts, a status form appears showing the current optimization action, which helps the user to get a feedback that the process is running properly, especially that bulk testing can take more than one day. After the analysis completion, the last PSPAV tab will display the overall analysis report (figure 9.21). The report consists of four sections: *Report Summary* section, which shows general analysis statistics such as the total analysis time and the average time needed to reach best solutions; *Custom Parameters* section, which lists the algorithm parameters selected by the user for the analysis; and *Optimization Outputs* section, which lists the best solution achieved per problem and a comparison with the best result achieved in literature. In addition, the details of any analyzed problem can be displayed through selecting the problem from the tree on the left side of the report form. Finally, the user can also open old analysis reports for any necessary results comparison.
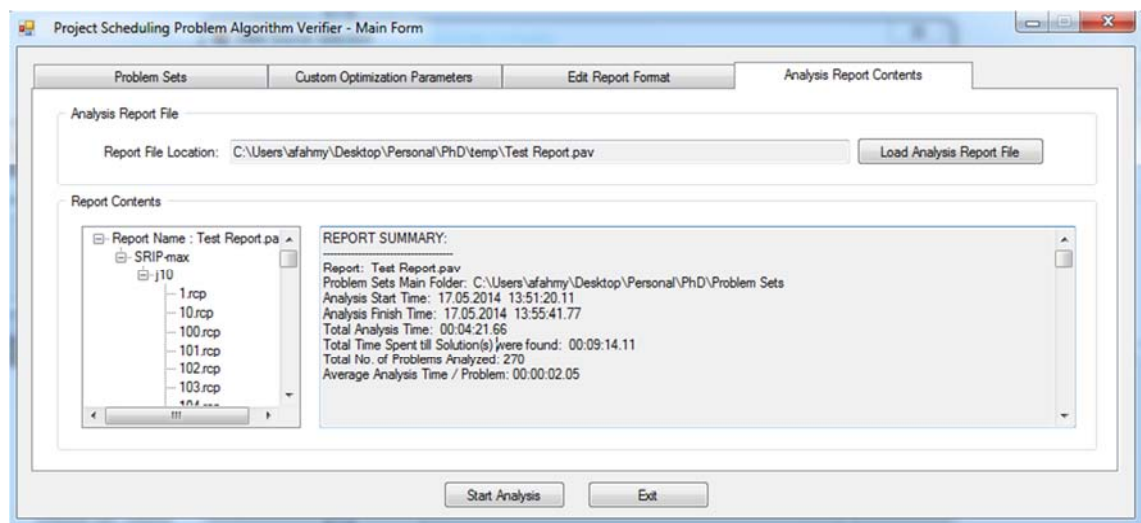
Figure 9.21: Dynamic Scheduler – *PSPAV* form – Optimization analysis report

9.3. Overview of the software programming process

In the previous section, the *Dynamic Scheduler* details and functionalities were explained from a user perspective; while this section briefly reviews the software from a software programming perspective.

The software was programmed in C# programming language, and using the Microsoft Visual Studio® 2010. The software code is more than 50,000 lines, and is grouped inside six code libraries as detailed in this section.

9.3.1. Dynamic Scheduler libraries architecture

The *Dynamic Scheduler* software code was developed under about 60 classes, which were grouped under six code libraries. As shown in figure 9.22, the code libraries can be categorized under two main groups: Algorithm testing libraries and the DS model libraries.

From the group name, it can be understood that the algorithm testing libraries were mainly developed for the purpose of testing the *Multi-Objective Particle Swarm (MOPS)* algorithm developed under this research. However, the libraries were arranged tin a generic way to enable using them, after minor code arrangement, for testing any PSP algorithm.

The second group, the DS model libraries, represents the main code of the solution presented in this research: the *Multi-Layer Scheduling (MLS)* concept, the *MOPS* algorithm, and the *CDS* model and the *Dynamic Scheduler* software user interface.
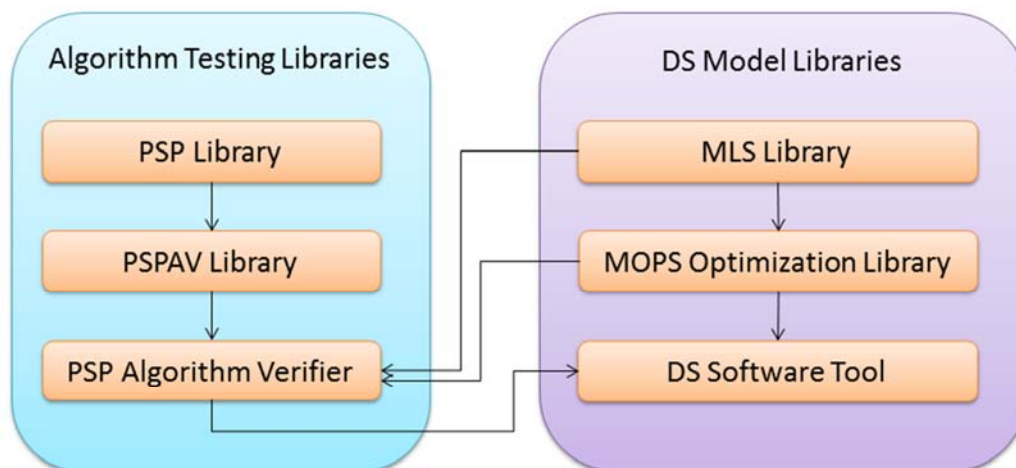
Figure 9.22: Code libraries dependencies for Dynamic Scheduler

9.3.2. Dynamic Scheduler code libraries details

Code libraries are generally encapsulation of interrelated classes. The following points review briefly the general class contents for each of the *Dynamic Scheduler's* code libraries:

1. *PSP Library:* Contains 7 classes which are needed to integrate the software with almost all types of problem sets in literature. Each type of problem sets contains its own text format which must be integrated to provide the ability to test these problem types with any developed optimization algorithm.

2. *PSPAV Library:* This library contains 9 classes representing the user interface for the *PSPAV* form and the related classes for reading and displaying analysis reports.

3. *PSP Algorithm Verifier:* This library is a dummy library that is used to segregate the content of the *PSPAV* library contents from any library which will use it for testing a PSP algorithm. This enables the ease of reusing the PSPAV library with any Microsoft Visual Studio coded PSP algorithm.

4. *MLS Library:* This is the core library which contains all scheduling classes and functions. It contains 13 classes representing an object oriented encapsulation for the MLS concepts and the general scheduling elements (activities, resources, logic, modes, profiles ...etc.).

5. *MOPS Optimization Library:* This library contains the classes related to the multi-objective particle swarm optimization algorithm.

6. *DS Software Tool:* This is the main library for the proposed software tool, the *Dynamic Scheduler*. The library consists of 23 user interface classes which represent the code for all the software's forms and controls.

9.4. The Dynamic Scheduler initial testing

The *Dynamic Scheduler* will be tested in detail in the next chapter; but for initially testing the tool and for performing a simple comparison with the planning software *Primavera P6* with respect to the optimization capabilities, a problem from the problem sets used for static verification in the previous chapter was used. The problem, j-120 [1-1], was loaded in *P6*, and scheduled to determine the minimum schedule duration (T_{min}=99 days).
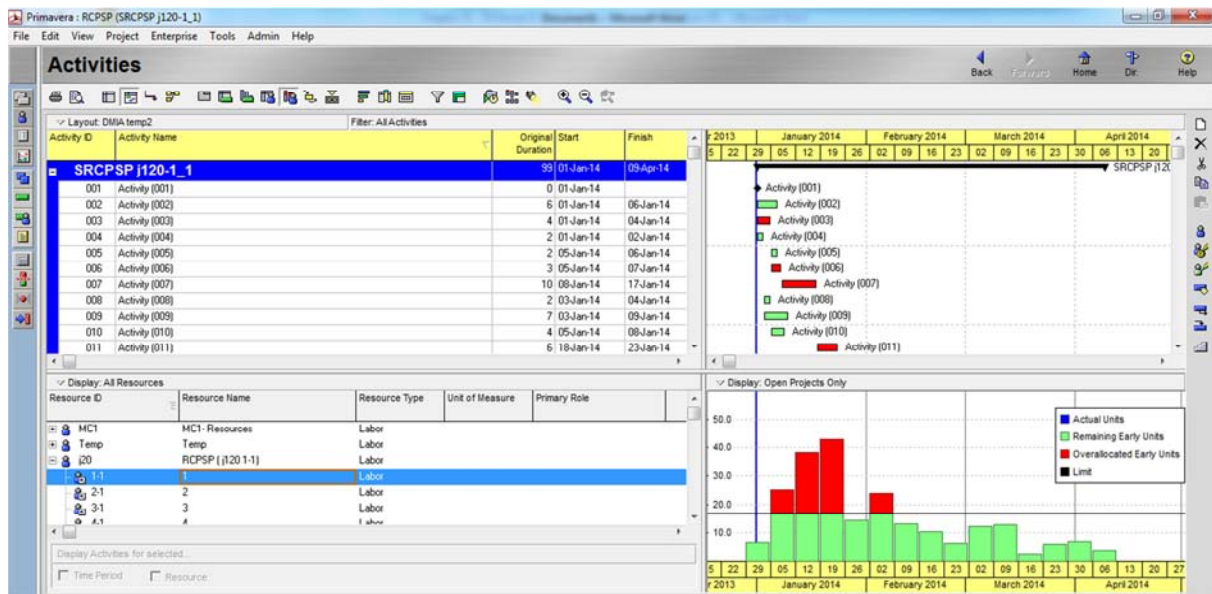
Figure 9.23: Sample problem loaded on P6 – Resource constraints unfulfilled (T=99)

The schedule contains four constrained resources, which are not fulfilled in the original schedule (as shown in figure 9.23). To achieve resources constraints, a schedule leveling process was performed using *P6*. The output of leveling was a schedule with a time span of 147 days (figure 9.24).
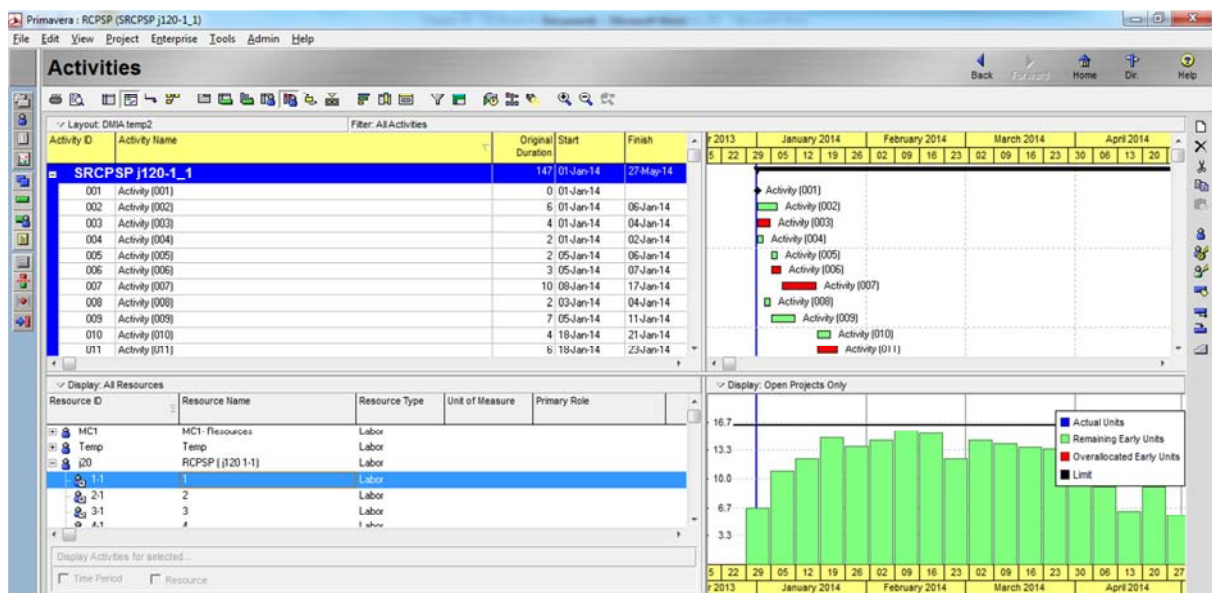
Figure 9.24: Sample problem – Output of P6 resource leveling (T=147)

The schedule was imported to *Dynamic Scheduler*, and an optimization process was performed with a *minimize-time* objective. The optimization achieved a minimum time span of 106 days (figure 9.25), with all resource constraints fulfilled. It is clear from this simple example that the *Dynamic Scheduler* strongly outperformed the planning software's leveling process and produced an optimized solution with 30% better for the time objective.
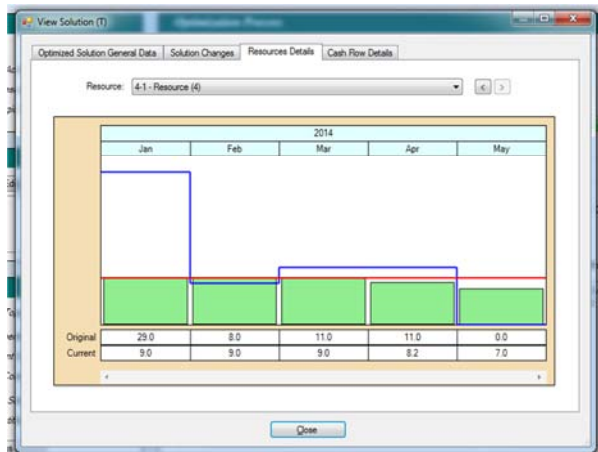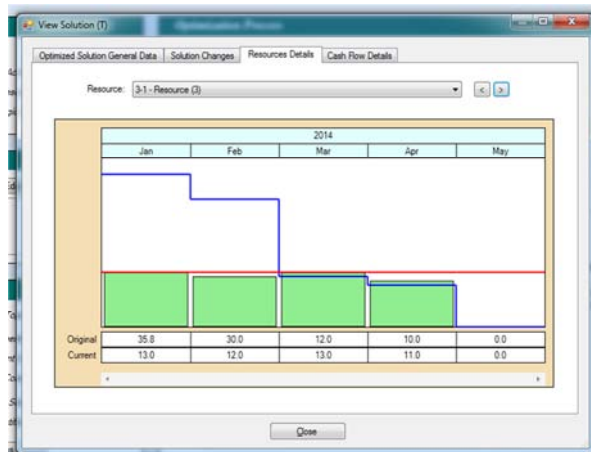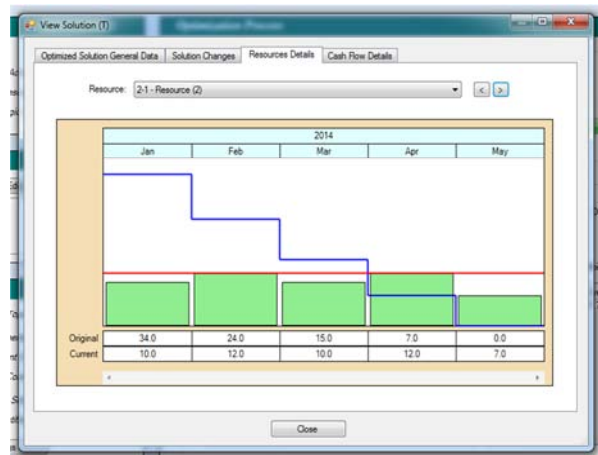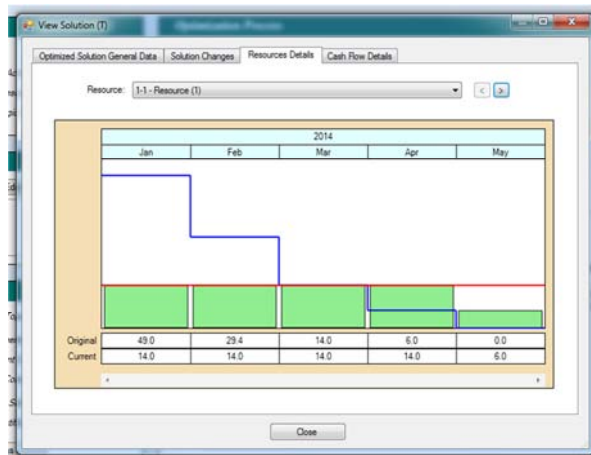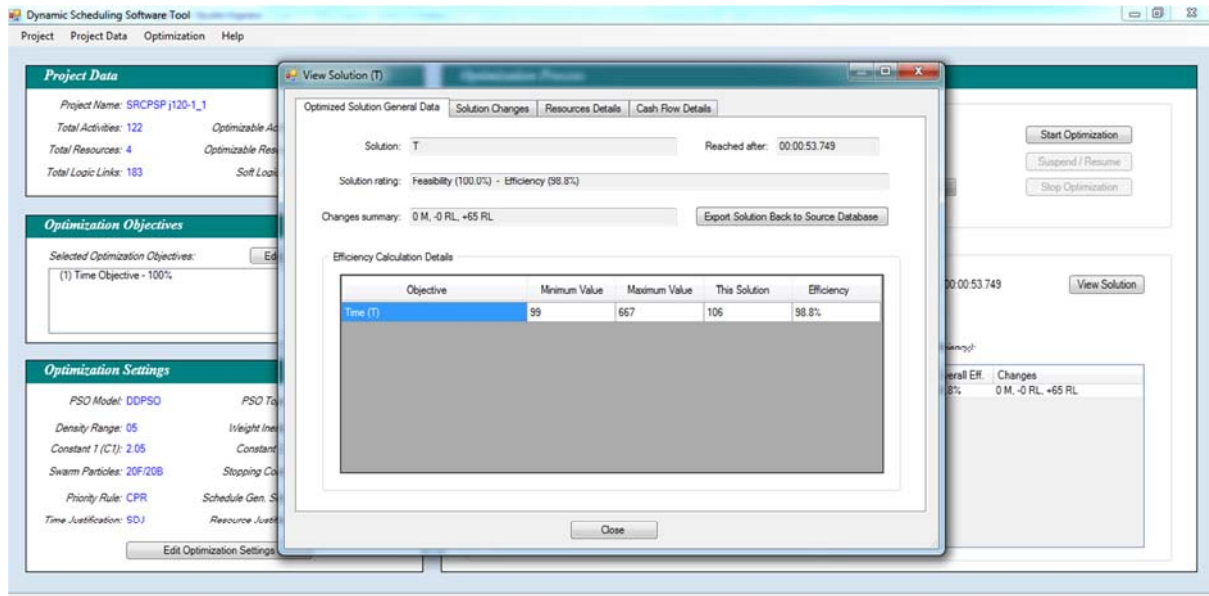
Figure 9.25: Sample problem – Optimization results on Dynamic Scheduler (T=106)

Finally, the optimized schedule was exported back to *P6* (as shown in figure 9.26), with an additional 65 resources logic required to generate a schedule achieving all resources constraints and with a near-optimum time span.
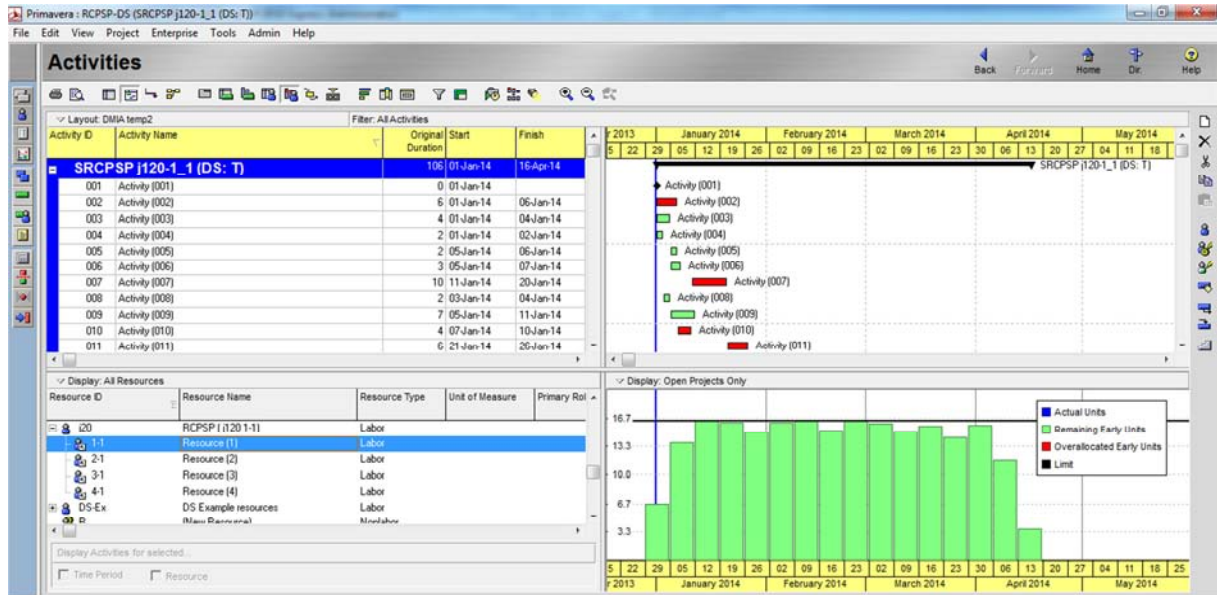
Figure 9.26: Sample problem – Exported project back to P6 (T=106)

9.5. Summary

The dynamic scheduling software tool, or the *Dynamic Scheduler*, presented in this Chapter was the last element of the overall proposed dynamic scheduling solution for construction enterprises.

The Chapter reviewed the development process of this software tool, the general software's functionality, and the software's architecture form an IT perspective. At the end of the Chapter, a simple comparison was made for the *Dynamic Scheduler's* optimization capabilities in comparison with current available project management software packages (namely Primavera P6®).

Chapter 10: DS Model & Software Tool Dynamic Verification

The verification process performed in Chapter 8 showed the static capabilities of the DS model and the optimization algorithm. This chapter will verify the dynamic capabilities of the overall proposed DS solution for construction enterprises, including the DS mathematical model, the optimization algorithm, the *Dynamic Scheduler* software tool, and the overall system's framework. To simplify the dynamic verification process, the chapter will start with a simple solved example designed to illustrate & verify the model's detailed dynamic functionality, and then a case study construction entity will be used to verify the proposed system's scalability and practicality.

10.1. Dynamic verification using solved example

A construction project with the information shown in figure 10.1; the activities information are shown in 10.1(a) including resource requirements, logic relations, fixed costs, and selling price. Three of the schedule activities (1, 7 & 8) are having two possible execution modes. Resources information are listed in 10.1(b) including the one-time cost for the renewable resource R1, the monthly rental rate for the non-renewable resource N1, and the mobilization/demobilization costs for both resources. The maximum available units for R1 are 4; while N1 is to be levelled. Figure 10.1(d) shows the resources distribution (as per original precedence).

The project is having an indirect cost of $30,000 per month, an advance payment of 10% to be paid before the project start, and retention of 5% to be paid with the last invoice; taking into consideration that invoicing will be made at the same month end, and there is an expected delay of 1 month between invoicing and payment. The optimization objectives are: minimize time (weight 35%), minimize cost (30%), level resources (20%), minimize negative cash flow (10%), and minimize schedule deviation (5%).

Table 10.1 shows the corresponding original cash-flow (simplified to periodical cash in/out figures at each month end). Noting that, according to the original schedule logic, the resource distribution for R1 is crossing the allowable limit, the cash flow is having high negative peak at the project start, and the project is in overall loss where the total cost became $829,000 ($49,000 higher than contract price) due to the poor resources allocation.

(a) Activities information

Act.	Dur.	R1	N1	Succ.	F. Cost	Price
1	4,5	1,1	2,1	5	20,000	164,000
2	3	0	1	-	10,000	38,000
3	2	2	3	6	-	108,000
4	5	1	2	9	5,000	185,000
5	1	4	1	-	-	28,000
6	3	3	3	7	-	162,000
7	3,4	3,2	1,1	-	-	29,000
8	1,2	2,1	0,0	-	-	20,000
9	1	1	2	-	4,000	46,000
						780,000
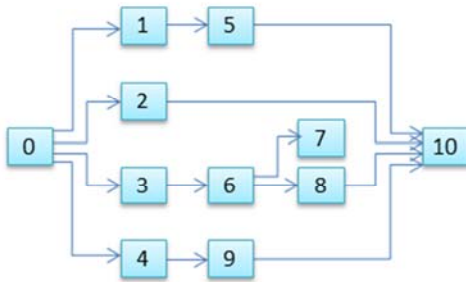
(b) Resources information

Res.	One time cost	Monthly rate	Mob. cost	Demob. cost
R1	50,000	-	1,000	1,000
N1	-	3,000	500	500

(c) Precedence network
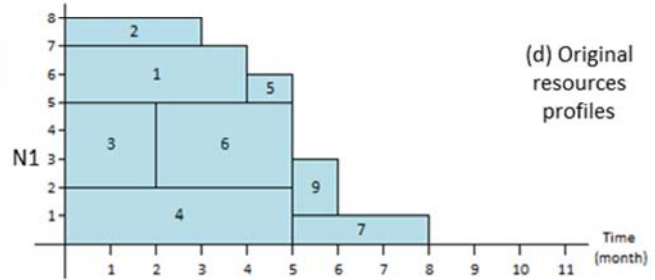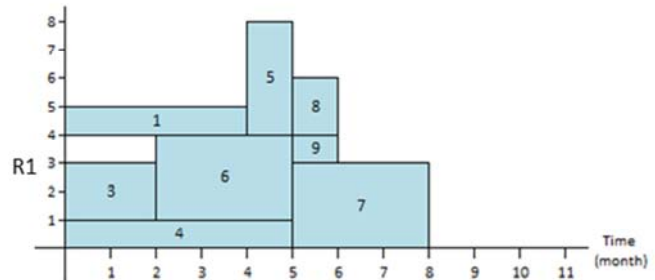
(d) Original resources profiles

Figure 10.1: Example 10.1 – Project details, network & original resources

Item	End of Month												Total
	0	1	2	3	4	5	6	7	8	9	10	11	
Work completed	-	25% of 1, 33% of 2, 50% of 3, 20% of 4	25% of 1, 33% of 2, 50% of 3, 20% of 4	25% of 1, 33% of 2, 20% of 4, 33% of 6	25% of 1, 20% of 4, 33% of 6	20% of 4, 100% of 5, 33% of 6	33% of 7, 100% of 8, 100% of 9	33% of 7	33% of 7	-	-	-	
Fixed Cost	-	9,333	9,333	9,333	6,000	1,000	4,000	0	0	0	0	0	39,000
R1 Cost	0	204,000	0	51,000	0	153,000	2,000	3,000	0	3,000	0	0	416,000
N1 Cost	0	28,000	24,000	24,000	21,500	18,500	10,500	4,000	3,000	500	0	0	134,000
Indirect cost	0	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	0	0	0	240,000
Cash-out	0	271,333	63,333	114,333	57,500	202,500	46,500	37,000	33,000	3,500	0	0	829,000
Price of work completed	0	144,667	144,667	144,667	132,000	119,000	75,667	9,667	9,667	0	0	0	780,000
Value invoiced	0	122,967	122,967	122,967	112,200	101,150	64,317	8,217	8,217	0	0	0	663,000
Adv. Payment / Retention	78,000	0	0	0	0	0	0	0	0	39,000	0	0	117,000
Cash-in	78,000	0	122,967	122,967	122,967	112,200	101,150	64,317	8,217	47,217	0	0	780,000
Cash-flow this period	78,000	-271,333	59,633	8,633	65,467	-90,300	54,650	27,317	-24,783	43,717	0	0	-49,000
Cumulative cash-flow	78,000	-193,333	-133,700	-125,067	-59,600	-149,900	-95,250	-67,933	-92,717	-49,000	-49,000	-49,000	

Table 10.1: Example 10.1 – Original cash flow

10.1.1. Baseline optimization

The first step, as per the CDS model, is to pass the original baseline schedule to the optimization algorithm to prepare several optimized baseline alternatives for the planner's selection. Before starting the optimization process, the search space limits must be calculated as per equations 6.33 to 6.46. Table 10.2 shows the calculation results for search space limits, as well as the original objectives values.

Objective	Minimum	Maximum	Original
T	= Original CP length = 8	= Sum of largest duration for all tasks = 26	= 8
C	= Indirect cost + FC + Mob/Demob. for $N1_{min}$ + Minimum N1 assignments x monthly rate + (One time cost + Mob/Demob.) for $R1_{min}$ = 30,000x8 + (20,000+10,000+5,000+4,000) + (500+500)x3 + 39 x 3,000 + (50,000+1,000+ 1,000)x4 = 607,000	= Indirect cost @ Tmax + FC + M/D. for $N1_{max}$ + Maximum N1 assignments x monthly rate + (One time cost + Mob/Demob.) for $R1_{max}$ = 30,000x26 + (20,000+10,000+5,000+4,000) + (500+500)x15 + 43 x 3,000 + (50,000+1,000+ 1,000)x17 = 1,847,000	= 829,000 (as per the previous table)
RLI	= log(R1 unit rate x sum of (dur. x $request^2$) + N1 unit rate x sum of (dur. x $request^2$)) = log(50,000/8 x $(4x1^2+2x2^2+5x1^2+...+1x1^2)$+ + 3,000 x $(4x2^2+3x1^2+2x3^2+...+1x2^2)$) = 5.867	= log(R1 unit rate x D_{max} x (sum of requests)^2 + N1 unit rate x D_{max} x (sum of requests)^2) = log(50,000/8 x 5 $(1+2+1+4+3+3+2+1)^2$+ + 3,000 x 5 $(2+1+3+2+1+3+1+2)^2$) = 7.094	= log(6250 x $(4^2+4^2+...+3^2)$ +3000x$(8^2+...$ $+1^2)$) = 6.325
NCF	= No negative cash flow = 0	= (C_{max} - Advance Payment) = 1,772,000	= 193,333
SD	= No changes to modes & resource logic = 0	= All mode changes + All resource logic = 3 + (N1 requests-1) + (R1 requests-1) = 17	= 0

Table 10.2: Example 10.1 – Original search space limits

The optimization starts with the preparation of *Cumulative Objective Functions (COFs)* list. In this example, the *COFs* list will contain 31 possible objectives combinations (*T, C, RLI, NCF, SD, T-C, T-RLI … up to T-C-RLI-NCF-SD*). For the sake of simplicity, not all optimum solutions corresponding to the *COFs* will be listed; only the main Pareto Front alternatives, which will be needed to illustrate the CDS model's functionality, are presented in figure 10.2, and explained accordingly.

There are two main Pareto Front alternatives: solution (1_0, 7_0, 8_0, 4-1 & 9-7) and solution (1_0, 7_0, 9_0, 4-1, 6-2, & 9-7). The first solution represents the optimum for *SD* & almost all other combinations containing *SD*, including the overall *T-C-RLI-NCF-SD*, where a minimum of two resource logic are required to meet the resource constraint for R1. While the second solution represents the optimum for cost objective *(C)*; as well as, few other objectives combinations.

It is worth mentioning that, if the selection was left to the algorithm to be based on the overall efficiency (E_{Total}), the above mentioned first solution will be selected; however, the second solution will look definitely more favorable to planners, due to being with smaller cost, better cash flow, and more leveled resource profiles.

Solution: Modes (1₀, 7₀, 8₀), RL (4-1, 9-7)
Optimum for: T, SD, T-SD, …, T-C-RLI-NCF-SD

E_T	E_C	E_{RLI}	E_{NCF}	E_{SD}	E_{Total}
88.9%	94.2%	74.4%	92.6%	88.2%	87.92%

Item	End of Month												Total
	0	1	2	3	4	5	6	7	8	9	10	11	
Work completed	-	33% of 2, 50% of 3, 20% of 4	33% of 2, 50% of 3, 20% of 4	33% of 2, 20% of 4, 33% of 6	20% of 4, 33% of 6	20% of 4, 33% of 6	25% of 1, 100% of 8, 100% of 9	25% of 1, 33% of 7	25% of 1, 33% of 7	25% of 1, 33% of 7	100% of 5	-	
Fixed Cost	-	4,333	4,333	4,333	1,000	1,000	9,000	5,000	5,000	5,000	0	0	39,000
R1 Cost	0	153,000	0	51,000	0	0	0	0	0	0	0	4,000	208,000
N1 Cost	0	21,000	18,000	18,000	15,500	15,000	12,500	9,500	9,000	9,000	4,000	500	132,000
Indirect cost	0	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	0	300,000
Cash-out	0	208,333	52,333	103,333	46,500	46,000	51,500	44,500	44,000	44,000	34,000	4,500	679,000
Price of work completed	0	103,667	103,667	103,667	91,000	91,000	107,000	50,667	50,667	50,667	28,000	0	780,000
Value invoiced	0	88,117	88,117	88,117	77,350	77,350	90,950	43,067	43,067	43,067	23,800	0	663,000
Adv. Payment / Retention	78,000	0	0	0	0	0	0	0	0	0	0	39,000	117,000
Cash-in	78,000	0	88,117	88,117	88,117	77,350	77,350	90,950	43,067	43,067	43,067	62,800	780,000
Cash-flow this period	78,000	-208,333	35,783	-15,217	41,617	31,350	25,850	46,450	-933	-933	9,067	58,300	101,000
Cumulative cash-flow	78,000	-130,333	-94,550	-109,767	-68,150	-36,800	-10,950	35,500	34,567	33,633	42,700	101,000	

Solution: Modes (1₀, 7₀, 8₀), RL (4-1, 6-2,7-8,7-9)
Optimum for: C, T-C, C-NCF, T-C-NCF

E_T	E_C	E_{RLI}	E_{NCF}	E_{SD}	E_{Total}
88.9%	94.3%	75.1%	93.0%	82.4%	87.83%

Item	End of Month												Total
	0	1	2	3	4	5	6	7	8	9	10	11	
Work completed	-	50% of 3, 20% of 4	50% of 3, 20% of 4	20% of 4, 33% of 6	20% of 4, 33% of 6	20% of 4, 33% of 6	25% of 1, 33% of 2, 100% of 8, 100% of 9	25% of 1, 33% of 2, 33% of 7	25% of 1, 33% of 2, 33% of 7	25% of 1, 33% of 7	100% of 5	-	
Fixed Cost	-	1,000	1,000	1,000	1,000	1,000	12,333	8,333	8,333	5,000	0	0	39,000
R1 Cost	0	153,000	0	51,000	0	0	0	0	0	0	0	4,000	208,000
N1 Cost	0	17,500	15,000	15,000	15,000	15,000	15,000	12,500	12,000	9,500	4,000	500	131,000
Indirect cost	0	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	0	300,000
Cash-out	0	201,500	46,000	97,000	46,000	46,000	57,333	50,833	50,333	44,500	34,000	4,500	678,000
Price of work completed	0	91,000	91,000	91,000	91,000	91,000	119,667	63,333	63,333	50,667	28,000	0	780,000
Value invoiced	0	77,350	77,350	77,350	77,350	77,350	101,717	53,833	53,833	43,067	23,800	0	663,000
Adv. Payment / Retention	78,000	0	0	0	0	0	0	0	0	0	0	39,000	117,000
Cash-in	78,000	0	77,350	77,350	77,350	77,350	77,350	101,717	53,833	53,833	43,067	62,800	780,000
Cash-flow this period	78,000	-201,500	31,350	-19,650	31,350	31,350	20,017	50,883	3,500	9,333	9,067	58,300	102,000
Cumulative cash-flow	78,000	-123,500	-92,150	-111,800	-80,450	-49,100	-29,083	21,800	25,300	34,633	43,700	102,000	

Figure 10.2: Example 10.1 – Baseline optimization, two of the main PF alternatives

10.1.2. Progress updates optimization

A progress update scenario was considered as follows: after period 2, the duration of activity 3 extended to 4 months where 2 months are remaining after cut-off date, activity 4 progressed as planned, and activity 6 cannot start before the start of month 8 due to related procurement delays. If we considered that the baseline optimized alternative (1₀, 7₀, 9₀, 4-1, 6-2 & 9-7) was selected for construction; then the schedule & cash flow status after the progress update of 2ⁿᵈ month will be as shown in figure 10.3.
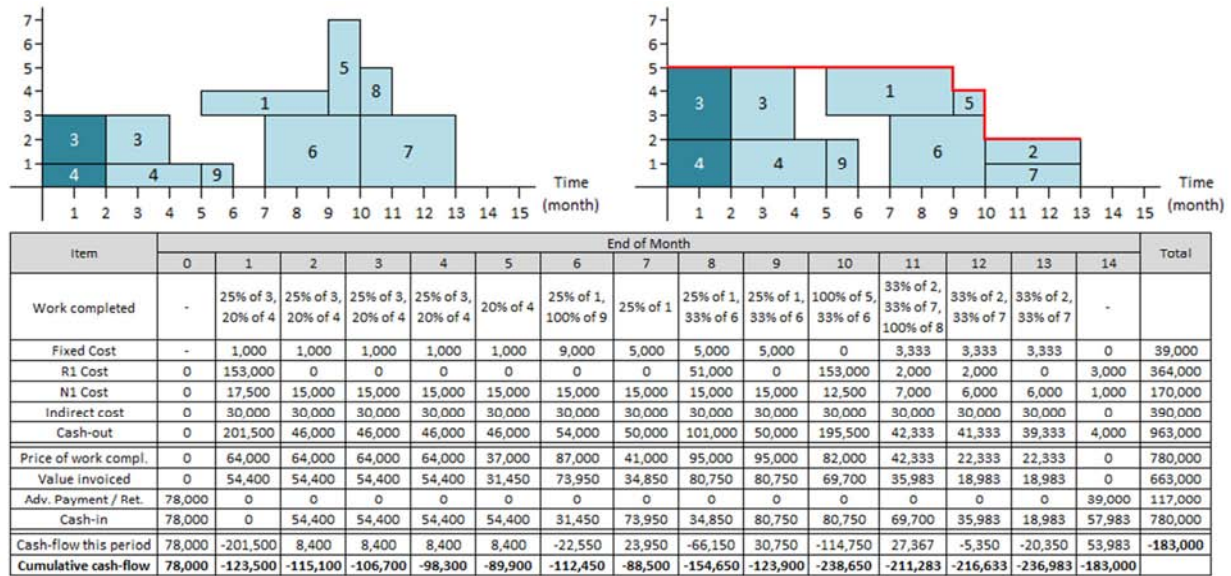
Figure 10.3: Example 10.1 – Schedule & cash flow status after the 2nd month progress update

Item	End of Month															Total
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Work completed	-	25% of 3, 20% of 4	25% of 3, 20% of 4	25% of 3, 20% of 4	25% of 3, 20% of 4	20% of 4	25% of 1, 100% of 9	25% of 1	25% of 1, 33% of 6	25% of 1, 33% of 6	100% of 5, 33% of 6	33% of 2, 33% of 7, 100% of 8	33% of 2, 33% of 7	33% of 2, 33% of 7	-	
Fixed Cost	-	1,000	1,000	1,000	1,000	1,000	9,000	5,000	5,000	5,000	0	3,333	3,333	3,333	0	39,000
R1 Cost	0	153,000	0	0	0	0	0	0	51,000	0	153,000	2,000	2,000	0	3,000	364,000
N1 Cost	0	17,500	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	12,500	7,000	6,000	6,000	1,000	170,000
Indirect cost	0	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	0	390,000
Cash-out	0	201,500	46,000	46,000	46,000	46,000	54,000	50,000	101,000	50,000	195,500	42,333	41,333	39,333	4,000	963,000
Price of work compl.	0	64,000	64,000	64,000	64,000	37,000	87,000	41,000	95,000	95,000	82,000	42,333	22,333	22,333	0	780,000
Value invoiced	0	54,400	54,400	54,400	54,400	31,450	73,950	34,850	80,750	80,750	69,700	35,983	18,983	18,983	0	663,000
Adv. Payment / Ret.	78,000	0	0	0	0	0	0	0	0	0	0	0	0	0	39,000	117,000
Cash-in	78,000	0	54,400	54,400	54,400	54,400	31,450	73,950	34,850	80,750	80,750	69,700	35,983	18,983	57,983	780,000
Cash-flow this period	78,000	-201,500	8,400	8,400	8,400	8,400	-22,550	23,950	-66,150	30,750	-114,750	27,367	-5,350	-20,350	53,983	-183,000
Cumulative cash-flow	78,000	-123,500	-115,100	-106,700	-98,300	-89,900	-112,450	-88,500	-154,650	-123,900	-238,650	-211,283	-216,633	-236,983	-183,000	

Objective	Minimum	Maximum	Original
T	= T (for schedule with minimum durations and no resource logic) = 13	= Data date + Sum of largest remaining durations = 2 + 24 = 26	= 13
C	= 30,000x13 + (20,000+10,000+5,000+4,000) + (500+500)x5 + 45 x 3,000 + (50,000+1,000+ 1,000)x4 = 777,000	= 30,000x26 + (20,000+10,000+5,000+4,000) + (500+500)x15 + 49 x 3,000 + (50,000+1,000+ 1,000)x17 = 1,865,000	= 963,000 (as shown in figure 10.3)
RLI	$= \log(50{,}000/13 \times (3^2+3^2+(4x1^2+2x2^2+3x1^2+...+1x1^2))+$ $+ 3{,}000 \times (5^2+5^2+(5x1^2+3x1^2+2x3^2+...+1x2^2))) = 5.866$	$= \log(50{,}000/13 \times (3^2+3^2+5x(1+2+1+4+3+3+2+1)^2))+$ $+ 3{,}000 \times (5^2+5^2+5x(2+1+3+2+1+3+1+2)^2)) = 7.939$	= 6.095
NCF	= No negative cash flow = 0	= (C_{max} - Advance Payment) = 1,787,000	= 238,650
SD	= No changes to modes & resource logic = 0	= 3 M + BRL + (N1 req. - 1) + (R1 req. - 1) = 20	= 0

Table 10.3: Example 10.1 – Search space limits for progress update of month 2

The optimization search space for this updated schedule will be as shown in table 10.3. Then, as explained earlier in the baseline schedule optimization, figure 10.4 shows 2 of the main Pareto Front's optimized solutions: (1_0, 7_0, 8_1, 3-2 , 5-4, 9-8) and (1_0, 7_0, 8_0, 3-2, 5-4, 9-7). The first solution represents the optimum for three of the single objectives: *T, C, & RLI*; as well as, many objectives combinations, including the overall *T-C-RLI-NCF-SD*. While the second solution represents the optimum for *SD, NCF-SD & C-RLI-SD*, where a minimum of four resource logic changes (2 old deleted: 4-1 & 6-2, and 2 new: 3-2 & 5-4) are required to meet the resource constraint for R1.

Note that the algorithm considers redundant resource logic as removed. For example in second solution, the old resource logic 9-7 was still valid; but since activity 7 was planned not following activity 9, then it was driven by other logic (here the original logic 6-7) and accordingly 9-7 was considered redundant and removed from new resource logic list.

The overall optimum solution is having a loss of $27,000; this is the minimum loss which can be achieved after the project completion is extended to 13 months due to the delay of activity 6. Taking into consideration that the loss due to this additional prolongation costs might be compensable if the delay is employer related.

Finally, for practical purposes, the profile for any resource with periodical hiring cost rate (such as N1 in this example), should be levelled as highlighted in figures 8 & 9 to avoid non-practical mobilization/de-mobilization cycles; and cost should be calculated accordingly.

Solution: Modes (1_0, 7_0, 8_1), RL (3-2,5-4,9-8)
Optimum for: T, C, RLI, ..., T-C-RLI-NCF-SD

E_T	E_C	E_{RLI}	E_{NCF}	E_{SD}	E_{Total}
100%	97.2%	89.7%	90.4%	65.0%	94.4%

Item	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
Work completed	-	25% of 3, 20% of 4	25% of 3, 20% of 4	25% of 1, 25% of 3	25% of 1, 25% of 3	25% of 1, 33% of 2	25% of 1, 33% of 2	33% of 2, 100% of 5	20% of 4, 33% of 6	20% of 4, 33% of 6	20% of 4, 33% of 6	33% of 7, 100% of 9	33% of 7, 50% of 8	33% of 7, 50% of 8	-	
Fixed Cost	-	1,000	1,000	5,000	5,000	8,333	8,333	3,333	1,000	1,000	1,000	4,000	0	0	0	39,000
R1 Cost	0	153,000	0	0	0	0	0	51,000	0	0	0	0	0	0	4,000	208,000
N1 Cost	0	17,500	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	10,000	4,000	3,000	500	170,000
Indirect cost	0	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	0	390,000
Cash-out	0	201,500	46,000	50,000	50,000	53,333	53,333	99,333	46,000	46,000	46,000	44,000	34,000	33,000	4,500	807,000
Price of work compl.	0	64,000	64,000	68,000	68,000	53,667	53,667	40,667	91,000	91,000	91,000	55,667	19,667	19,667	0	780,000
Value invoiced	0	54,400	54,400	57,800	57,800	45,617	45,617	34,567	77,350	77,350	77,350	47,317	16,717	16,717	0	663,000
Adv. Payment / Ret.	78,000	0	0	0	0	0	0	0	0	0	0	0	0	0	39,000	117,000
Cash-in	78,000	0	54,400	54,400	57,800	57,800	45,617	45,617	34,567	77,350	77,350	77,350	47,317	16,717	55,717	780,000
Cash-flow this period	78,000	-201,500	8,400	4,400	7,800	4,467	-7,717	-53,717	-11,433	31,350	31,350	33,350	13,317	-16,283	51,217	-27,000
Cumulative cash-flow	78,000	-123,500	-115,100	-110,700	-102,900	-98,433	-106,150	-159,867	-171,300	-139,950	-108,600	-75,250	-61,933	-78,217	-27,000	

Solution: Modes (1_0, 7_0, 8_0), RL (3-2,5-4,9-7)
Optimum for: SD, NCF-SD, C-RLI-SD

E_T	E_C	E_{RLI}	E_{NCF}	E_{SD}	E_{Total}
92.3%	94.5%	90.7%	90.4%	80.0%	91.8%

Item	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
Work completed	-	25% of 3, 50% of 4	25% of 3, 50% of 4	25% of 1, 25% of 3	25% of 1, 25% of 3	25% of 1, 33% of 2	25% of 1, 33% of 2	33% of 2, 100% of 5	33% of 6	33% of 6	33% of 6	100% of 8, 100% of 9	33% of 7	33% of 7	33% of 7	-	
Fixed Cost	-	1,000	1,000	5,000	5,000	8,333	8,333	3,333	1,000	1,000	1,000	4,000	0	0	0	0	39,000
R1 Cost	0	153,000	0	0	0	0	0	51,000	0	0	0	1,000	0	0	0	3,000	208,000
N1 Cost	0	17,500	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	7,500	3,500	3,000	3,000	500	170,000
Indirect cost	0	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	0	420,000
Cash-out	0	201,500	46,000	50,000	50,000	53,333	53,333	99,333	46,000	46,000	46,000	42,500	33,500	33,000	33,000	3,500	837,000
Price of work compl.	0	64,000	64,000	68,000	68,000	53,667	53,667	40,667	91,000	91,000	91,000	66,000	9,667	9,667	9,667	0	780,000
Value invoiced	0	54,400	54,400	57,800	57,800	45,617	45,617	34,567	77,350	77,350	77,350	56,100	8,217	8,217	8,217	0	663,000
Adv. Payment / Ret.	78,000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	39,000	117,000
Cash-in	78,000	0	54,400	54,400	57,800	57,800	45,617	45,617	34,567	77,350	77,350	77,350	56,100	8,217	8,217	47,217	780,000
Cash-flow this period	78,000	-201,500	8,400	4,400	7,800	4,467	-7,717	-53,717	-11,433	31,350	31,350	34,850	22,600	-24,783	-24,783	43,717	-57,000
Cumulative cash-flow	78,000	-123,500	-115,100	-110,700	-102,900	-98,433	-106,150	-159,867	-171,300	-139,950	-108,600	-73,750	-51,150	-75,933	-100,717	-57,000	

Figure 10.4: Example 10.1 – Optimization of month 2 progress update, main Pareto Front

10.1.3. Verification results on Dynamic Scheduler

This example was prepared first on *Primavera P6*, with all main schedule and resources data (as shown in figure 10.5). Then, a project was created in *Dynamic Scheduler*, with a link to the *P6* project; and the DS

project was then loaded with project data which cannot be added to the P6 project (activity modes, resources total availability, project indirect cost … etc.). The last step before starting optimization was to define optimization objectives, objectives weightages and optimization settings (as shown in figure 10.6).
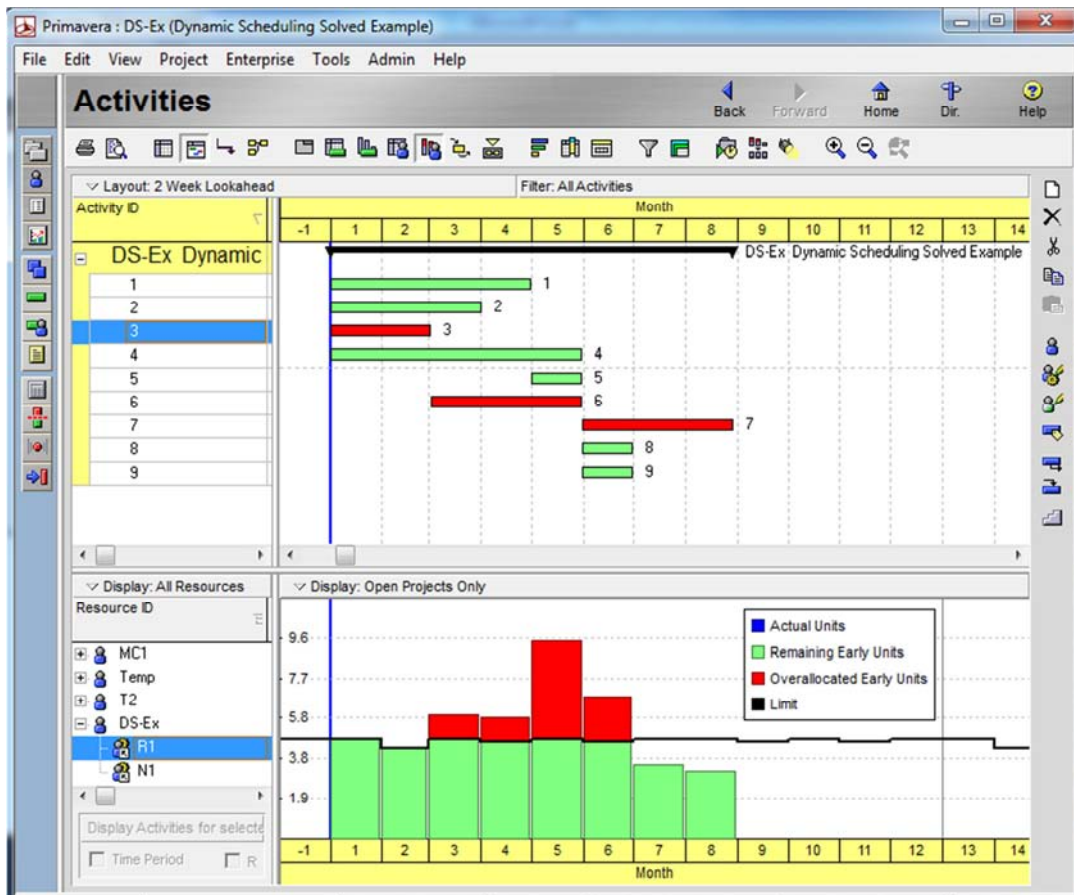
Figure 10.5: Example 10.1 – Schedule & R1 histogram in Primavera P6 before sending to dynamic scheduler for optimization
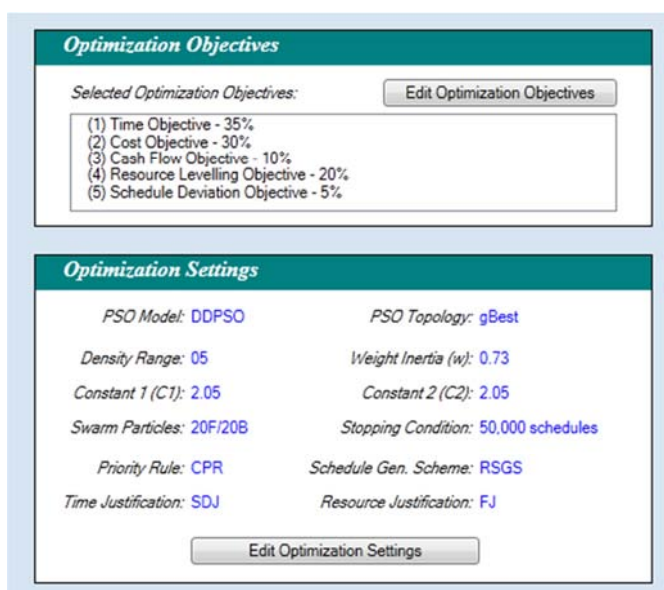
Figure 10.6: Example 10.1 – Screen shot from Dynamic Scheduler showing the definition of optimization objectives, weightages & settings

Figures 10.7 to 10.10 show the optimization outputs in *Dynamic Scheduler* for the baseline schedule. Baseline optimization results were matching to the results solved deterministically as shown in figure 10.2.
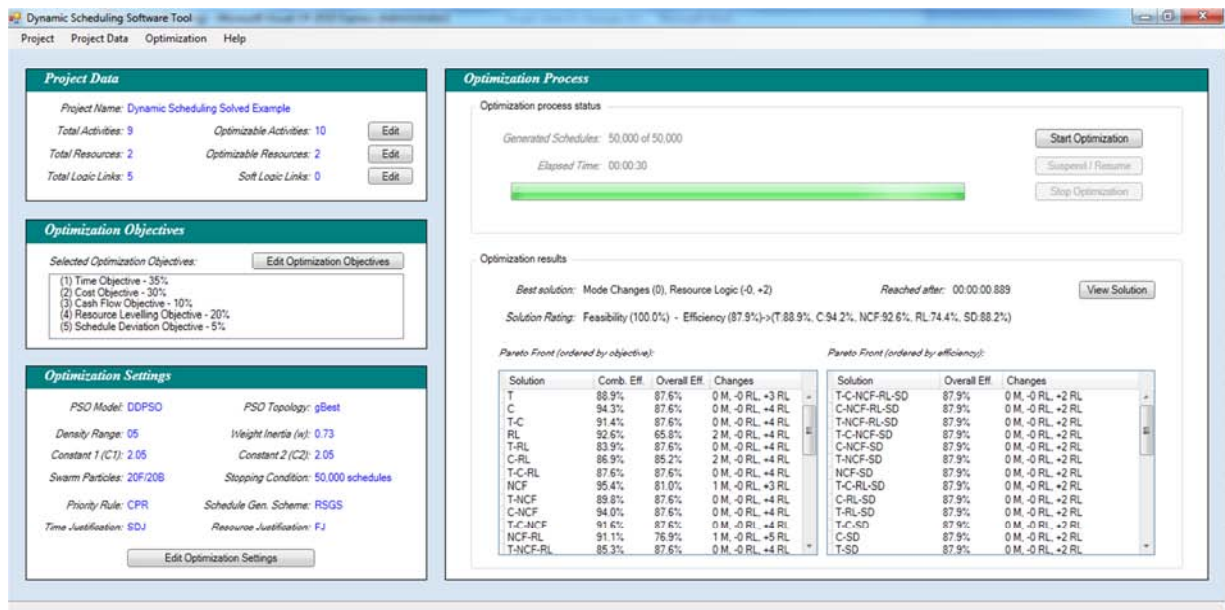
Figure 10.7: Example 10.1 – Dynamic Scheduler main interface after the baseline optimization cycle
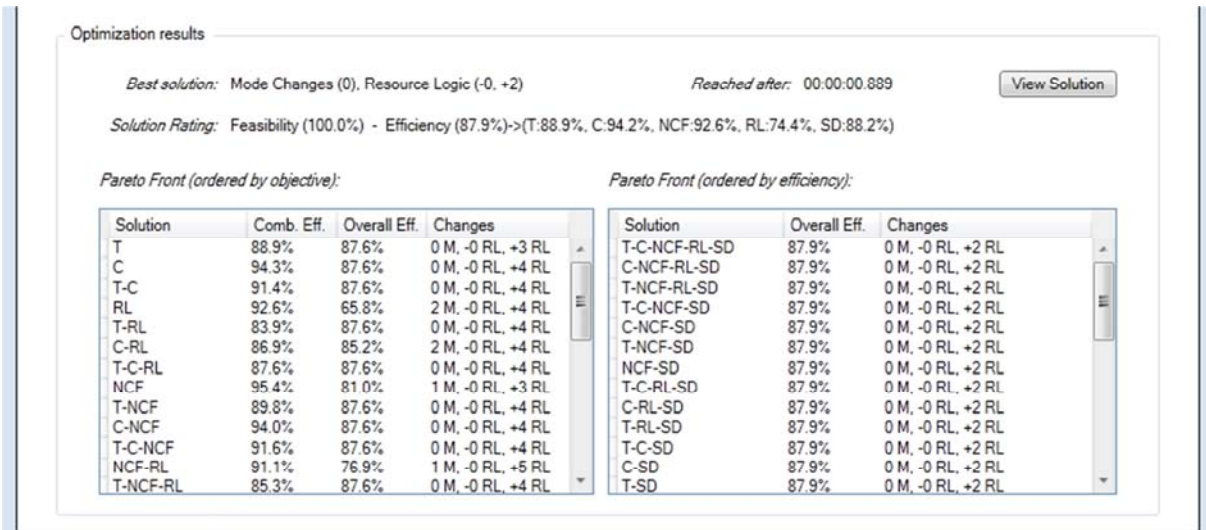
Figure 10.8: Example 10.1 – Baseline optimization results: Best solution and Pareto Front ordered by objectives & overall efficiency

Figures 10.9 & 10.10 show few screen shots from the *Dynamic Scheduler* where the main Pareto Front's solutions were viewed (note: durations in some forms are shown in days, where each month was assumed in this project as 25 working days); while figure 10.11shows the optimized alternative solutions after being exported back to *Primavera P6*.
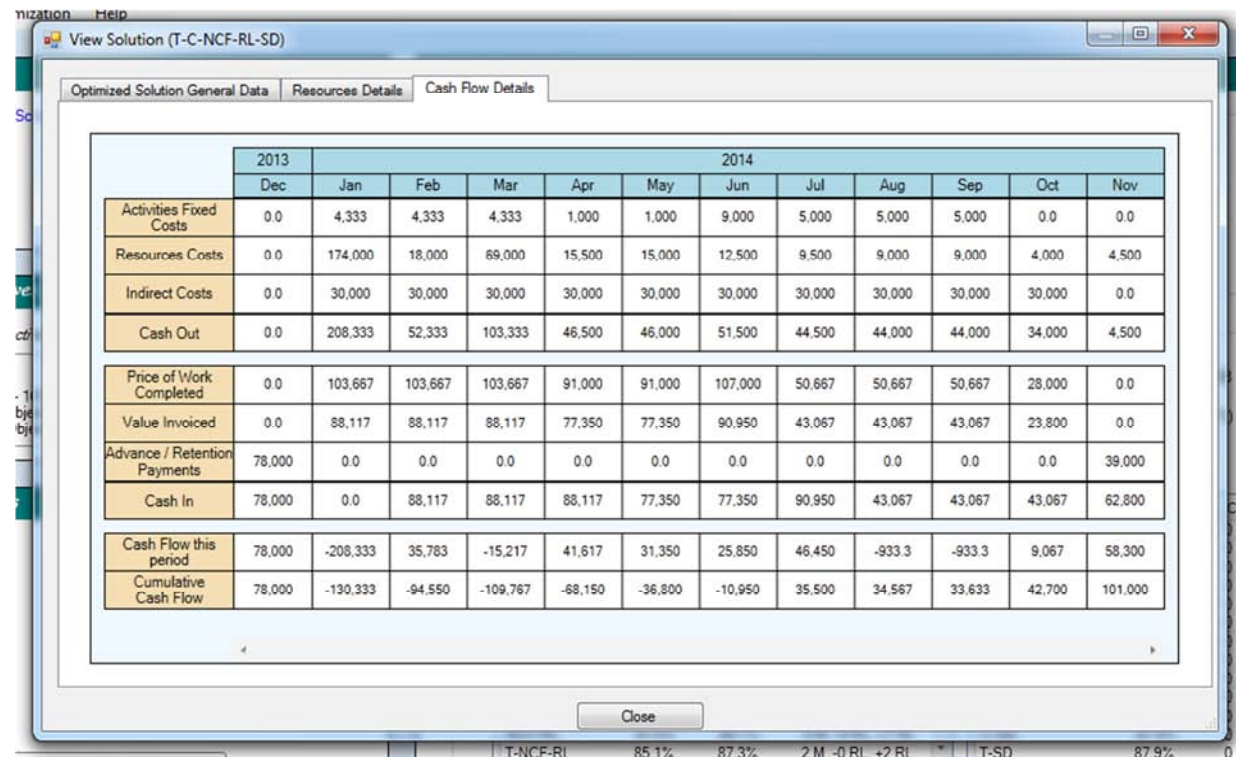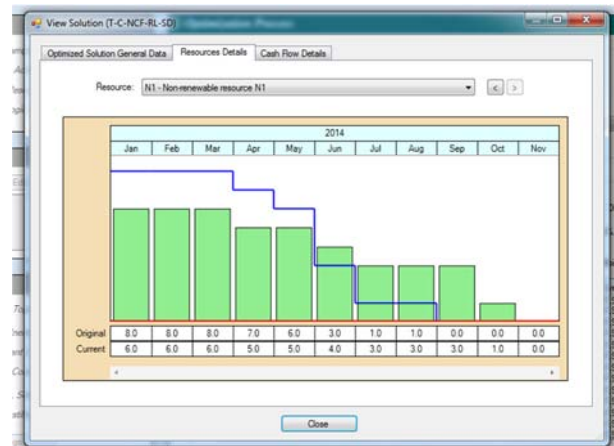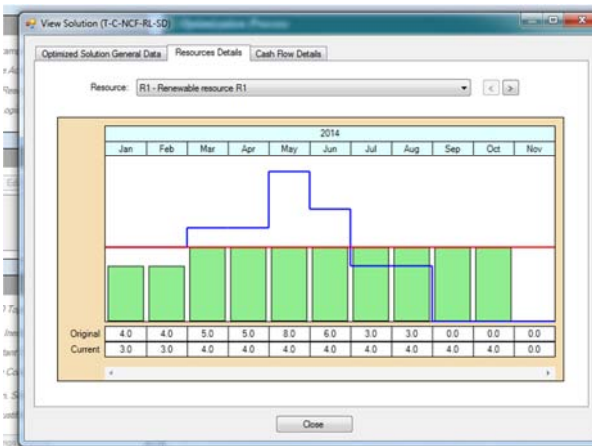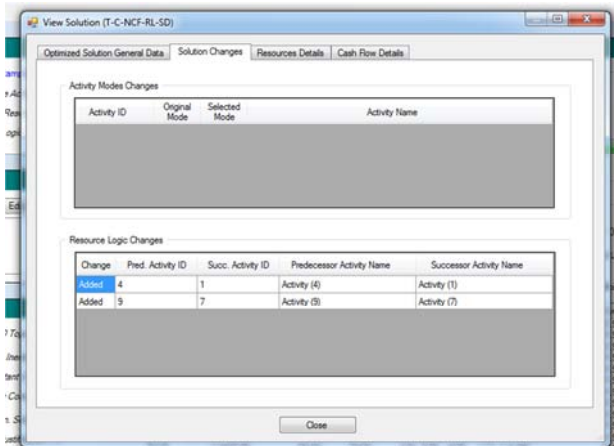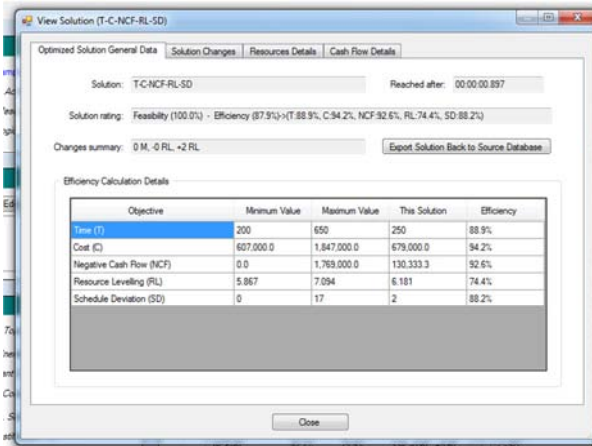
Figure 10.9: Example 10.1 – Baseline optimization results: Details of best solution
(T-C-NCF-RL-SD)
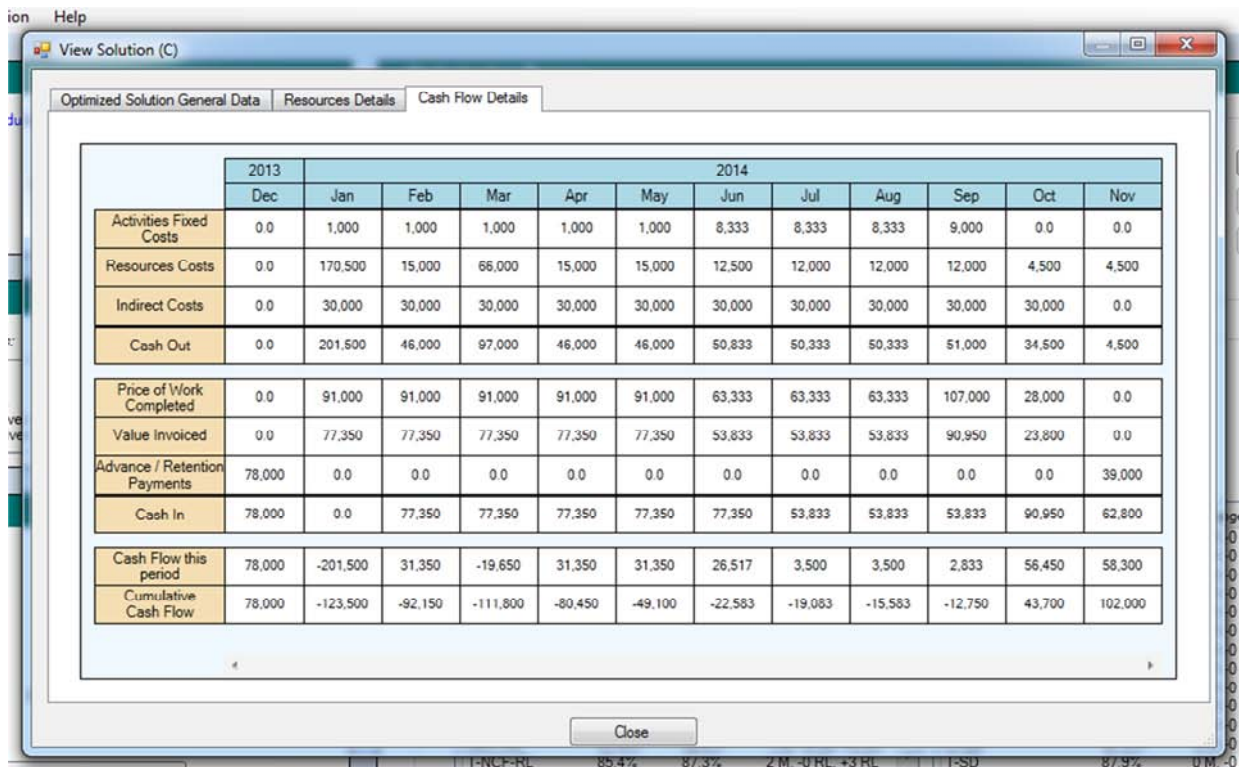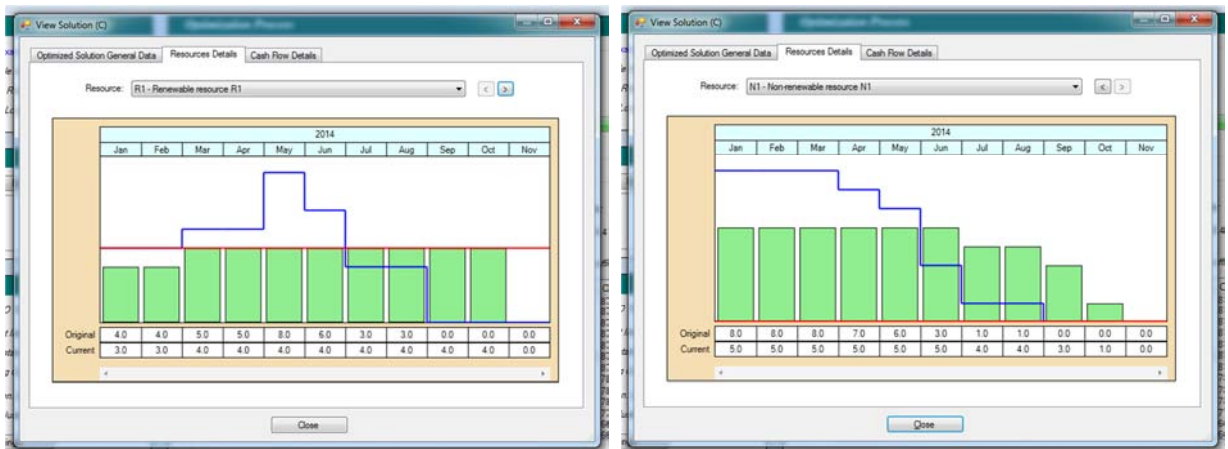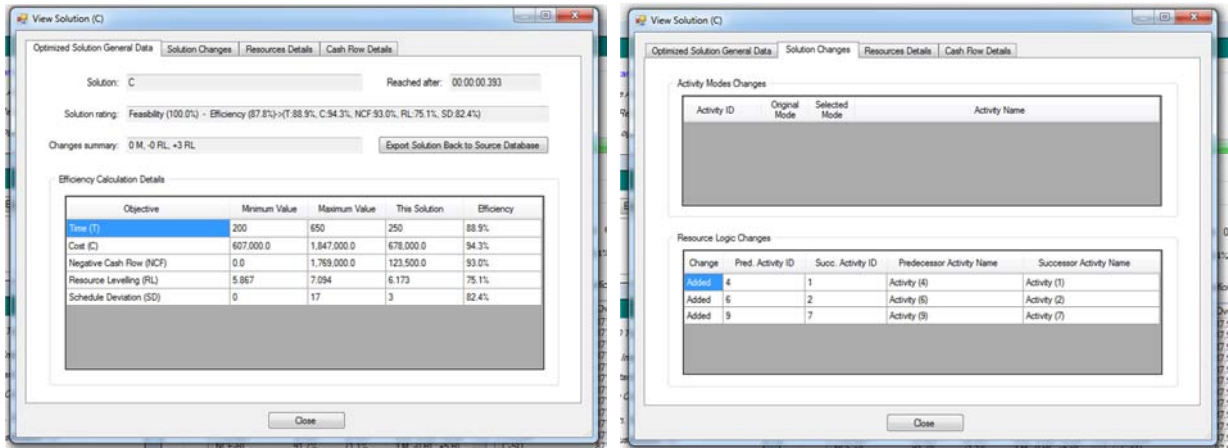
Figure 10.10: Example 10.1 – Baseline optimization results: Details of another Pareto Front solution *(C)*
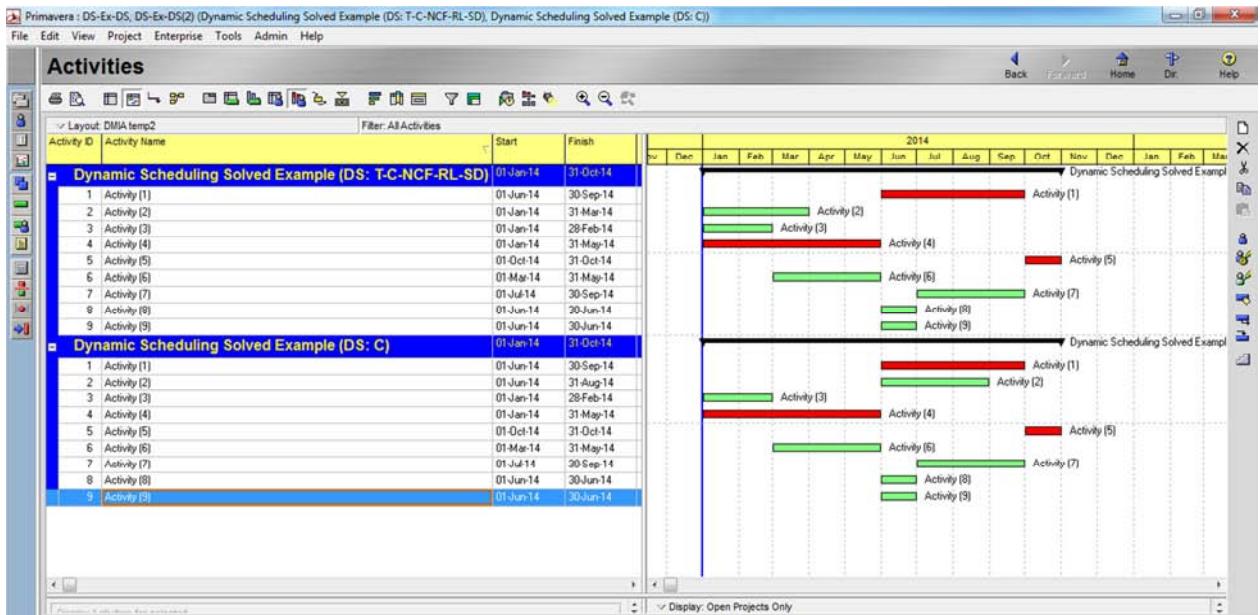
Figure 10.11: Example 10.1 – Exported baseline optimized alternative solutions

And finally, figures 10.12 to 10.15 show the optimization outputs for the progress update in *Dynamic Scheduler* and after being exported back to *Primavera P6*. Progress update optimization results were also matching to the results solved deterministically as shown in figure 10.4, which confirms the full functionality of the model, the optimization algorithm and the software tool from data import stage to optimized solutions export stage.

Optimization results

Best solution: Mode Changes (1), Resource Logic (-3, +3)   Reached after: 00:00:01.312   [View Solution]

Solution Rating: Feasibility (100.0%) - Efficiency (94.4%)->(T:100.0%, C:97.2%, NCF:90.4%, RL:89.7%, SD:65.0%)

Pareto Front (ordered by objective):

Solution	Comb. Eff.	Overall Eff.	Changes
SD	80.0%	91.8%	0 M, -2 RL, +2 RL
T-SD	95.6%	94.1%	1 M, -3 RL, +3 RL
C-SD	92.6%	94.4%	1 M, -3 RL, +3 RL
T-C-SD	96.3%	94.4%	1 M, -3 RL, +3 RL
RL-SD	90.2%	86.0%	2 M, -2 RL, +2 RL
T-RL-SD	93.6%	94.1%	1 M, -3 RL, +3 RL
C-RL-SD	91.8%	91.8%	0 M, -2 RL, +2 RL
T-C-RL-SD	94.8%	94.4%	1 M, -3 RL, +3 RL
NCF-SD	86.9%	91.8%	0 M, -2 RL, +2 RL
T-NCF-SD	94.6%	94.1%	1 M, -3 RL, +3 RL
C-NCF-SD	92.1%	94.4%	1 M, -3 RL, +3 RL
T-C-NCF-SD	95.6%	94.4%	1 M, -3 RL, +3 RL
NCF-RL-SD	90.6%	86.0%	2 M, -2 RL, +2 RL

Pareto Front (ordered by efficiency):

Solution	Overall Eff.	Changes
T-C-NCF-RL-SD	94.4%	1 M, -3 RL, +3 RL
T-C-NCF-SD	94.4%	1 M, -3 RL, +3 RL
C-NCF-SD	94.4%	1 M, -3 RL, +3 RL
T-C-RL-SD	94.4%	1 M, -3 RL, +3 RL
T-C-SD	94.4%	1 M, -3 RL, +3 RL
C-SD	94.4%	1 M, -3 RL, +3 RL
T-C-NCF-RL	94.4%	1 M, -3 RL, +3 RL
T-C-NCF	94.4%	1 M, -3 RL, +3 RL
T-C-RL	94.4%	1 M, -3 RL, +3 RL
T-C	94.4%	1 M, -3 RL, +3 RL
C	94.4%	1 M, -3 RL, +3 RL
T-NCF-RL-SD	94.1%	1 M, -3 RL, +3 RL
T-NCF-SD	94.1%	1 M, -3 RL, +3 RL

Figure 10.12: Example 10.1 – Progress update optimization results
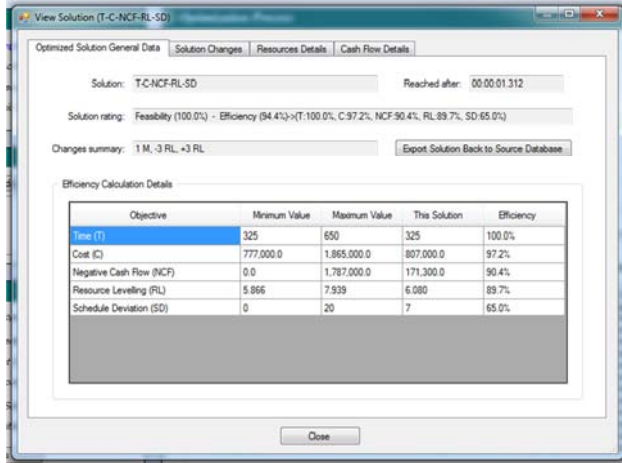
(a) Solution rating
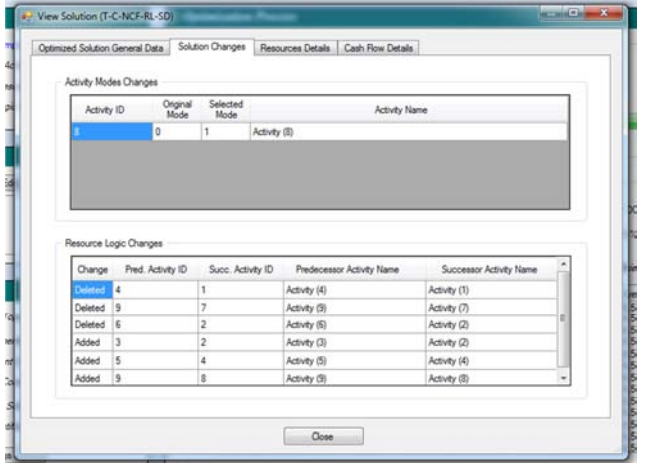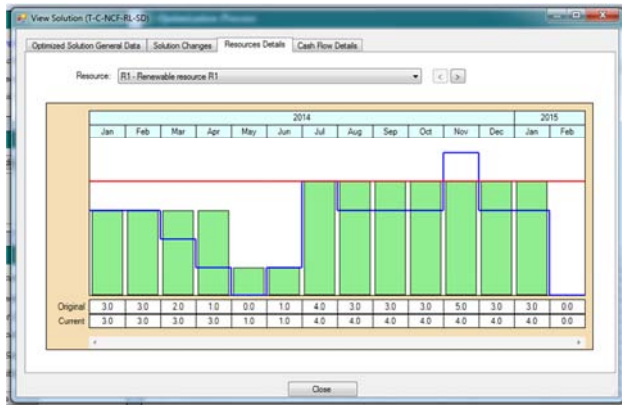
(b) Solution changes

(c) Resource R1 histogram
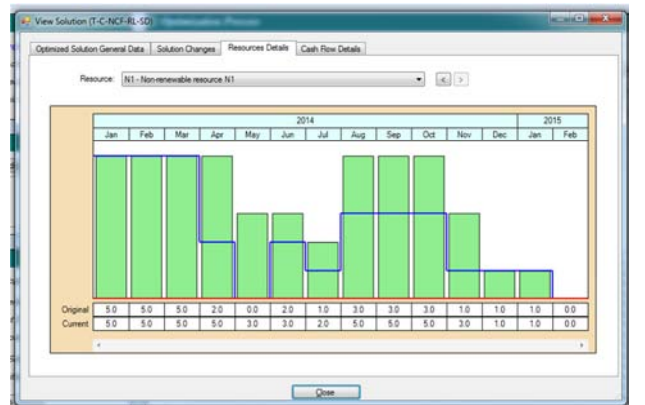
(d) Resource N1 histogram
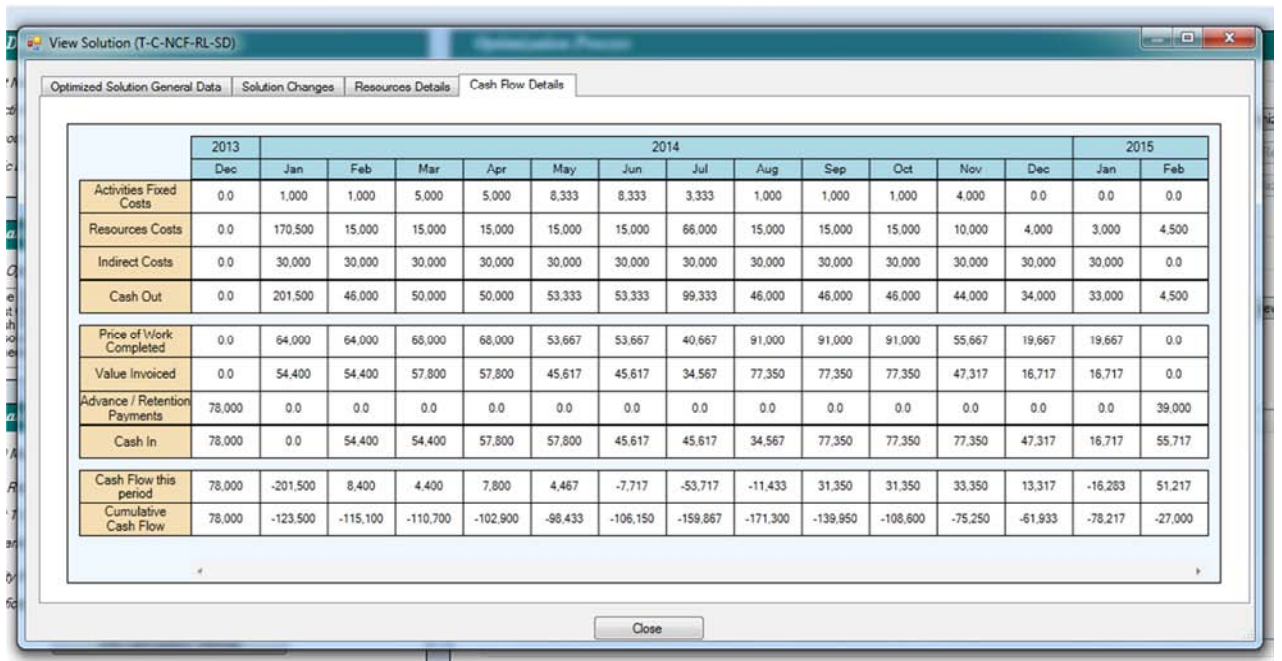
(e) Cash flow

Figure 10.13: Example 10.1 – Progress Update optimization results: Details of another Pareto Front solution *(T-C-RLI-NCF-SD)*
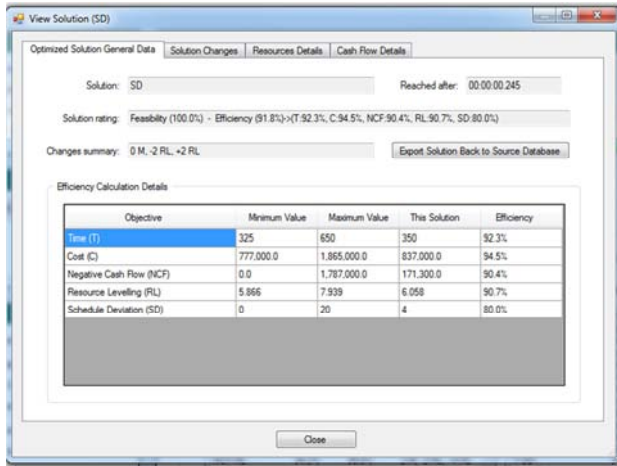
(a) Solution rating
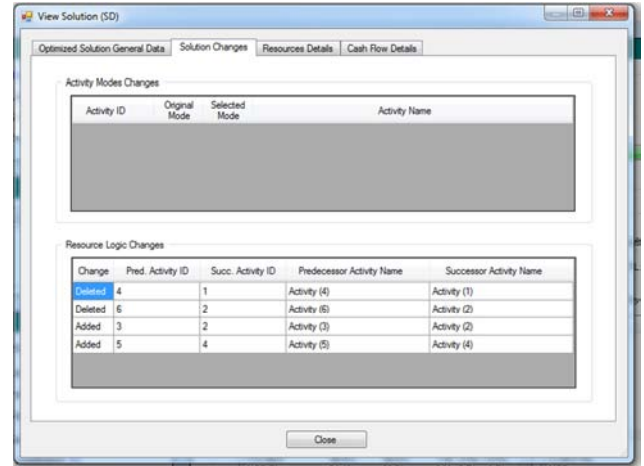
(b) Solution changes
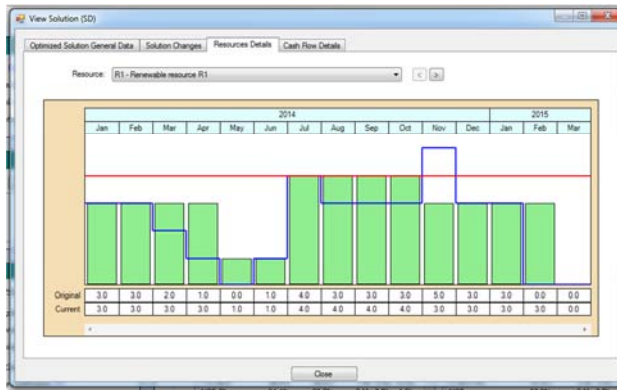
(c) Resource R1 histogram
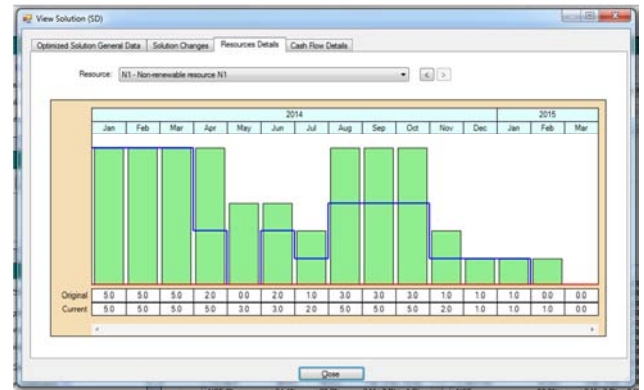
(d) Resource N1 histogram
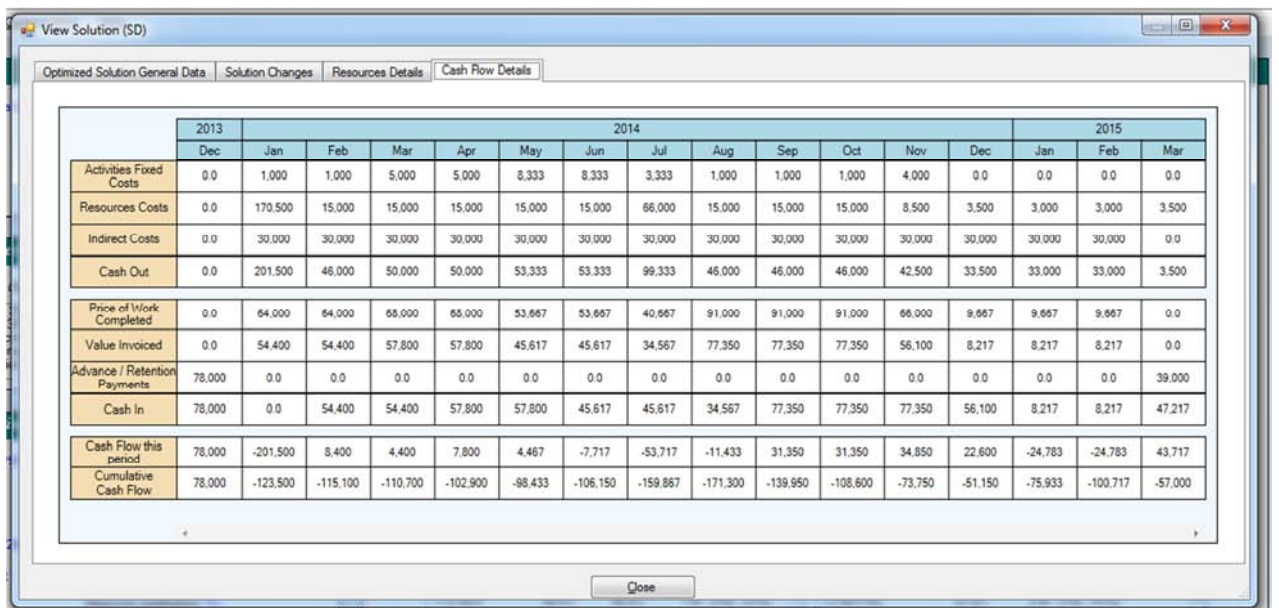
(e) Cash flow

Figure 10.14: Example 10.1 – Progress Update optimization results: Details of another Pareto Front solution *(SD)*
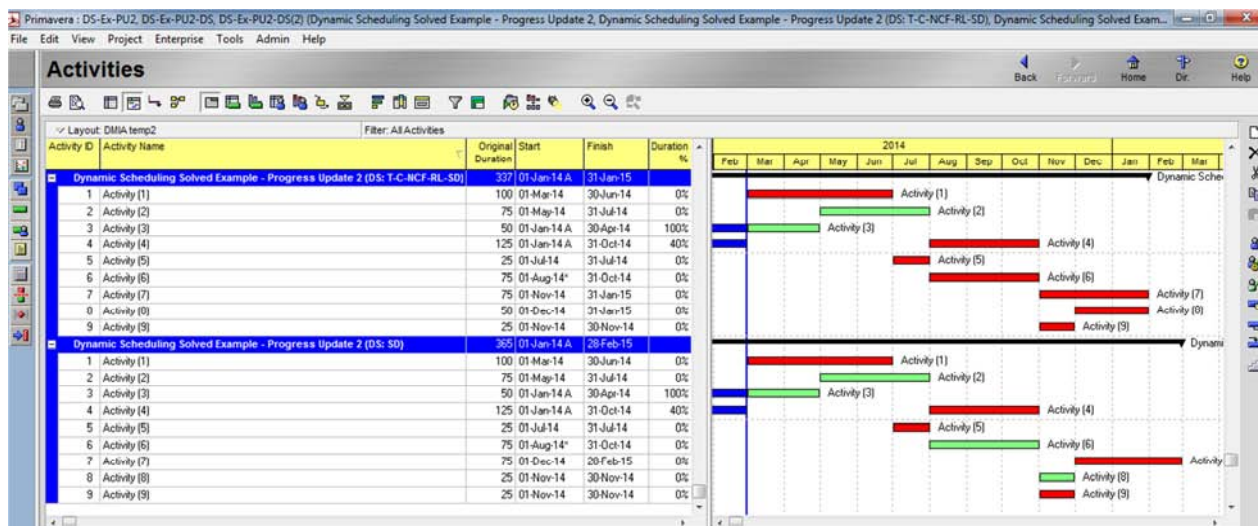
Figure 10.15: Example 10.1 – Exported optimized alternative solutions for 2nd progress update

10.2. Dynamic verification using case study: CCC/TAV JV Oman

For the purpose of verifying the main functionalities of the proposed dynamic scheduling model and the developed software tool, a simple solved example was considered in the previous section. Although verification results were satisfactory, this does not confirm the scalability of the model & the software tool. Accordingly, a large scale construction entity was considered as a case study in this section to confirm the scalability of the proposed solution, and to support in confirming its practicality as well by presenting the case study's results to field experts for solution validation (as detailed in the next chapter).

The case study entity is CCC/TAV JV, a joint venture between two reputable international contractors: Consolidated Contractors Company (CCC), a major international contractor, and TAV construction, one of the largest aviation construction companies. The two companies entered a JV in Oman to execute contracts within the Development of Muscat International Airport (DMIA) project. The works awarded to CCC/TAV JV (or will be referred to as CTJ through the rest of the chapter) included the construction of a new airfield (4km runway, 23 taxiways & 10 aprons), the refurbishment of an existing airfield (runway & 8 taxiways), the construction of about 60km of roads (landside & airside), the construction of the whole new airport's utilities (potable water, firefighting, sewerage, storm water, chilled water, fuel system, high/medium voltage networks, and LV/IT), the construction of a fuel farm, 8 bridges, 43 buildings, and few other works as detailed in appendix D.

Appendix D also provides details of the schedule breakdown, resources and project organization. But for the purpose of starting the case study analysis, it is important to mention that CTJ scope was divided internally into four projects, with four different teams starting from project manager level; while there were few support functions shared between the four projects, such as Planning, Engineering, Document Control …etc.

Each of these four projects was having its own resources; and accordingly, the whole CTJ entity was used as a case study resembling a complete enterprise, where inter-project resource allocations can be considered during optimization.

The DMIA project is still on-going; and accordingly, all information (resource levels, costs …etc.) included in this research were displayed in percentages. For example, for resource levels, the resource constraints (or maximum level) were represented by 100%, and any other level within resource histograms were displayed in percentage of these constraints levels. This allowed the validation participants to properly visualize the quality of optimized solutions in comparison with original schedules without the need for disclosing actual values of project information.

10.2.1. DS case study overview

The application of the new DS system on DMIA project involved three main stages corresponding to three schedule quality gates:

1. DS project creation, definition of additional project data and optimization inputs; and then performing the baseline schedule optimization and selecting an optimized alternative.

2. Using the selected optimum baseline for progress updating using available historical records for progress, variation orders, and delay events. Then optimization of these updated schedules for the purpose of creating construction look-ahead schedules.

3. Selecting one of the progress updates with a major delay event in order to check the functionality for preparing an optimized what-if schedule mitigating this delay event(s).

Taking into consideration that the last schedule quality gate, *revised schedule optimization*, was not considered because it is almost the same as the baseline schedule optimization.

10.2.2. DS Strategy & optimization objectives

As explained in Chapters 4 &5, the dynamic scheduling strategy depends mainly on the project conditions and requirements. For the DMIA project, the main targets for the optimization process were *resources levelling*, and *minimization of project's direct costs*. In addition, *minimize schedule deviation* and *minimizing total float consumption* were added with small weightages to the optimization objectives to avoid the addition of unnecessary resource logic which might be added for resource levelling fine tuning; thus optimum solutions are achieved with the best possible resource levelling with minimum additional logic.

During progress updates, *minimizing schedule changes* weight was increased to avoid large schedule disruption. Finally, *minimizing time* was not included to objectives because the project works was already time constrained with 9 contractual milestones.

10.2.3. Optimizable resources

The project schedule contained hundreds of resources, between labour crews, equipment crews, material supplies, and commodities (or output products). Not all resources were necessarily required to be optimized; however, the following resources were marked for optimization throughout the case study testing:

- Constrained resources due to resources availability: Concrete paving crews, piling crews, stone columns installation crews, power cabling crews, in addition to several mechanical & electrical equipment installation crews.

- Constrained resources due to plant productivity constraints: Concrete (for planned concrete plants' productivity), asphalt (for asphalt plant's productivity), and rock fill (for available crushers' productivity). Any requirements above the productivity of available plants were considered with extra cost for outsourcing.

- Resources to be levelled to minimize resources costs: Aggregate paving crews, asphalt paving crews, excavation crews, backfilling crews, and piping crews.

10.2.4. Baseline schedule optimization

According to the project requirements, the baseline optimization process was performed using the following project parameters:

Objectives: Minimize Cost [C] (weight=60%), Resource Levelling [RLI] (35%), Minimize Schedule Deviation [SD] (2%) & Min. Total Float Consumption [TFC] (3%)

Constrained Activities: 9 milestones

Constrained Resources: 15 resources

Optimizable Activities: All (7604 activities)

Optimizable Resources: 23 resources (15 constrained & 8 to be levelled)

It is clear from the optimized efficiency time chart shown in figure 10.16 that the optimization algorithm almost reached efficiency saturation after 5 hours of analysis. It is also important to notice that the best solution achieved within the first hour was having a good efficiency in comparison to the best solution

Figure 10.16: Case Study – Baseline optimization – Optimized efficiency time chart

achieved after 5 hours; this can allow planners to trade between available analysis time & solutions quality.

Solution	Efficiency				
	C	RLI	SD	TFC	Overall
(Original)	54.37%	44.96%	100.00%	100.00%	53.36%
C-RLI-SD-TFC	56.22%	45.45%	96.25%	91.86%	54.32%
SD-TFC	54.98%	45.08%	98.86%	96.24%	53.63%

Table 10.4: Case Study – Baseline optimization – Detailed efficiencies for 2 main Pareto Front's solutions

The original schedule was having an overall efficiency of 53.36%; while the best achieved solution was the C-RLI-SD-TFC, with an overall efficiency of 54.32%. The Pareto Front consisted of 15 solutions, corresponding to all possible combinations of the optimization objectives (C, RLI, SD & TFC). The most important solutions to discuss are the SD-TFC & the C-RLI-SD-

TFC. The SD-TFC solution had 43 schedule changes (42 new & 1 deleted resources logic); where these logic changes are the minimum changes needed to achieve resources constraints. While the C-RLI-SD-TFC solution had 141 schedule changes; which improved both the efficiency of both *Cost (C)* and *Resource Levelling Index (RLI)*.

It is worth mentioning that improving the solutions' efficiencies with respect to C & RLI comes with reduction in efficiencies of SD & TFC; which explains the need to have SD & TFC with low weights in order to get high quality solutions with minimal schedule changes.

Resource	Constrained	Peak Level		RLI	
		Original Schedule	Best Solution	Original Schedule	Best Solution
Concrete Paving Crews	✔	149.5%	99.7%	51.2%	50.4%
Sub-Base Paving Crews	✘	100.0%	99.0%	56.0%	55.9%
Base Course Paving Crews	✘	100.0%	92.6%	55.7%	55.5%
Asphalt Paving Crews	✘	100.0%	79.8%	61.6%	60.0%
Excavation Crews for Embankments	✘	100.0%	91.5%	46.2%	43.3%
Trenches Excavation Crews	✘	100.0%	82.3%	49.7%	48.9%
Rock Filling Crews	✘	100.0%	89.6%	55.2%	54.8%
Soil Filling Crews	✘	100.0%	85.2%	56.2%	54.9%
Trenches Backfilling Crews	✘	100.0%	100.9%	50.9%	50.2%
Stone Columns Crews (S/C)	✔	117.3%	98.6%	56.6%	55.6%
Piling Crews (S/C)	✔	101.1%	97.3%	55.4%	53.7%
HV Cabling Crews (S/C)	✔	155.7%	93.3%	72.3%	66.1%
MV Cabling Crews (S/C)	✔	195.1%	99.4%	66.7%	59.3%
Chilled Water Piping Crews (S/C)	✔	52.3%	50.4%	62.7%	62.7%
HV Transformers Installation Crews (S/C)	✔	82.4%	88.9%	76.0%	78.3%
MV Transformers Installation Crews (S/C)	✔	125.2%	96.1%	63.3%	59.9%
HV Switchgears Installation Crews (S/C)	✔	101.8%	98.0%	75.0%	75.0%
MV Switchgears Installation Crews (S/C)	✔	125.3%	69.8%	91.4%	80.5%
Pumps Installation Crews (S/C)	✔	105.5%	81.0%	57.6%	55.2%
Chillers Installation Crews (S/C)	✔	100.6%	48.5%	81.5%	67.7%
Rock filling Supply	✔	92.2%	82.6%	55.1%	54.6%
Concrete Supply	✔	80.0%	80.6%	50.6%	50.4%
Asphalt Supply	✔	123.0%	97.8%	61.7%	59.9%

Table 10.5: Case Study – Baseline optimization – RLIs for best solution vs. original schedule *(Note: Better resource levelling produces lower RLI value)*

As shown in the above table, all resource constraints were achieved and the RLI was improved (or at least remained the same) for all optimizable resources. Figures 10.17 to 10.22 show the resources histograms for the best solution in comparison to the original schedule.
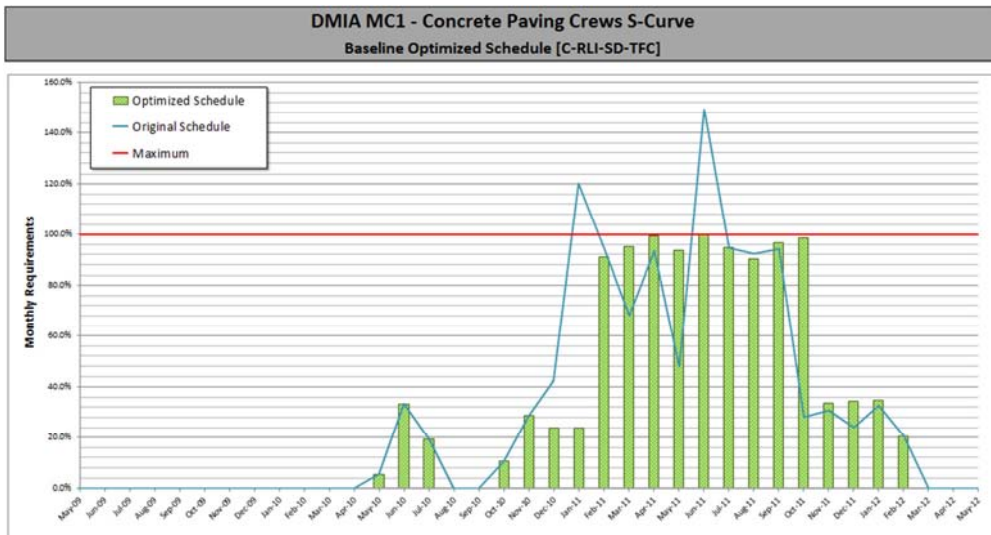
Figure 10.17: Case Study – Baseline optimization – Concrete paving crews' histogram for best solution
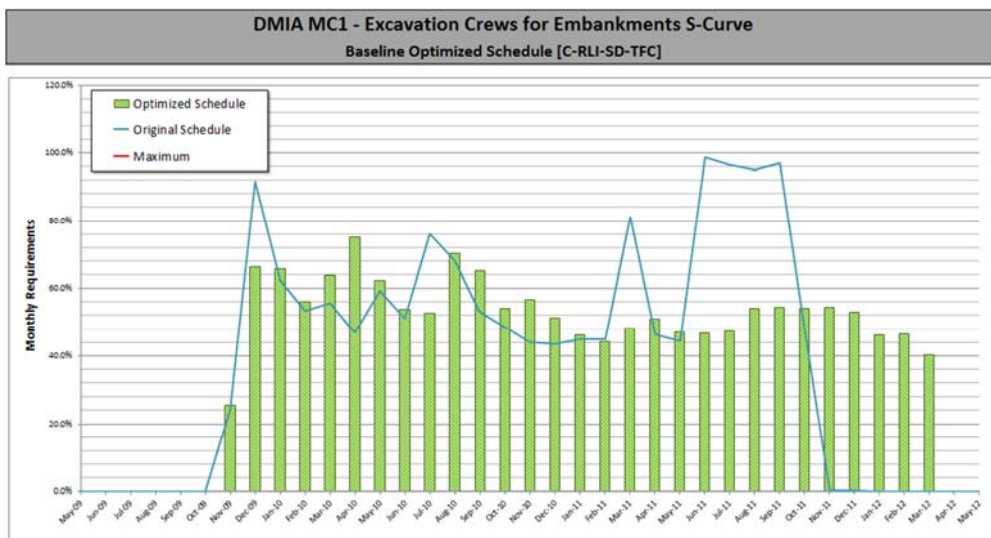
Figure 10.18: Case Study – Baseline optimization – Excavation crews' histogram for best solution
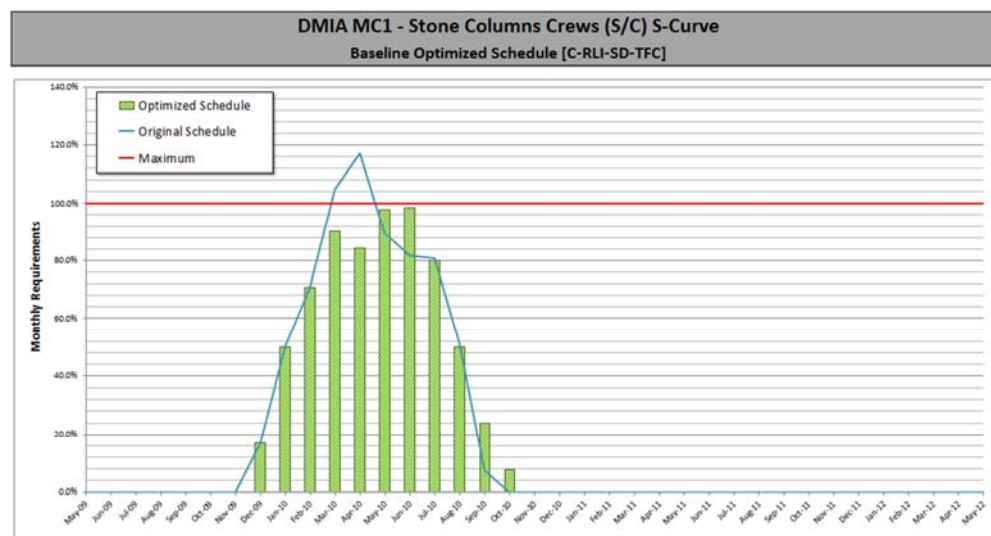
Figure 10.19: Case Study – Baseline optimization – Stone column crews' histogram for best solution
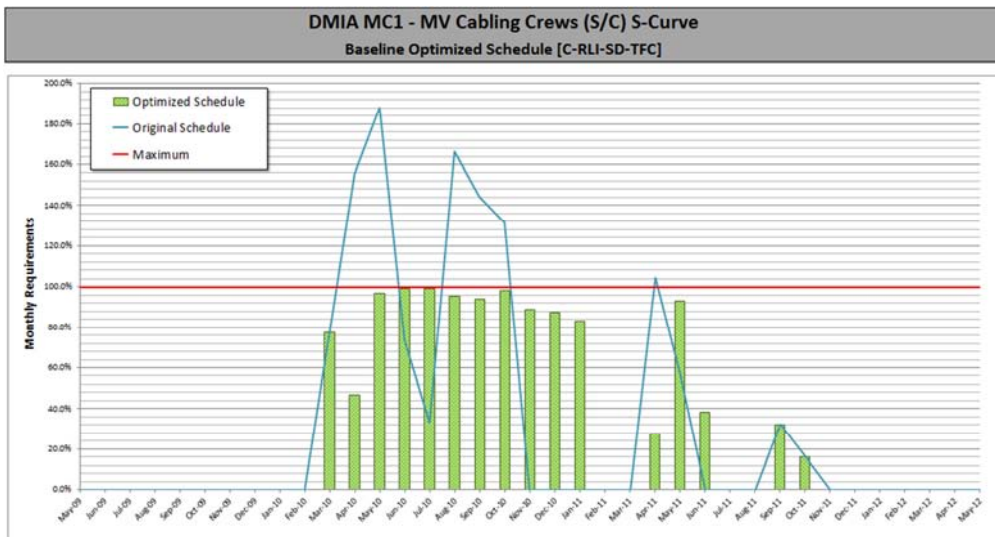
Figure 10.20: Case Study – Baseline optimization – Concrete paving crews' histogram for best solution
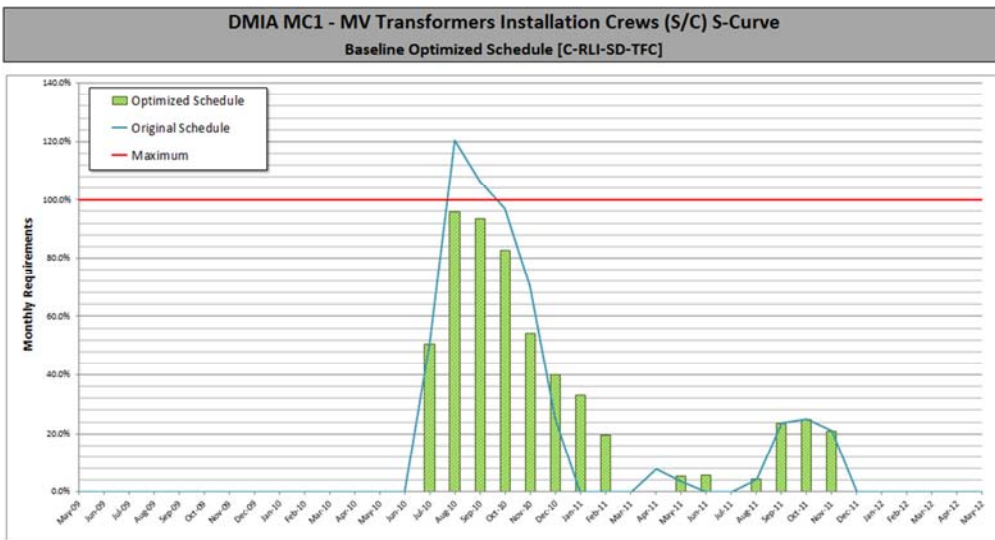
Figure 10.21: Case Study – Baseline optimization – MV transformers installation crews' histogram for best solution
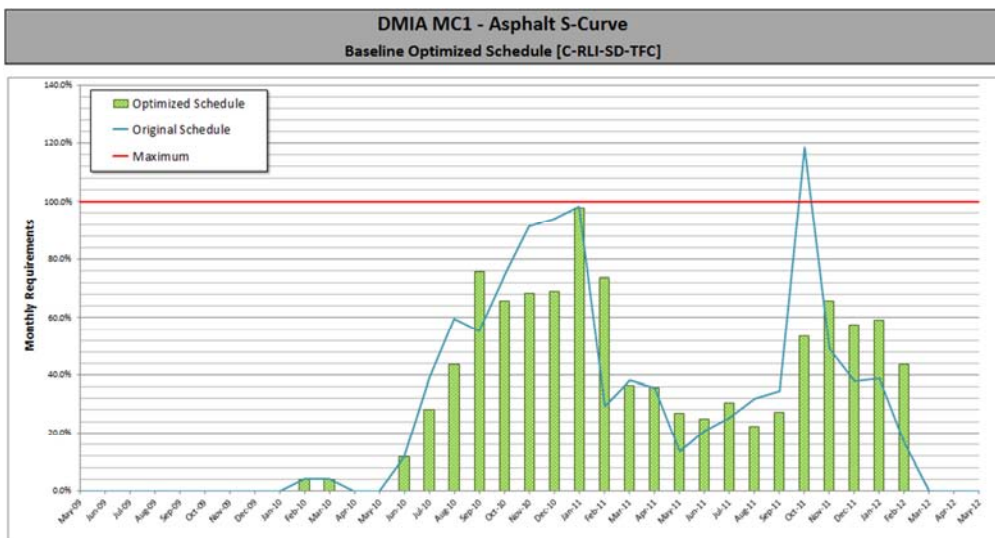
Figure 10.22: Case Study – Baseline optimization – Asphalt crews' histogram for best solution

10.2.5. Progress updates optimization overview

The best achieved solution in the baseline optimization process was selected for progress updates. Generally, progress updates were performed in DMIA every 2 weeks. The purpose of the case study was to provide a proof of concept for the DS application during progress updates; so it was not necessarily required to apply all progress updates historical data; accordingly, only two progress updates were selected for the testing process. These two updates were carefully selected, with selection criteria to include few major disruption events to enable proper visualization of the benefits of applying the proposed DS solution.

During progress updates, large schedule changes were not acceptable; in addition, it was agreed with the project Engineer to apply schedule changes only within a period of 2-3 months following the cut-off date, in order to allow the coordination of construction look-ahead schedules. Accordingly, *Optimizable Activities* were selected corresponding to 3 months look-ahead, and the weights of SD & TFC objectives were increased to 20% & 5% respectively.

Finally, to make the updated schedules suitable for construction, resources were constrained with their current levels on site and with the expected mobilization rates.

10.2.6. Progress update 1 (31-Oct-2009)

The first progress update was selected for the progress period ending on 31-Oct-2009. According to initial soil investigations results, the Engineer decided that the soil under all roads of the Northern Development Area (NDA) require surcharging, and sent a variation order accordingly. This process involves placing 1-3 meters of fill above road embankments for few months until the designed settlement is achieved.

During this update, there were no major progress delays, but the impact of this VO was large on the general resources distribution. The VO affected the distribution of several resources, but we will focus here on the main affected
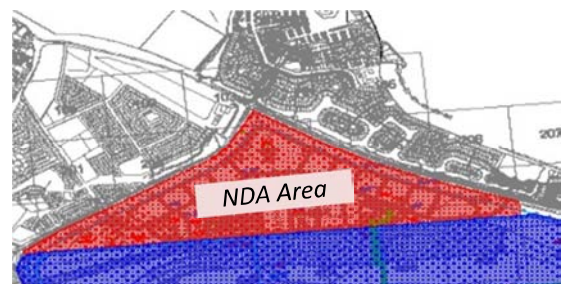
resources (i.e.: earthworks crews), in addition to Stone Columns works which was one of the major work types which commenced.

Since the data to be optimized was relatively small (activities within the 3 months period following the schedule's cut-off date), the optimization process took less than 10 minutes. The resulting schedule met the main optimization objective by re-arranging the resources requirements for 3 months period to fall within the available resources levels as per the forecast mobilization rates.

Solution	Efficiency				
	C	RLI	SD	TFC	Overall
(Original Updated Schedule)	51.70%	45.88%	100.00%	100.00%	52.08%
C-RLI-SD-TFC	52.99%	45.07%	99.92%	95.21%	52.43%

Table 10.6: Case Study – Progress update 1 optimization – Detailed efficiencies

After progress update until 31-Oct-2009, it can be noticed that disruption events caused the schedule's overall efficiency to drop from 54.32% (as obtained from the baseline optimization process) to 52.08%. The optimization process increased the schedule's efficiency up to 52.43%; however, the efficiency would have increased further if the optimization cycle was performed for all activities and not only for the activities within the following 3 months.

Figures 10.23 to 10.25 show the resources histograms for the best solution in comparison to the original updated schedule.
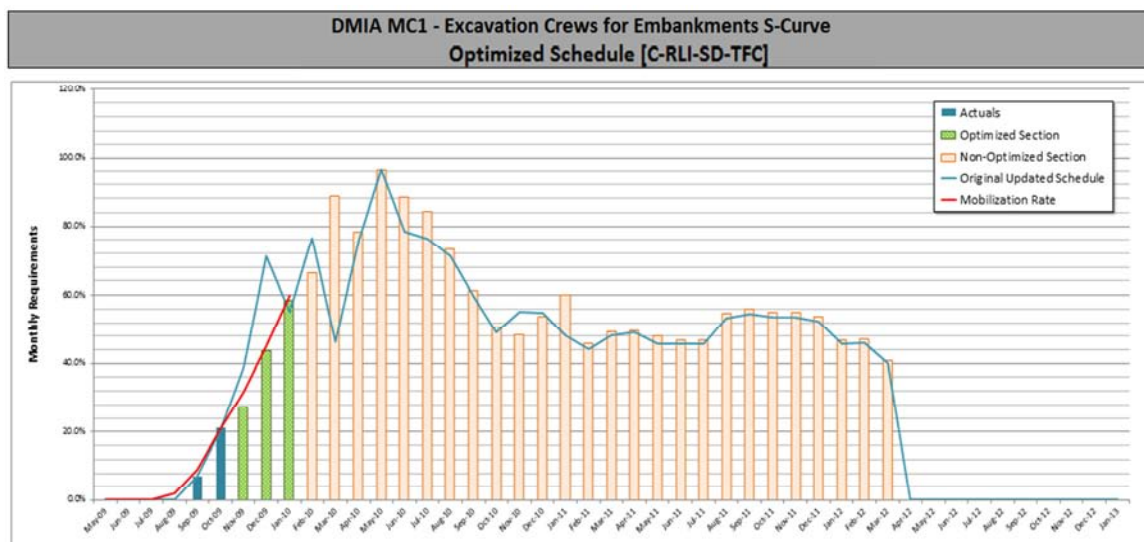
Figure 10.23: Case Study – Progress update 1 optimization –
Excavation crews' histogram for best solution
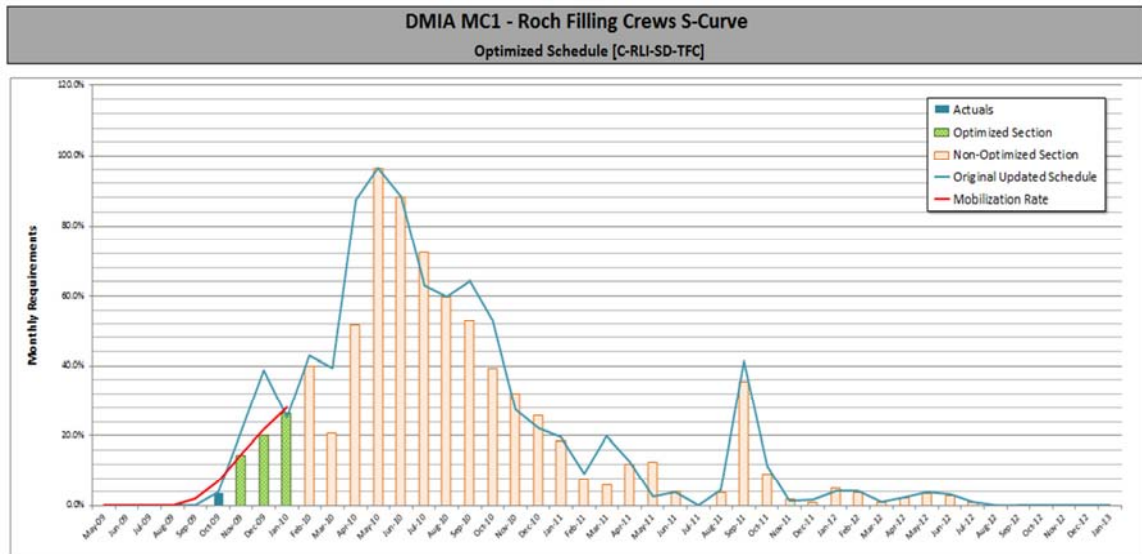
Figure 10.24: Case Study – Progress update 1 optimization – Rock filling crews' histogram for best solution
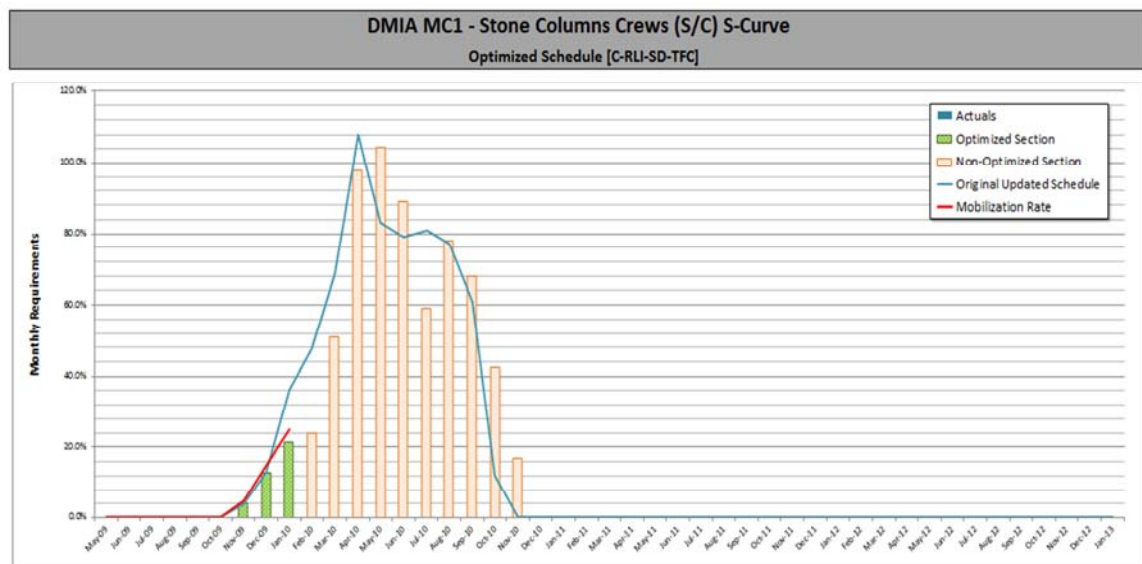
Figure 10.25: Case Study – Progress update 1 optimization – Stone columns crews' histogram for best solution

10.2.7. Progress update 2 (30-Apr-2010)

The second selected progress update was for the progress period ending on 30-Apr-2010. As of this cut-off date, more than 100 variation orders were received, including major changes to utility networks, additional surcharging to roads and buildings, modifications to stone columns ground improvement areas, changes in specifications …etc.

In addition, the mass of schedule disruption increased further due to the struggle in re-arranging the resources on site based on the very dynamically changing open fronts especially that within the month of April, major portion of MC1 works was suspended to be re-designed.

Another important point which must be noted is that the agreed schedule update method was *"Progress Override"*. This method can support proper schedule control for remaining works if the update process is done carefully with solving all out-of-sequence progress and re-arranging soft logic accordingly. But in DMIA-MC1 project, due to the mass of changes and out-of-sequence works every period, this method added huge burden on the project's planning team to maintain the schedule's integrity during each update.

As shown in the s-curves presented in figures 10.26 to 10.29, the mass of out-of-sequence works which occurred in this period (and in most progress periods of the project) caused almost all resources histograms to have large spikes after the data date, which required an optimization cycle to enable construction look-ahead schedule preparation within the resource limits available on site.

The optimization process took about 25 minutes, and the optimization algorithm succeeded to re-arrange schedule's resource requirements for 3 months period following the schedule's cut-off date to fall within the available resources levels as per the forecast mobilization rates. The overall solution efficiency of the best solution showed an increase of about 3% as detailed in the following table.

Solution	Efficiency				
	C	RLI	SD	TFC	Overall
(Original Updated Schedule)	47.53%	36.45%	100.00%	100.00%	46.27%
C-RLI-SD-TFC	51.24%	39.23%	98.95%	89.08%	49.12%

Table 10.7: Case Study – Progress update 2 optimization – Detailed efficiencies

It is worth mentioning that when the optimization process is set for look-ahead schedule, then resources requirements after the 3 months period are not optimized. If the full resource requirements are required to be optimized for one or more resources, then a what-if optimization cycle should be performed as explained in the section 10.2.8.
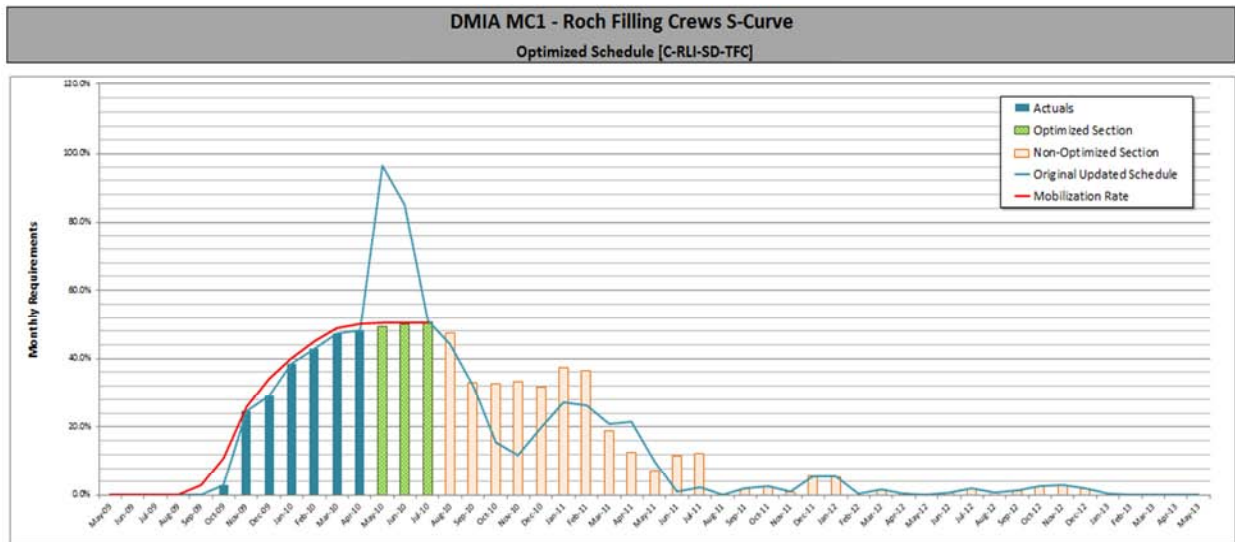
Figure 10.26: Case Study – Progress update 2 optimization – Rock filling crews' histogram for best solution
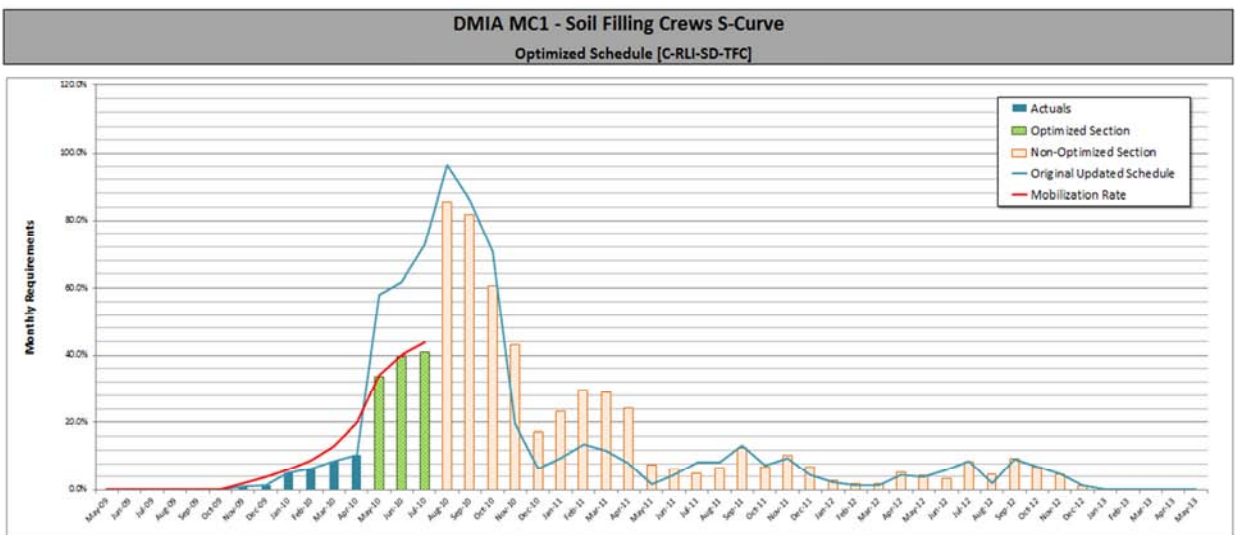
Figure 10.27: Case Study – Progress update 2 optimization – Soil filling crews' histogram for best solution
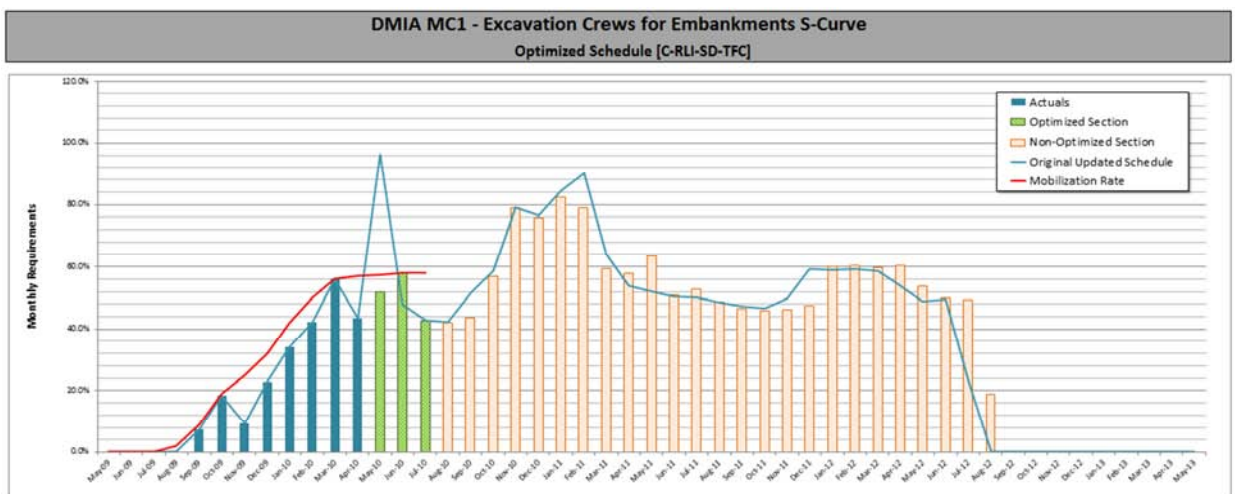
Figure 10.28: Case Study – Progress update 2 optimization – Excavation crews' histogram for best solution
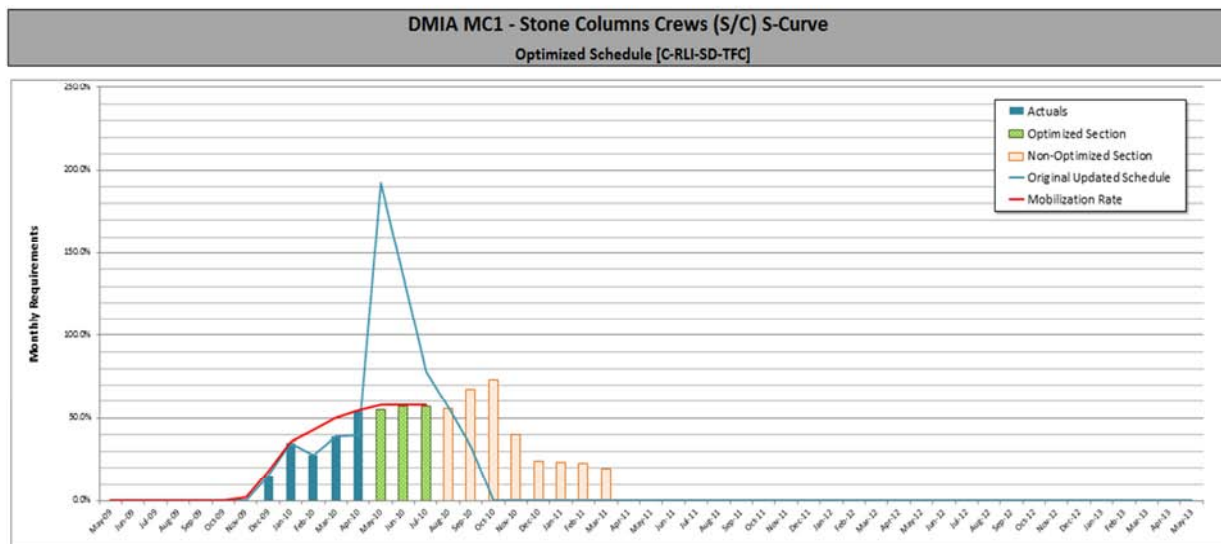
Figure 10.29: Case Study – Progress update 2 optimization – Stone column crews' histogram for best solution

10.2.8. What-if schedule optimization

The main purpose for a what-if schedule is the preparation of a schedule scenario representing partial/full schedule re-arrangement to include the impact of a forecasted issue(s) or mitigate the impact of an actual issue(s); and most probably submit schedule to concerned parties for discussion/approval.

In DMIA, several occasions required the preparation of a what-if schedule. For the purpose of this case study, we will take one incident with the same cut-off date as the previously presented progress update 2 (cut-off: 30-Apr-2010). During this update, and due to several cumulative minor delay events, the progress of Stone Columns activities was noticeably affected and started to drive the related contractual milestone. Accordingly, a what-if schedule was required to check the possibility of mitigating these delays by increasing the number of Stone Columns installation crews.

The target of the optimization process was to take the prepared progress update and apply an optimization cycle to advise the optimum resource level & the most suitable re-arrangement of stone column activities to return the contractual milestone to its original date or to mitigate as much as possible from the incurred delays.

The optimization process was performed with the following parameters:

Objectives: Minimize Resource Levelling [RLI] (weight = 60%), and Minimize Time [T] (40%)

Constrained Resources: 1 resource (stone column crews)

Optimizable Activities: 13 activities (stone column works)

Optimizable Resources: 1 resource (stone column crews)

Since the data to be optimized was very small, the optimization process took only few seconds. The resulting schedule reduced the delay in the contractual milestone by more than 4 months, with an increase of about 49% in the number of stone columns crews and 19 schedule changes (8 added & 11 deleted resource logic relations).
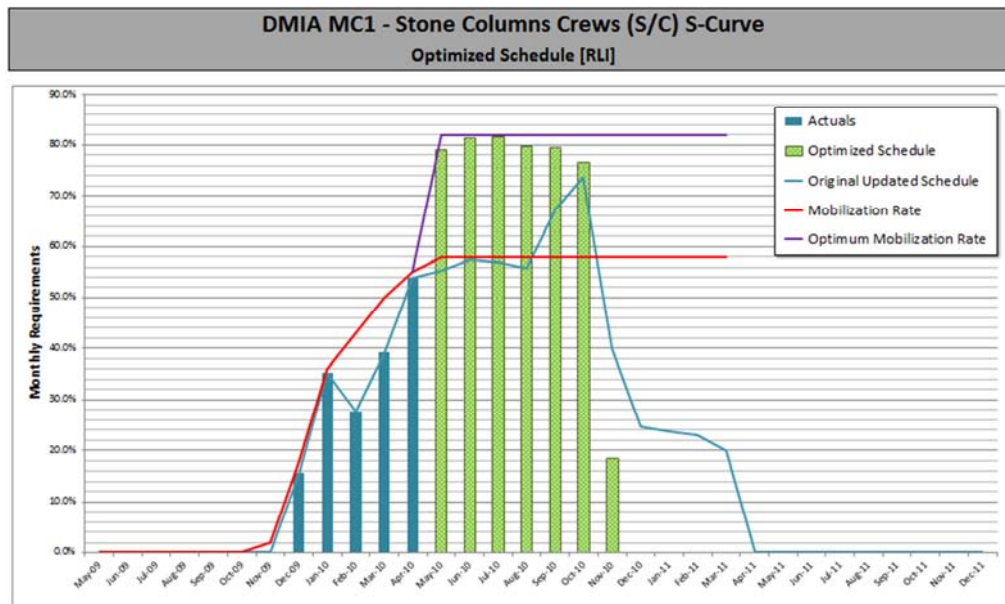
Figure 10.30: Case Study – What-if schedule optimization – Stone column crews' histogram for best solution

10.3. Summary of the dynamic verification process

This chapter verified the dynamic capabilities of the overall proposed DS solution (the DS mathematical model, the optimization algorithm, the *Dynamic Scheduler* software tool, and the overall system's framework). The verification results showed that the model successfully achieved the required dynamic functionality whether under the small solved example or under the complex case study.

It is also important to state that the results of this verification Chapter cannot be compared with a corresponding output from the planning software, because all current available planning software packages does not have the ability to re-arrange the schedule's soft logic, and accordingly cannot produce any optimized schedules. The only optimization capability of these packages is the resource levelling feature, which was proven to produce very poor outputs as detailed in Section 9.4.

Chapter 11: Model & Software Tool Validation

In Chapters 8 & 10, the proposed model and software tool functionalities were verified against several problem sets, solved examples, and construction project case study. The proposed solution was proven to be functional under different problem conditions and sizes. The last step of the research process was to validate the practicality of using this proposed solution in construction enterprises. This Chapter will go through the performed validation process from approach selection to data analysis.

11.1. Validation approach

Validation, as a term, implies that something is judged to be valid and is accordingly conducted by a person or body competent to judge *(Church 1983)*. The validation of a model can be achieved if it is accepted as reasonable for its intended purpose by people who are knowledgeable about the system under study, and is termed as face validity *(McGraw-Hill Encyclopaedia of Science and Technology, 2002)*. Furthermore, *Pidd (2003)* stated that the social and historical perspectives imply that a model is valid when it gains acceptance by the surrounding scientific and expert community.

Several approaches were presented in literature for the validation methodologies and where each can be adopted. However, *Miser (1993)* notes that there are no universal criteria for validation, and that any validity judgment depends on the situation in which the model is used and the phenomena being modelled.

In light of the above, the validation approach was necessarily pursued seeking project management field experts' judgement on the developed construction DS framework, software tool, and the overall DS solution. This was conducted by presenting the several aspects of the proposed solution and the test results to field experts, and collecting their feedback about the solution's validity and its implementation practicality.

Collecting experts' feedbacks was implemented using *Feedback Forms* containing the validation questions to achieve the objectives explained in next section. These forms included a presentation about the solution and the results, and a questionnaire form for experts to provide their feedback. Finally, the review forms were distributed by emails, and responses were collected and analysed as detailed in this Chapter. During responses

collection, several email correspondences and phone interviews were conducted in order to provide all necessary guidance to participants to understand the developed solution before they can provide their feedback.

11.2. Feedback review forms design

11.2.1. Proposed solution presentation

To introduce the topic, solution and results to field experts before asking their opinions, a presentation was prepared and included as the first part of the review form. The presentation included the following items:

a) A brief summary of the dynamic scheduling topic and the problem under study.

b) The proposed dynamic scheduling solution design.

c) A simplified example to explain how the system works.

d) The test results for the system application on the construction project used as a case study.

11.2.2. Questionnaire form

The second part of the feedback forms was a simple questionnaire to collect the field experts' opinions about the solution. The form's questions varied between quantitative close-ended question (in the form of *Likert [1993]* scale) and qualitative open-ended questions (to allow comments and suggestions), and were designed to achieve the following objectives (the form questions are included in Appendix F):

a) Acknowledging the necessity for a new DS system to improve the scheduling process of the construction industry.

b) Determine whether or not the proposed DS solution can fit easily within the current PM practices.

c) Investigate how efficient the developed model and the software tool achieved the objectives of the proposed solution.

d) Provide sufficient open-ended questions for the participants to comment and/or suggest improvements to both the DS framework and the developed software tool.

11.3. Forms distribution & responses analysis

11.3.1. Sampling

The purpose of this validation process was to get feedback from variety of project management backgrounds and experience levels about the proposed DS system; accordingly, convenience sampling *(Sekaran, 2003)* with relatively small size was sufficient to perform the validation if the required variety was achieved.

The review forms were distributed by emails to expert participants of the empirical survey (as detailed in Chapter 5); in addition to randomly selected field experts, which can allow generalisation beyond the original research sample *(Gill & Johnson, 2002)*.

11.3.2. Validation participants

Received responses were fairly distributed among several project management backgrounds and experience levels as shown in figure 11.1; with larger rate of participation within contractors and medium to senior experience level. This can be to the benefit of the analysis, since these categories specifically, are the prospect users/benefiters of any proposed DS system.
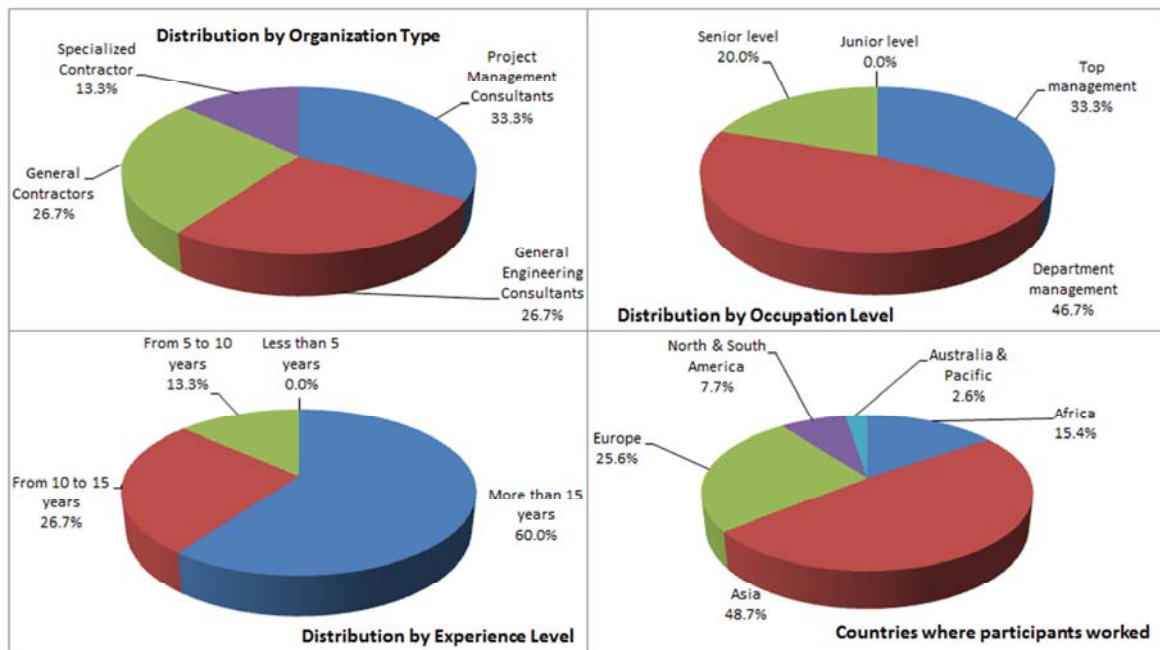
Figure 11.1: Validation participants' distribution

In addition, feedbacks were received from 20 participants, who have previously worked in more than 39 countries. More than 53% of participants did not attend the empirical survey performed, which indicates that results are less biased to favouring the developed solution, and accordingly gives more credibility to the validation results.

11.3.3. Responses analysis

The general outcome of the validation was very positive from most experts/practitioners. The summary of participations' quantitative ratings and feedback is illustrated in Tables 11.1 to 11.4, and discussed in this section; while improvement suggestions/comments are discussed in the following section.

General Information			
Q1	**Organization Category**	**No.**	**%**
1	Project Management Consultants	5	33.3%
2	General Engineering Consultants	4	26.7%
3	General Contractors	4	26.7%
4	Specialized Contractor	2	13.3%
	Total	**15**	**100.0%**
Q2	**Occupation Level**	**No.**	**%**
1	Top management	5	33.3%
2	Department management	7	46.7%
3	Senior level	3	20.0%
4	Junior level	0	0.0%
	Total	**15**	**100.0%**
Q3	**Project Management Experience**	**No.**	**%**
1	More than 15 years	9	60.0%
2	From 10 to 15 years	4	26.7%
3	From 5 to 10 years	2	13.3%
4	Less than 5 years	0	0.0%
	Total	**15**	**100.0%**
Q4	**Planning/Scheduling Experience**	**No.**	**%**
1	More than 15 years	8	53.3%
2	From 10 to 15 years	6	40.0%
3	From 5 to 10 years	1	6.7%
4	Less than 5 years	0	0.0%
	Total	**15**	**100.0%**
Q6	**Participated in the DS Model's Design Questionnaire**	**No.**	**%**
1	Yes	7	46.7%
2	No	8	53.3%
	Total	**15**	**100.0%**

Table 11.1: Validation results – Responses summary for the *General information* section

The proposed Dynamic Scheduling system's design			
Q7	**Necessity for Schedules Optimization**	**No.**	**%**
1	Baseline schedules preparation	12	80.0%
2	Revised schedules preparation	13	86.7%
3	Progress updates & look-ahead schedules preparation	8	53.3%
4	What-If schedules preparation	10	66.7%
	Total	**15**	**71.7%**
Q8	**Practical application of proposed DS system**	**No.**	**%**
1	Baseline schedules preparation	12	80.0%
2	Revised schedules preparation	13	86.7%
3	Progress updates & look-ahead schedules preparation	10	66.7%
4	What-If schedules preparation	9	60.0%
	Total	**15**	**73.3%**
Q9	**DS Solution's Effectiveness in Baseline/Revision Opt.**	**No.**	**%**
1	Strongly effective	10	66.7%
2	Seems effective	5	33.3%
3	Not sure	0	0.0%
4	Not effective	0	0.0%
	Total	**15**	**100.0%**
Q10	**DS Solution's Effectiveness in Progress Updates Opt.**	**No.**	**%**
1	Strongly effective	5	33.3%
2	Seems effective	7	46.7%
3	Not sure	3	20.0%
4	Not effective	0	0.0%
	Total	**15**	**100.0%**
Q11	**DS Solution's Effectiveness in What-if schedules Opt.**	**No.**	**%**
1	Strongly effective	9	60.0%
2	Seems effective	3	20.0%
3	Not sure	2	13.3%
4	Not effective	1	6.7%
	Total	**15**	**100.0%**
Q12	**Ease of use of the proposed DS Solution**	**No.**	**%**
1	Easy to use	4	26.7%
2	Easy to use after practicing	7	46.7%
3	Complicated and requires a lot of practice	3	20.0%
4	Only very experienced planners can use it	1	6.7%
	Total	**15**	**100.0%**

Table 11.2: Validation results – Responses summary for the *Dynamic Scheduling system's design* section

The responses summary for the Dynamic Scheduling system's design (shown in Table 11.2) shows clearly the positive trend of participants' feedback. Where almost all participants confirmed the need for a DS system for optimizing schedules under one or more of the schedule quality gates; especially for baseline/revised schedules preparation; and more than 90% of

participants accepted that the proposed DS system can be used as a solution for these schedules improvement requirements.

In addition, responses to questions 9-11 showed that almost all participants acknowledged the effectiveness of the proposed DS system under various schedule quality gates. And more than 73% felt from the system's presentation sent to them that the proposed system can be easily used after some practicing (question 12).

The Dynamic Scheduler user interface			
Q14	Dynamic Scheduler's Integration Effectiveness	No.	%
1	Strongly effective	9	60.0%
2	Seems effective	5	33.3%
3	Not sure	1	6.7%
4	Not effective	0	0.0%
	Total	15	100.0%
Q15	Ability to define/modify additional project/optimization data	No.	%
1	Strongly effective	5	33.3%
2	Seems effective	10	66.7%
3	Not sure	0	0.0%
4	Not effective	0	0.0%
	Total	15	100.0%
Q16	Ability to view optimized alternatives	No.	%
1	Strongly effective	4	26.7%
2	Seems effective	10	66.7%
3	Not sure	1	6.7%
4	Not effective	0	0.0%
	Total	15	100.0%

Table 11.3: Validation results – Responses summary for the *Dynamic Scheduler user interface* section

Similarly, in the *Dynamic Scheduler user interface* section, responses to questions 14-16 showed that almost all participants acknowledged the effectiveness of the developed software tool in providing the required functionalities as per the designed DS system's framework.

In the last section of the survey, the *Future communications* section (Table 11.4), the participants' responses confirmed their positive feedback about the proposed solution; where, all participants requested a complimentary copy of the developed software tool, and requested to receive copy of the summary results of the new system's validation process.

Future Communications			
Q18	**Receive a copy of the Dynamic Scheduler after completion**	**No.**	**%**
1	Yes	15	100.0%
2	No	0	0.0%
	Total	**15**	**100.0%**
Q19	**Receive a summary of the survey's results**	**No.**	**%**
1	Yes, for research purposes	1	6.7%
2	Yes, interested to know	14	93.3%
3	No, not interested	0	0.0%
	Total	**15**	**100.0%**
Q20	**Receive any updates in future for researches with similar topics**	**No.**	**%**
1	Yes, in the planning/scheduling field	11	73.3%
2	Yes, for research topics related to Schedules Optimization	7	46.7%
3	Yes, for research topics related to Dynamic Scheduling	12	80.0%
	Total	**15**	**66.7%**

Table 11.4: Validation results – Responses summary for the *Future Communications* section

11.3.4. Improvement Suggestions

The validation survey forms included two open-ended questions (13 & 17) for participants to include their improvement suggestions or comments for the proposed system. Responses to these questions are listed in the following points, with some objective discussion/explanation from the system's design perspective:

1. *Added logic might extend the project duration and change the project's critical path, which might not be acceptable in some projects.*

   Explanation: With respect to project duration, in the model and the software tool's design, it is up to the user whether or not to constrain the project's end date, and accordingly the optimization algorithm will not extend the project's duration. For the critical path changes, the algorithm will make some changes to the critical path only if it originally contains resource logic relations which can be altered to improve the schedule's quality; and the improved alternative will be presented to the user to confirm whether or not these changes can be accepted as per the project's conditions and requirements.

2. *The system should allow manual modifications by users beyond the modifications proposed in the optimized alternatives.*

Explanation: As per the system's general framework, proposed solutions are exported back to the main planning software, where the user reviews and confirm the proposed solutions, and can perform any additional manual modifications.

3. *The system's model should include in the schedule's optimization process the associated schedule risks.*

   Discussion: There are few additional complexities in the construction project management processes (such as Risk Management) which can be included in future improved versions of the proposed model. This has been included under the suggested future research tracks in the conclusions chapter (Chapter 12).

4. *The system should verify that the hard logic & the contractual constraints are not violated.*

   Explanation: The system does not alter any of the schedule's hard logic relations; it only alters the relations marked by the user as soft logic. For contractual constraints, all constraints added by user (time constraints, resource levels, budget, liquidity ...etc.) are considered during the analysis; and as explained in Chapters 9 & 10, the software includes a numerical value (the *schedule's feasibility rate*) which indicates that, if equals to 100%, then the algorithm was able to optimize the schedule in the proposed solution without violating any of the provided constraints.

5. *The software tool needs some improvement in the graphical reports.*

   Discussion: The software tool is a prototype, which was developed for the proof of concept that DS can be implemented within construction projects. We agree with the participant's comment, any software which will be developed for commercial use should include several other improvements with respect to user interface and graphical presentation of solutions and reports.

Chapter 12: Conclusions & Recommendations

This final Chapter reflects on the work carried out under this research, and draws accordingly conclusions and recommendations for using the proposed dynamic scheduling solution and for future works.

The contents of the Chapter are organized under four sections; the first section provides a recapitulation of the research, giving an overview and brief discussion of the previous chapters. The second section presents the contribution of the research, or the proposed dynamic scheduling solution for construction industry and explains how the research objectives have been met. The third section addresses the benefits and limitations of the proposed solution. The final section derives from the research conclusions few suggestions for future research tracks.

12.1. Research overview

Construction projects are extremely dynamic, and the integrity of construction projects' schedules is vulnerable to large disruptions due to real-time events. Accordingly, the successful implementation of construction projects planning is subjective to the project's or the organization's strategy on how to mitigate these disruptions on a real-time basis. This makes the presence and implementation of a predefined Dynamic Scheduling (DS) strategy for mitigation of schedules disruptions a must to ensure efficient planning within construction projects.

Although the dynamic scheduling topic is widely researched, and its concepts are adopted in practical applications within various industries, especially manufacturing and computer engineering, the research for automated dynamic scheduling applications in relation to the construction industry is very scarce.

The overall aim of the research, as explained in Chapter 1, was to develop a dynamic scheduling solution to be used by construction industry for the dynamic management of construction projects' schedules. A research plan was developed in Chapter 2 with the detailed processes and research methodologies.

A literature review was performed and presented in Chapter 3 for the dynamic scheduling categories, techniques, strategies and policies. The

review confirmed the gap in literature for construction related dynamic scheduling researches. To further confirm the need for the research, an empirical questionnaire survey was performed, as explained and detailed in Chapter 4, to collect the construction project management practitioners' opinions about the problem under study, in order to investigate the problem & prospects of developing an automated solution from a practical perspective, and to enable defining the functional specifications of a dynamic scheduling solution for construction enterprises. The survey results confirmed the existence of a general scheduling problem, where the time available during schedules preparation is not sufficient to perform manual schedules optimization, especially with respect to resources allocation and cost/cash-flow analysis. The survey results were also used to define an initial framework for the solution, which has been further elaborated along with the solution's modelling in Chapter 5. The framework was in the form of a software tool fully integrated with current planning/scheduling practices with all core modelling which can support the integration of the dynamic scheduling processes to the current planning/scheduling process with minimal experience requirement from users about optimization

The framework of the proposed DS solution basically comprises of a mathematical model, an optimization algorithm, and a prototype software tool. The details of the mathematical model were presented in Chapter 6, along with a literature review of the various scheduling models in literature. The optimization algorithm was developed and explained in Chapter 7 with an explanation of the basis of its development in relation to other algorithms in literature. The software tool was programmed and then described in Chapter 9. The verification process was divided into two parts: the static verification (Chapter 8) and the dynamic verification (Chapter 10).

The purpose of the static verification Chapter was to experimentally test the performance of the developed model and algorithm from an operational research perspective, and compare its results with other state-of-the-art scheduling models and algorithms in literature. While the dynamic verification Chapter was intended to test the dynamic aspects of the model from a construction industry perspective using solved examples and a complex case study.

The results of the static verification were very competitive, and the algorithm's performance was recorded in a publication in the *"Expert Systems*

with Application" journal as the best PSO algorithm for single mode resource constrained scheduling problems *(Fahmy et al, 2014-a).* The results of the dynamic verification of the model, the algorithm, and the software tool were also successful, and achieved the required objectives. These results were validated with construction project management experts and experienced practitioners, and the proposed solution practicality was confirmed as explained in Chapter 11.

12.2. Main research Conclusions

The research's main conclusions are summarized under the following headings, indicating beside each heading the corresponding research objective(s) as identified in Chapter 1:

1. The need for a Dynamic Scheduling solution in construction industry (objective 2).

2. The proposed DS solution for construction enterprises (objective 4).

3. The multi-objective DS mathematical model for construction enterprises (objectives 1 & 5).

4. The multi-objective DS optimization algorithm (objectives 3 & 6).

5. The DS software tool (objectives 7 & 8).

6. Verification & validation of the proposed solution (objectives 9 &10).

12.2.1. The need for a Dynamic Scheduling solution in construction industry

Project Scheduling, especially in the construction field, is inherently complex and dynamic, involving multiple feedback processes and nonlinear relationships. While problems encountered during construction are fundamentally dynamic, the literature review has shown that they have been treated statically within a partial view of a project. As a result, schedule delays and cost overruns are common in construction projects in spite of advances in construction equipment and management techniques. To overcome these chronic symptoms, enormous efforts have been devoted to the planning and control aspects of construction management.

The static and deterministic approach adopted in most of the research efforts presented in the project scheduling context is impractical to real world scheduling; especially in the construction industry. The optimal or near-optimal solutions generated statically will become obsolete from the

beginning of the project execution when actual regular or irregular events start occurring. This dynamic nature of construction projects makes the maintenance of schedules integrity and optimality under continuous real-time events a tedious job for project management teams; especially that almost all current planning/scheduling practices are based on static architecture. Accordingly, developing an automated DS solution for the mitigation of real time events will support in the continuous improvement of construction schedules' quality, and thus enhance the overall construction project management process.

The results of the empirical questionnaire survey performed confirmed the necessity for a DS as concluded from the literature review; where 87.5% of the survey participants acknowledged that the time available before schedules submissions was always not sufficient to review and improve several schedule quality aspects, especially in relation to resources distribution and cash flow analysis.

12.2.2. *The proposed dynamic scheduling solution for construction industry*

The main contribution of the research is the development of a dynamic scheduling solution which can be used by construction enterprises for the real-time analysis and improvement of construction schedules.

The developed solution serves as a 'brain' to the main planning software packages, where it continuously analyses the schedules (baseline or updated) and provides, within a pre-defined schedule quality gates, optimized alternatives to planners to select the most appropriate solutions to their projects' conditions and requirements.

The architecture of the proposed DS solution was based on a fully integrated software tool (titled in the research as the *Dynamic Scheduler*); where the construction enterprise's main construction projects' data and progress updates are performed in the main planning software, and the *Dynamic Scheduler* collects these data, perform the optimization process, and returns back the optimized data to the main database as per the planner's selection from the proposed alternatives.

This tool encapsulated inside its programming the main elements of the framework elements of the proposed construction DS solution: the formulated mathematical model, the optimization algorithm, and the prototype DS

software tool. The following sections will summarize these elements and their related research contributions.

12.2.3. The multi-objective construction DS mathematical model

The multi-objective construction DS mathematical model was formulated based on the combination of scheduling models available in literature with several additional extensions to accommodate the construction planning & scheduling process related requirements as identified through the inputs of construction project management experts/practitioners within the empirical questionnaire survey.

As per the construction scheduling literature review, the construction planning & scheduling process contains four main quality gates, or schedule preparation process where optimization is important to improve the schedule's quality. The DS framework was developed to include a schedule optimization cycle within one or more of the schedule quality gates as identified in a predefined DS policy and strategy. In addition to the full integration with current construction planning practices, the DS framework also provided easy integrity between the consequent scheduling stages; where the outputs of each optimization cycle, produced in the form of added/deleted resource logic and changed activity modes, are used as inputs to the following schedule optimization cycle in order to provide high quality solutions with minimal schedule deviation.

For the mathematical model, the literature review and the empirical survey identified several optimization objectives which are essential for construction schedules optimization process. The basic mathematical model and the formulation of these main objectives (minimize time, minimize cost, resource levelling ... etc.) were already available in literature; however, the first objective for the formulated mathematical model was to combine them in a multi-objective construction oriented model. The second objective for this formulation process was to extend the model with several other construction-related parameters and objectives (as identified in the empirical survey) in order to ensure the practical implementation of the solution within construction enterprises. These extensions involved the following:

        a) Consideration of cross-projects resources allocation (including related time/costs impacts).

b) Incorporation of construction cash flow analysis parameters and objective; such as contractual payment terms, payment delays, liquidity constraints, variable indirect costs …etc.

c) Few additional schedule quality related objectives (such as minimizing schedule deviation and minimizing total float consumption).

12.2.4. The multi-objective DS optimization algorithm

Scheduling optimization algorithms generally consist of an optimization method to generate solutions, and scheduling heuristics to generate schedules from the generated solutions. The main purpose of the DS optimization algorithm development in this research was to create an algorithm capable of searching the solutions space bounded with complex constraints structure, with the ability to explore all optimization objectives and produce a Pareto front of optimized alternatives in a reasonable analysis time.

To achieve this purpose, several scheduling heuristics were adopted from literature and amended with few other techniques developed under this research. These proposed techniques included:

a) The *Stacking Justification (SJ)*, a heuristic technique to improve solutions quality for resource-constrained problems; especially when combined with the original Double Justification (DJ) technique.

b) The *Float Justification (FJ)*, a heuristic technique to improve solutions quality for time-constrained problems.

c) The *Rectified Schedule Generation Scheme (RSGS)*, an improved version of the original Schedule Generation Scheme (SGS), which improves the distribution of the search space

For the optimization technique, the particle swarm optimization was adopted with the general scheduling model available in literature. In addition, few modifications were also suggested to the technique's formulation and the swarm initialization process:

a) The *Combined Priority Rules (CPR)*, a technique to initialize particle swarm initialization for proper spreading of swarm particles among good quality areas of the search space. The verification results detailed in Chapter 8 showed a steady

improvement to schedules quality when *CPR* is used in comparison with any other priority rule.

b) The *Differential Density Particle Swarm Optimization (DDPSO)*, a modified PSO with the introduction of density parameters to swarm particles to overcome the algorithm's early convergence. This modification provided a significant improvement to the original PSO with respect to scheduling solutions quality, and the test results showed that the *DDPSO* algorithm outperformed all other PSO algorithms in scheduling literature, and its performance was very close to the best algorithm presented in literature for the resource-constrained scheduling problem.

12.2.5. The DS software tool

The Dynamic Scheduling software tool, or the *Dynamic Scheduler*, was designed and programmed as a prototype software tool representing the proposed DS solution, in order to enable the verification & validation of the DS model's functionalities and the overall solution's practicality and scalability.

The software tool was developed with full integration with the most commonly used planning software (Primavera P6®) in order to optimize the data transfer processes and to minimize unnecessary double entries of construction schedules data and progress updates. The software tool's main functionalities involve the following:

a) Importing schedules data from the planning software database.

b) Providing the necessary user interface to add additional schedule's data which cannot be added in the planning software; such as activity modes, contractual payment terms, overall resource units for double-constrained resources … etc.

c) Definition of optimization settings and objectives (including objectives weights).

d) Performing optimization cycles and storing optimization results.

e) Providing the necessary user interface to view the optimized schedule alternatives.

f) Exporting the selected optimized solution(s) back to the planning software database for further analysis and/or implementation.

12.2.6. Verification & validation of the proposed solution

The proposed solution was proven to be statically functional under different problem conditions and sizes using several problem sets available in literature. For the dynamic functionality and the scalability of the solution, it has been tested on a complex construction entity in Oman, with a complicated projects combination; and the solution has also shown efficient performance.

The case study involved the application of the proposed solution on the historical schedules data for the entity's ongoing projects (4 projects & more than 7600 activities) under several schedule quality gates. The case study results showed that the proposed solution reasonably performed under large scale practical application for all designed schedule preparation processes (baseline, progress updates, look-ahead schedules, and what-if schedules). Based on the projects' conditions and requirements, certain optimization objectives were set within each of the schedule quality gates. The results showed that the proposed DS solution had managed in all stages to achieve the required constraints and perform the balance between schedules quality and the associated mass of changes (resource allocations within each project & cross-projects).

To confirm the validity of the proposed solution for practical application within construction enterprises, the solution's framework and the case study results were presented to construction project management experts/practitioners to validate the proposed solution and to collect their feedback on its practicality. The feedback was very positive; and the validation participants acknowledged the necessity for DS in construction projects and that the proposed solution achieved this purpose.

12.3. Contributions to the construction industry

The benefits which the developed construction DS solution provides for the improvement of the construction scheduling process were demonstrated through the solved examples and the case study application; and can be summarised as follows:

a) The developed construction DS solution proposed a framework for the dynamic scheduling of construction schedules. This provides a powerful tool for construction projects' planning teams to perform tedious schedule optimization processes necessary to mitigate the disruption effects of real-time events.

b) The optimization algorithm developed within the solution was able to solve efficiently hundreds of static scheduling problems in literature with several designed scheduling complexities. This ensures the efficient performance of the algorithm under most practical cases.

c) The formulated mathematical model included several practical considerations with respect to projects' costs and cash flows as identified in the empirical survey (such as resources mobilization/de-mobilization time/cost, contractual payment terms … etc.).

d) The developed software tool associated with the proposed solution provided an interface relatively easy to understand and use; with the ability to perform several optimization cycles for schedules under main schedule quality gates, and propose optimized alternatives for planners to choose from.

e) Finally, the model and the software tool were developed with full integration with current scheduling practices, which minimizes any need for double entries and enables non IT-experienced planners to manage easily the optimization processes from import schedules data to exporting optimized alternatives back to the main planning software.

12.4. Limitations of the proposed DS solution

After the continuous testing of the proposed solution, and based on the suggestions and recommendations of field experts provided during the validation process, the proposed solution's limitations were identified under two main points:

a) Although the solution is not very complicated, its full aspects might not be easily to digest by non-experienced planners. It requires good planning skills to properly select from the proposed alternatives the most suitable optimized schedule which provides the maximum benefit with minimal acceptable schedule changes. This balance between schedule changes and their benefits requires sound knowledge of the overall project's requirements and its contractual scheduling limitations, and a good understanding of the DS solution to be able to translate the project requirements into a good estimate for the optimization objectives' weights.

b) The proposed solution focuses on the rearrangement of schedule to achieve certain predefined objectives. However, there are few additional complexities in the construction project management processes (such as Risk Management) which are not considered in the analysis and can be included in future research works to improve the proposed model.

12.5. Future works recommendations

Based on the outcomes of the research and its conclusions, the following recommendations for future research can be driven:

a) The research has proved the efficiency of the proposed solution with respect to resources allocation within project or inter-project with the consideration of mobilization/demobilization time and cost. Further research should be undertaken to extensively study all aspects which affect such allocations and their detailed impacts on the related projects and the organization in general.

b) Although the results of testing the solution using a complex construction entity was positive, it might be important to understand the impact of real-time changes to schedules on the behaviour of projects' teams and affected resources. This will require a detailed future research to apply the proposed solution on a construction entity and study these behaviours on a real-time to ensure the solution's smooth implementation, and probably suggest some improvements to overcome any identified shortfalls.

c) As discussed in the proposed solution's limitations, the solution does not cover few project management aspects such as risk management. This can be a rich track for future researches to investigate these additional aspects and propose possibilities of their integration into the proposed DS solution.

d) The optimization objectives weights were considered in the case study based on assumption for the differential importance of each objective. This might require a future research to assess the appropriate weights to be considered under each schedule quality gate.

e) Finally, the developed solution proposes optimized alternatives as per the schedule quality gates identified in the predefined DS strategy. With respect to look-ahead schedules quality gate, it might be important to investigate in a future research how frequent it can be practically used, because the proposed model can be further improved if look-ahead schedules can be dealt with separately with a partial schedule update and optimization in between contractual schedule periodical updates.

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Appendix A: The Multi-Objective Branch & Bound (MOBB) algorithm

Several attempts were made during the research course for using one of the deterministic algorithms existing in literature and modifying it to solve both problems categories RCPSP & TCPSP. Each of the modified algorithms was well performing for most of the problem types under the same category; but unfortunately, none of these modification attempts were successful to function properly for both categories. So, in order to proceed with the verification process, a new algorithm was developed to match multi-objectives requirement; the branch & bound was also used as the solution method, and the algorithm was titled the Multi-Objective Branch & Bound (MOBB) algorithm.

The MOBB algorithm is the first attempt to use a deterministic approach in solving multi-objective scheduling problems. Since, the Branch & Bound (BB) is the most common way to deal with scheduling problems *(cf. Brucker et al., 1998)*; the algorithm is based on the Branch & Bound solution method but with different structure of the analysis tree, pruning rules and weighing rules than any of the BB algorithms presented in literature.

Combining different optimization targets under one deterministic algorithm might seem to add more complexity to an already complex NP-Hard problem (as defined by *Blazewicz et al., 1983*). However, as explained in the previous chapter, the need for multi-objective solution techniques is essential for practical applications of schedule optimization, especially in construction industry, where multi-objective environment is the general case and objectives and their weights can vary dramatically between different optimization runs based on the construction site's dynamic conditions and the overall project's requirements. This might lead to a great added value if an exact algorithm can be developed to guarantee the optimum solution, which makes the attempt to develop such algorithm worth the research time.

A.1. MOBB elements and processes

The MOBB is based on the two main concepts of MLS: the resource profile is the base for any optimization process, and all resources profiles are expandable in both directions (time & resource level) unless restricted by a constraint. Accordingly, in the branch and bound tree, each pruning process will allow the addition of two extra child nodes (if needed), one for extending the schedule target completion time to match the current minimum completion time for parent node, and another for increasing the target resources levels as per parent node minimum resources levels.

A.1.1. MOBB optimization process

The following points will briefly explain the MOBB optimization process (as shown in Figure A.1), while each main step will be detailed further in the following sections:

1. *Initialization:* Involves the preparation of schedule date and initializes the BB tree (step is detailed in section A.1.2).

2. *Setting Initial Current Node:* During the optimization process, the tree node (or tree branch) under analysis is termed as *Current Node (N_C)*; and the initial N_C is set to the BB tree root node.

3. *Pruning:* If N_C is previously pruned, the algorithm will jump to step 6; otherwise, child nodes (or prunes) will be created for N_C (step is detailed in section A.1.3).

4. *Child Nodes Evaluation:* Each of the pruned child nodes will be evaluated to calculate its *Maximum* possible *Upper Bound Efficiency (UBE_{max})*. The UBE_{max} will be detailed in later sections but in general it represents how much the schedule corresponding to the current node can achieve from the project's lower bound. The evaluation step and UBE_{max} are further detailed in sections A.1.4 & A.1.5 respectively.

Flowchart (Figure A.1):
- Initialize Schedule & BB Tree
- Set Root Node as Current Node
- Current Node Pruned? — Yes
- No → Prune Current Node
- Evaluate Current Node's Childs
- Feasible Solution Child exists? — Yes
- No → Set Upper Bound as Feasible Solution Child if efficiency is better
- Current Node Childs > 0 — No
- Yes → Remove Child Nodes with Efficiency less than Current Upper Bound Eff.
- Select Child with Best Opportunity
- Best Child Efficiency > UB — No
- Yes → Remove Best Child from Current Node's Childs
- Set Best Child as Current Node
- Set Current Node's parent as Current Node

Figure A.1: MOBB optimization process

5. *Logging Upper Bound Effeciency (UBE):* If one of the pruned child nodes contains a feasible schedule (or feasible solution), and its *Schedule Efficiency (Sch_{Eff})* (explained in section A.1.6) is higher than the current *UBE*, the *Upper Bound (UB)* solution is set as this feasible solution child and the current *UBE* is set to the child's Sch_{Eff}.

6. *Removing Unnecessary Childs:* If any of the pruned child nodes' UBE_{max} is lower or equal to current *UBE*, then there is no purpose in its analysis and accordingly it is removed from N_C's chid nodes list.

7. *Selection of Best Child Node:* The best child node is selected from the pruned child nodes based on several criteria which will be detailed in

section A.1.8. If best node exists, then N_C is set to best child node and the algorithm returns back to step 2.

A.1.2. Analysis initialization process

The initialization process contains various preparation works in which several variable sets are prepared to reduce the analysis time during the optimization process. This process contains the following initialization steps:

1. *Preparation of Full Distances Matrix (FD):* The concept of distances matrix is well-known in deterministic algorithms researches, it was used by most BB algorithms in literature (for ex.: *Demeulemeester & Herroelen, 1992; Brucker et al., 1998;Heilmann, 2003)*, its main idea is to prepare an initial set D_{ij} representing the minimum time lag between the starts of activities *i* & *j*, also time lags involving activities completions (Finish-Start, Finish-Finish & Start-Finish relations) can be converted to Start-Start relation using activities' durations *(Bartusch et al., 1988).*

   In the MOBB algorithm, a different implementation of the distances matrix was used, where the matrix includes all network relations and not only direct ones. To explain this concept, let's consider a simple 4 activities network as shown in figure A.2a:
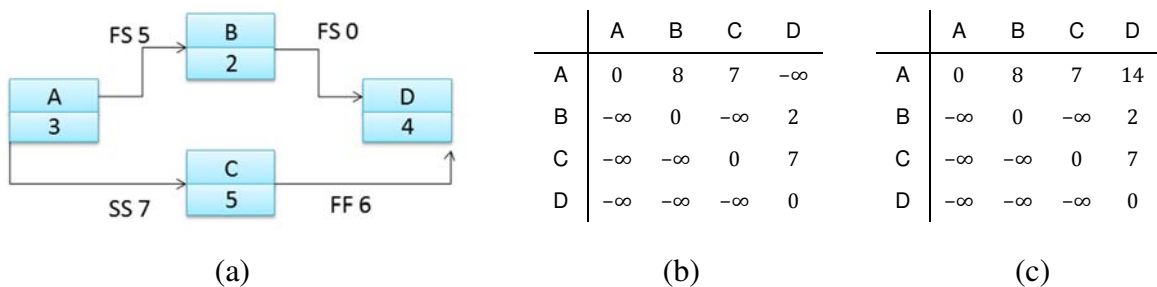
Figure A.2: Example for full distance matrix preparation
a) Network Example, b) Distances Matrix, c) Full Distances Matrix

   The regular distances matrix D_{ij} (A.2b) contains 4 time lags corresponding to the direct network relations; while the *Full Distances (FD$_{ij}$)* matrix (A.2c), contains 5 time lags. The additional time lag is related to the indirect logic between activities A & D, where time lag is considered as the maximum of the two paths (A-B-D: 10 and A-C-D: 14).

   The benefits of having FD_{ij} will appear during the detailed explanation of the optimization steps.

2. *Initializing schedule:* Calculation of activities early and late dates. This is the first benefit of having FD_{ij} , where the process of scheduling (which will be needed intensively during optimization) will only involve fetching the dates from the matrix. For the same example shown in figure A.2, the

Early Start (ES) for all activities are represented with the time lags row corresponding to the project start (row 1 corresponding to activity A); so, the ESs of A, B, C & D are 0, 8, 7 & 14. And *Late Start (LS)* for all activities are represented with the start date of project finish (14: start of activity D) minus the time lags column corresponding to the project finish (column 4 corresponding to activity D); so, the LSs of A, B, C & D are 0, 12, 7 & 14.

3. *Define Maximum Lag Cycles (MLC):* This is a new proposed set of activities loops to be defined for schedules including maximum time lag relations. These sets will be used during the definition and updates of *Minimum Resources Requirements R_{min}* (to be explained later within this chapter). To explain the MLC concept, consider the network with maximum lags shown in figure A.3; within this network there are 2 MLCs, (1-4) & (3-6-7). These loops in simple terms will move with each other if any one of its activities is delayed in the overall project time frame.
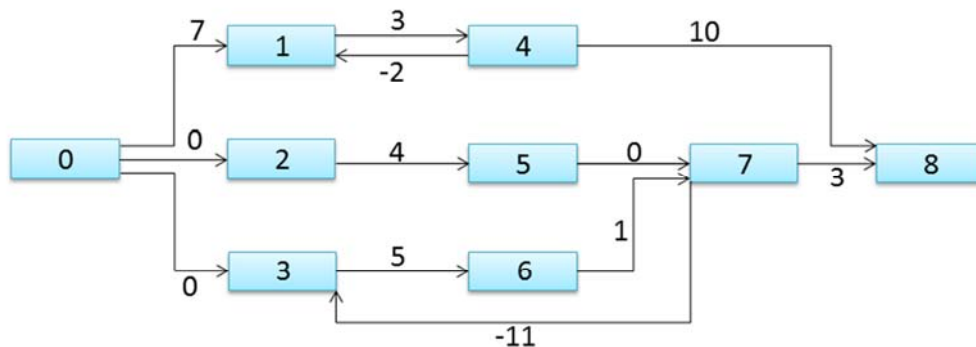
Figure A.3: Example network for maximum lag cycles

4. *Define Resources Logic Possibilities (RLP_i):* This is another new proposed set to be defined for each activity; it contains all possible resources logic relations which can drive the activity into different locations within the resource's profile; taking into consideration that any relation to be defined must have both activities with at least one common resource in their resources requests. For example, for the network shown if figure A.2, if we assumed that all activities are having resource requests from a common resource, then the possible resources logic list will contain two relations: B→C and C→B.

5. *Define Solutions Space Limits:* The solution space limits the bounding values for each objective; the possibility of having a solution with one of these limits is sometimes impossible, however their calculation is necessary for two main purposes: first for efficiency calculations (detailed in section A.1.5), and second for the graphical presentation of the final Pareto Front & solution space. The following points describe the

calculation method for the bounding limits for all possible objectives defined in the previous chapter:

- *Minimize Time:* For *Minimum Timespan T_{min}*, a minimum durations schedule V_{min} is prepared based on the minimum duration mode for each activity, and the T_{min} is the completion date of the last activity after scheduling. While Maximum Timespan T_{max} is the summation of all activities maximum durations

$$T_{min} = C_n \ (at \ V_{min}) \tag{A.1}$$

$$T_{max} = \sum_{i=1}^{n} max\{d_{im}\} \tag{A.2}$$

$$where: m \ \in M_i$$

- *Minimize Cost:* For cost limits, the cost is the summation of four cost elements: Indirect cost, fixed activities cost, renewable resources cost & non-renewable resources cost. For indirect cost, T_{min} is used for the calculation of *Minimum Cost C_{min}*, while T_{max} is used for *Maximum Cost C_{max}*. Activities fixed cost for C_{min} is the summation of minimum fixed cost modes, and vice versa for C_{max}. For renewable resources, the minimum resource requirement is taken as one unit, assuming no parallel requests; while the maximum resource requirement as the summation of all requests, assuming all requests are executed in parallel. And finally, for non-renewable resources, the cost is summed for modes with minimum resource requests for C_{min}, and for modes with maximum requests for C_{max}.

$$C_{min} = PIC * T_{min} + \sum_{i=1}^{n} min\{FC_{im}\} + \sum_{k \in R}(mc_k + dc_k + c_k) + \sum_{k \in N} c_k * \sum_{t=0}^{T} \sum_{i=1}^{n} min\{r_{imk} * d_{im}\} \tag{A.3}$$

$$C_{max} = PIC * T_{max} + \sum_{i=1}^{n} max\{FC_{im}\} + \sum_{k \in R}(mc_k + dc_k + c_k * \sum_{i=1}^{n} r_{ik}) + \sum_{k \in N} c_k * \sum_{t=0}^{T} \sum_{i=1}^{n} max\{r_{imk} * d_{im}\} \tag{A.4}$$

- *Resources Levelling:* The *Minimum Resources Levelling RL_{min}* occurs when all resource requests are executed in series; while the *Maximum Resources Levelling RL_{max}* occurs when all requests are executed in parallel.

$$RL_{min} = \sum_{k \in R} c_k * \sum_{i=1}^{n}(r_{ik} * d_i)^2 \tag{A.5}$$

$$RL_{max} = \sum_{k \in R} c_k * (\sum_{i=1}^{n} r_{ik})^2 \tag{A.6}$$

- *Minimum Negative Cash Flow:* The *Minimum Negative Cash Flow NCF_{min}* is zero (i.e. no financing required by contractor); while the

Maximum Negative Cash Flow NCF$_{max}$ equals to *C$_{max}$* (i.e. assuming, theoretically, that all project costs are financed by the contractor, and that all payments are delayed until the project completion).

- *Minimum Resources Logic Deviation:* The *Minimum Resource Logic Deviation RLD$_{min}$* is zero (same resources logic is utilized in the new schedule); while the *Maximum Resource Logic Deviation RLD$_{max}$* equals to *n* (number of activities), assuming that all activities are driven by new resources logic in the optimized schedule.

- *Minimum Schedule Crashing:* The *Minimum Schedule Crashing SC$_{min}$* is zero (no crashing made), while the *Maximum Schedule Crashing SC$_{max}$* is the summation of squared variances between maximum and minimum durations of each activity.

$$SC_{max} = \sum_{i=1}^{n}(max\{d_{im}\} - min\{d_{im}\})^2 \qquad (A.7)$$

6. *Initialize the BB Solutions Tree:* The initialization of the BB tree involves the following:

- Setting current *Upper Bound Efficiency (UBE)* to zero.
- Calculation of *Lower Bound Efficiency (LBE)* (detailed in section A.1.7).

A.1.3. The pruning process

First, the resources profiles are explored for conflicts with the predefined target resources levels (initially set to the minimum levels defined along with the *LBE* calculation). If no conflict exists, then no child will be created; otherwise, an activities list is prepared containing the all activities involved in the first resources conflict.

For each of the involved activities, a child is created for each of the possible resource logic relations defined during the
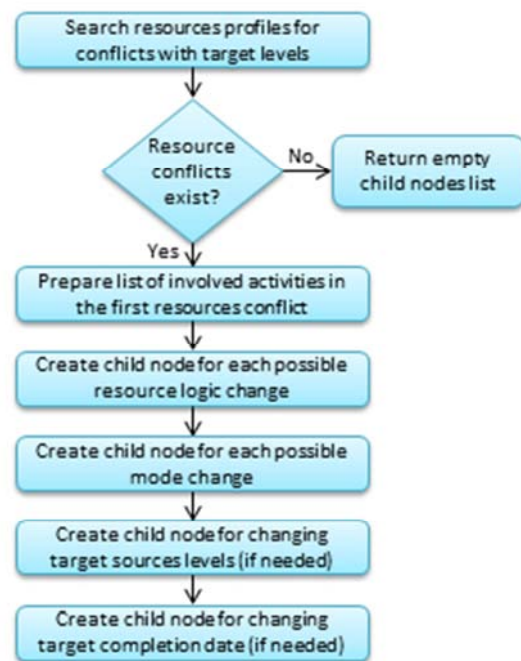
Figure A.4: Child nodes pruning process

initialization process. If any of the involved activities was previously logic linked in the parents of this branch node, then the activity is excluded from further logic linking; this condition reduces the final size of the search tree.

Then, for each of the involved activities, a child is created for each possible mode change. Similarly, if any of the involved activities was previously involved in a mode change in the parents of this branch node, then the activity is excluded from mode changing.

Finally, two child nodes are created for expanding the resources profiles if needed. The idea behind the creation of these child nodes is to allow the algorithm to search beyond the original profile target limits (defined along with the *LBE*) if these targets are no more feasible. The new targets are defined based on the new *LB* for the current tree branch based on its current schedule; if the current schedule's *LBs* for time and resources levels are still matching with its parent branch node, then no profile expansion child is created.

The creation of profiles expansion child nodes is the key reason for the MOBB to be suitable for all types of schedule problems, giving the algorithm the ability to automatically adapt according to the problems predefined limits for time and resource levels.

A.1.4. Child nodes evaluation

For each child in the pruned children, the child is first checked for feasibility; this is required only for logic changes, where some logic might be infeasible if they are causing unsolvable logic cycles. If the schedule change passes the feasibility check, the schedule corresponding to the child node is then prepared; and then its profiles are passed to another feasibility check for any excess to limits. Infeasible solutions from both checks are removed from the children list.
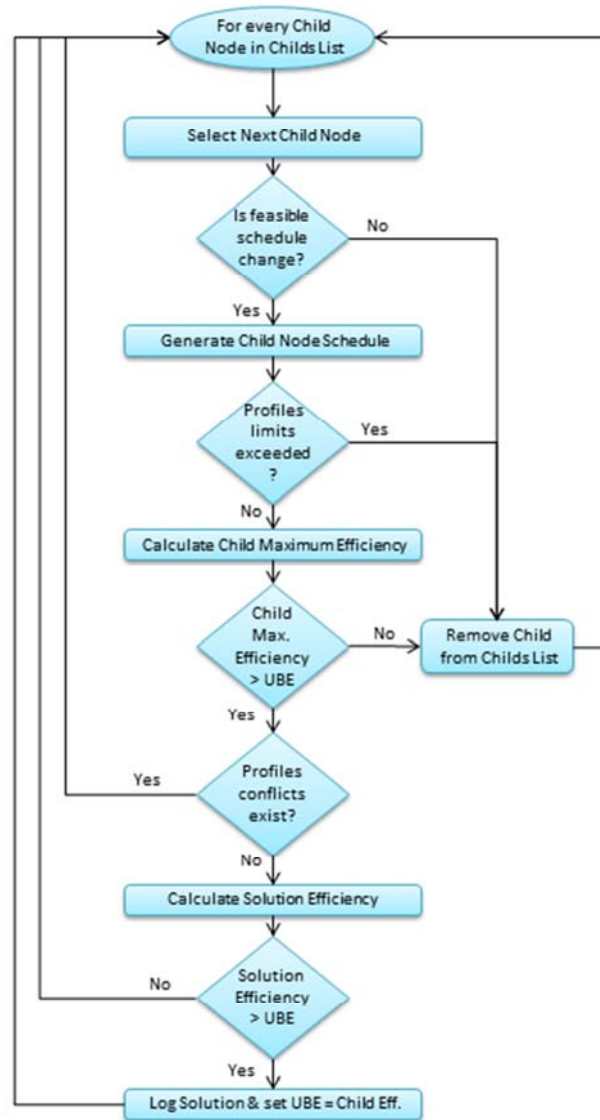
Figure A.5: Child nodes evaluation process

Then, the child node's *Maximum Efficiency UBE$_{max}$* is calculated (detailed in section A.1.5). If the child's *UBE$_{max}$* is not higher than *UBE* (the efficiency of the best found solution), the solution is also removed from the children list.

The profiles are then checked against their current targets (not limits); if the no conflict occurred, then this child node can be treated as a solution node (or leaflet), otherwise it is treated as branch node and it is kept in the children list until it is selected for pruning.

If the node can be treated as a solution node, then its *Schedule Efficiency (Sch$_{Eff}$)* is calculated and checked against the *UBE*. If the *Sch$_{Eff}$* is higher, the solution is logged and the *UBE* is set equal to the *Sch$_{Eff}$*.

A.1.5. Calculation of Maximum Upper Bound Efficiency (UBE$_{max}$)

The term *efficiency* is used within this BB algorithm to determine how much a solution achieved from its objectives; or other words, how close the solution is to the best possible value for all its objectives; where the best values are identified within the solution space limits (as calculated in section A.1.2). All efficiency variables are calculated a weighted summation of their solution's efficiency related to each objective.

The *Maximum Upper Bound Efficiency (UBE$_{max}$)* is calculated for any pruned tree branch to determine the efficiency of the best solution which can be obtained from that branch.

$$UBE_{max} = W_T * E_T + W_C * E_C + W_{RL} * E_{RL} + W_{NCF} * E_{NCF} +$$
$$W_{RLD} * E_{RLD} + W_{SC} * E_{SC} \qquad (A.8)$$

Where W_T, W_C, W_{RL}, W_{NCF}, W_{RLD} & W_{SC} are the weights for the objectives as defined before the analysis, while E_T, E_C, E_{RL}, E_{NCF}, E_{RLD} & E_{SC} are the efficiencies to be achieved for the objectives based on the target resource levels & target completion date. The following equation explains how E_T is calculated, and the other efficiencies are calculated similarly:

$$E_T = \left(T_{max} - T_{target}\right) / \left(T_{max} - T_{min}\right) \qquad (A.9)$$

A.1.6. Calculation of Solution Schedule Efficiency (Sch$_{Eff}$)

The *Schedule Efficiency (Sch$_{Eff}$)* is calculated the same way as *UBE$_{max}$* except that the calculation should use the schedule's values instead of the target values.

A.1.7. Lower Bound Efficiency (LBE) Calculation

Similarly, the *Lower Bound Efficiency (LBE)* is calculated the same way as *UBE$_{max}$* except that the calculation should use the *LB* values instead of the target values.

The concept of *LB* is a well-known research point in the scheduling literature. Several researches were presented trying to improve how *LB* values are calculated; the results of different method for calculation were tested by *Brucker et al. (1998)*, and the lower bound LB_2 from *Mingozzi et al. (1994)* was found to be of best results. A further improved *LB* calculation including multi-mode was presented by *Brucker & Knust (2003)*; this method was adopted for *LB* calculation in MOBB.

A.1.8. Weighing Rules

The process of best pruned child node selection follows a series of *Weighing Rules* in the following order: 1. the highest UBE_{max}, 2. the highest first resources conflict date, 3. and the highest resources utilization before the first conflict date

During the nodes evaluation process, two values related to weighing are calculated: first resources conflict date (the first day from the project start where the any of the resource requirements is larger than the target resource level), and the resources utilization (the summation of all requests before the first conflict date).

A.2. MOBB computational results & performance analysis

A.2.1. Computational results

The results were obtained using a personal laptop with Intel core processor i7 2.4GHz (only single core was utilized for the analysis). The computer was operated by Microsoft Windows 7, and the algorithm was programmed in Visual C#.Net 4.0.

The algorithm development passed through many cycles of testing and improvement; the results of three versions of the algorithm was logged and presented in this section.

The SRCPSP (j-30) 480 instances were used for the verification of the RCPSP category; figure A.6 shows the analysis results. The first table and chart represent the number of instances solved to optimality, while the second table and chart show the number of instances solved to feasibility.

The RIPSP/max was used for the verification of the TCPSP category. The problem set contains 270 instances for each of the j-10, j-20 & j-30 problems. Computational results are shown in figure A.8.

Solution Time	MOBB V04		MOBB V15		MOBB V22	
	Solved	%	Solved	%	Solved	%
10-Sec	225	46.9%	278	57.9%	318	66.3%
30-Sec	240	50.0%	291	60.6%	323	67.3%
60-Sec	245	51.0%	297	61.9%	328	68.3%
180-Sec	252	52.5%	301	62.7%	337	70.2%
300-Sec	257	53.5%	306	63.8%	339	70.6%
Total	480	100%	480	100%	480	100%
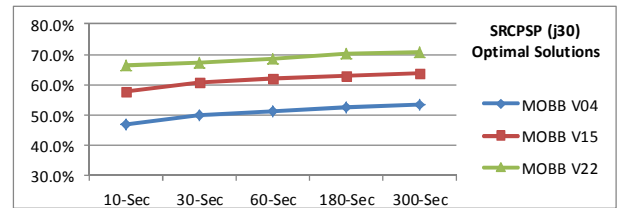
Solution Time	MOBB V04		MOBB V15		MOBB V22	
	Feasible	%	Feasible	%	Feasible	%
10-Sec	225	46.9%	425	88.5%	447	93.1%
30-Sec	15	50.0%	5	89.6%	4	94.0%
60-Sec	5	51.0%	5	90.6%	6	95.2%
180-Sec	7	52.5%	4	91.5%	9	97.1%
300-Sec	5	53.5%	3	92.1%	7	98.5%
Total	480	100%	480	100%	480	100%
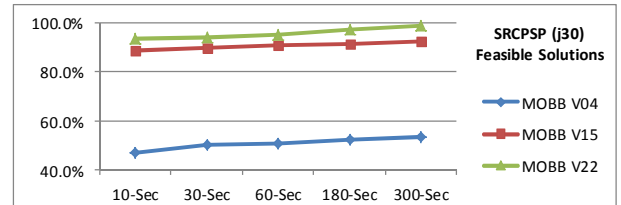
Figure A.6: MOBB computational results for testing SRCPSP (j-30)

Solution Time	SRIPmax (j10)		SRIPmax (j20)		SRIPmax (j30)	
	Solved	%	Solved	%	Solved	%
10-Sec	270	100.0%	156	57.8%	94	34.8%
30-Sec	270	100.0%	172	63.7%	103	38.1%
60-Sec	270	100.0%	179	66.3%	106	39.3%
180-Sec	270	100.0%	188	69.6%	116	43.0%
300-Sec	270	100.0%	195	72.2%	121	44.8%
Total	270	100%	270	100%	270	100%
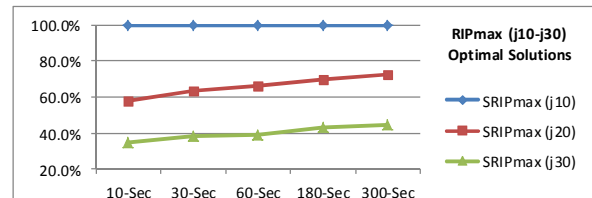
Figure A.7: MOBB computational results for testing RIPSP/max (j10 to j30)

A.2.2. Performance analysis for the MOBB algorithm

The algorithm's performance was not to a satisfactory level, especially if compared to the results of other algorithms in literature oriented for solving one scheduling problem type. However, it is not fair to compare a multi-objective algorithm to a single objective one; and for the first attempt for a deterministic algorithm to solve almost all scheduling problem types, the results can be considered reasonable, but should be subjected to several improvement cycles if the algorithm is to be used for practical applications.

Another negative side for the results is the impact of problem size, as shown in figure A.8, the amount of problems solved within the first minute decreased by more than 60% when the number of activities increased from 10 to 30. This definitely will not be an efficient solution for real projects with number of activities varying between several hundreds to few thousands.

Appendix B: Performance analysis for different elements of scheduling optimization algorithms

A detailed experimental analysis was performed on different scheduling algorithm's elements and parameters for optimum architectural design of the proposed *DDPSO* algorithm. This appendix contains the full results of this simulation.

B.1. Priority rules

For priority rules, table B.1 shows the effect on PSO performance for different SRCPSP sizes. *Base PSO* was used, with 20 single density particles, no FBS and no justification. The stopping condition was set to 1000 generated schedules. It is clear from the table that *LST & MTS* are having the best performances in general. *MTS* is better in the AD_{CP} and its performance increases clearly with the problem size, while *LST* is outperforming for the number of problems solved to optimality. *LFT* was also close to the best in all cases; so, these three PRs will be used alternatively during the rest of the testing process.

Priority Rule	Average CP Deviation (AD_{CP})				Problems Solved to Optimality			
	j-30	j-60	j-90	j-120	j-30	j-60	j-90	j-120
Activity Related PRs								
EST - Earliest Start Time	16.5%	15.9%	16.5%	50.1%	59.4%	60.2%	60.4%	10.3%
EFT - Earliest Finish Time	16.7%	16.2%	16.5%	50.2%	59.8%	58.5%	60.8%	10.2%
LST - Latest Start Time	**15.6%**	15.4%	15.5%	46.1%	**66.9%**	**63.8%**	**66.3%**	**19.2%**
LFT - Latest Finish Time	15.7%	15.7%	15.9%	47.2%	65.4%	62.5%	64.4%	17.8%
SPT - Shortest Processing Time	17.2%	16.2%	16.6%	50.1%	56.7%	56.0%	60.2%	10.7%
LPT - Longest Processing Time	17.2%	16.2%	16.6%	50.1%	56.7%	56.0%	60.2%	10.7%
MSLK - Minimum Slack	16.6%	15.6%	16.3%	49.4%	61.0%	61.3%	61.7%	12.5%
Resource Related PRs								
GRWC - Greatest Resource Work Content	36.7%	36.3%	47.7%	49.4%	23.9%	20.5%	17.6%	9.3%
GCRWC - Greatest Cum. Res. Work Content	34.8%	34.2%	40.0%	49.2%	25.3%	22.2%	18.6%	7.0%
Logic Related PRs								
MIS - Most Immediate Successors	17.1%	15.8%	16.2%	49.3%	54.8%	57.9%	61.7%	12.7%
MTS - Most Total Successors	17.1%	**14.8%**	**14.5%**	**43.1%**	54.8%	58.8%	64.0%	18.7%
LNRJ - Least Non-Related Jobs	16.2%	16.0%	16.7%	50.2%	63.1%	58.8%	61.0%	10.0%
GRPW - Greatest Rank Positional Weight	22.8%	19.2%	17.1%	48.8%	41.7%	42.7%	51.7%	10.1%

Table B.1: Priority rules performance comparison for SRCPSP

While for SRIP/max (or the TCPSP), table B.2 shows that *EST, LST & GRWC* were having the best performance, with a high increase in the performance of *GRWC* with the problems size; and accordingly, these three PRs will be used for further elements testing.

Priority Rule	Average Cost Saving (ACS)			Problems Solved to Optimality		
	j-10	j-20	j-30	j-10	j-20	j-30
Activity Related PRs						
EST - Earliest Start Time	26.6%	29.0%	29.9%	42.2%	**22.2%**	**16.8%**
EFT - Earliest Finish Time	25.4%	28.8%	29.1%	44.1%	20.0%	13.7%
LST - Latest Start Time	**27.8%**	28.2%	29.8%	**46.3%**	21.1%	13.3%
LFT - Latest Finish Time	27.1%	28.5%	29.8%	43.3%	21.5%	12.6%
SPT - Shortest Processing Time	23.2%	27.0%	29.4%	34.8%	15.6%	12.6%
LPT - Longest Processing Time	23.2%	27.0%	29.4%	34.8%	15.6%	12.6%
MSLK - Minimum Slack	24.1%	23.9%	22.6%	38.9%	19.3%	15.2%
Resource Related PRs						
GRWC - Greatest Resource Work Content	25.9%	**33.2%**	**37.4%**	36.7%	19.3%	15.9%
GCRWC - Greatest Cumulative Resource Work Content	25.1%	27.3%	30.7%	33.7%	17.0%	10.7%
Logic Related PRs						
MIS - Most Immediate Successors	24.1%	27.6%	30.3%	35.9%	18.5%	13.0%
MTS - Most Total Successors	27.7%	27.6%	26.9%	45.2%	19.3%	13.7%
LNRJ - Least Non-Related Jobs	22.6%	24.1%	23.4%	37.8%	20.0%	13.7%
GRPW - Greatest Rank Positional Weight	25.6%	27.9%	31.6%	34.1%	14.8%	11.9%

Table B.2: Priority rules performance comparison for SRIP/max

B.2. Forward/Backward scheduling (FBS)

For *FBS* testing, table B.3 & B.4 show the effect on PSO performance for the different problem sizes of SRCPSP and SRIP/max respectively. *Base PSO* was used, with 40 single density particles for forward scheduling only, and 20 forward and 20 backward for *FBS*; and no justification was implemented. The stopping condition was set to 1000 generated schedules. The performance figures are showing that FBS is not providing general improvement, but still there is improvement in almost 50% of all cases for both problem categories. So, both approaches will be used alternatively in further testing.

Schedule Generation Direction	Priority Rule	Average CP Deviation (AD_CP)				Problems Solved to Optimality			
		j-30	j-60	j-90	j-120	j-30	j-60	j-90	j-120
Forward Only	LST	16.0%	15.9%	15.6%	46.2%	64.6%	62.5%	**66.5%**	18.7%
	LFT	16.1%	16.3%	16.1%	47.3%	62.9%	61.3%	64.2%	17.8%
	MTS	16.7%	**14.8%**	**14.4%**	**43.0%**	55.4%	60.4%	64.4%	18.5%

Forward / Backward	LST	15.9%	15.7%	15.5%	46.1%	64.0%	63.1%	66.5%	19.0%
	LFT	15.8%	16.0%	16.0%	47.2%	66.3%	62.3%	64.6%	17.3%
	MTS	16.6%	14.8%	14.6%	43.6%	57.3%	62.1%	64.0%	17.3%

Table B.3: Forward/Backward scheduling performance comparison for SRCPSP

Schedule Generation Direction	Priority Rule	Average Cost Saving (ACS)			Problems Solved to Optimality		
		j-10	j-20	j-30	j-10	j-20	j-30
Forward Only	EST	26.4%	29.7%	30.2%	41.5%	21.1%	13.3%
	LST	27.8%	28.3%	30.7%	47.8%	20.7%	13.0%
	GRWC	26.2%	33.2%	37.0%	37.0%	20.0%	15.6%
Forward / Backward	EST	26.5%	29.6%	30.3%	43.3%	21.9%	15.9%
	LST	27.2%	28.1%	30.3%	44.4%	22.6%	13.0%
	GRWC	26.2%	33.1%	37.6%	37.4%	19.6%	16.3%

Table B.4: Forward/Backward scheduling performance comparison for SRIP/max

B.3. Double justification and mapping

For double justification testing, *Base PSO* was also used, with 20 single density forward particles. The stopping condition was also set to 1000 generated schedules. Tables B.5 & B.6 clearly show that *Double Justification* is providing a significant performance improvement for both problem categories; while *Mapping* is also showing some improvement, mainly in *RCPSPs* (also confirmed in the detailed analysis of DDPSO).

Schedule Generation Direction	Priority Rule	Average CP Deviation (AD$_{CP}$)				Problems Solved to Optimality			
		j-30	j-60	j-90	j-120	j-30	j-60	j-90	j-120
No Justification	LST	15.6%	15.4%	15.5%	46.1%	66.9%	63.8%	66.3%	19.2%
	LFT	15.7%	15.7%	15.9%	47.2%	65.4%	62.5%	64.4%	17.8%
	MTS	17.1%	14.8%	14.5%	43.1%	54.8%	58.8%	64.0%	18.7%
Double Justification	LST	14.7%	13.6%	13.4%	40.7%	73.3%	69.6%	70.6%	25.7%
	LFT	14.9%	13.6%	13.5%	40.7%	71.9%	70.4%	70.8%	26.8%
	MTS	15.9%	13.7%	13.2%	39.7%	62.7%	65.8%	69.0%	24.7%
Double Justification with Mapping	LST	15.3%	13.5%	13.2%	40.0%	69.4%	68.5%	69.6%	26.8%
	LFT	15.2%	13.3%	13.1%	39.9%	69.4%	70.6%	71.3%	27.8%
	MTS	15.3%	13.4%	13.0%	39.6%	68.5%	69.0%	70.6%	27.5%

Table B.5: Justification performance comparison for SRCPSP

Schedule Generation Direction	Priority Rule	Average Cost Saving (ACS)			Problems Solved to Optimality		
		j-10	j-20	j-30	j-10	j-20	j-30
No Justification	EST	26.6%	29.0%	29.9%	42.2%	22.2%	16.8%
	LST	27.8%	28.2%	29.8%	46.3%	21.1%	13.3%
	GRWC	25.9%	33.2%	37.4%	36.7%	19.3%	15.9%
Double Justification	EST	27.1%	31.0%	31.4%	48.5%	24.8%	17.8%
	LST	28.4%	29.9%	32.9%	51.1%	25.9%	19.6%
	GRWC	27.0%	33.7%	38.4%	43.7%	20.7%	18.9%
Double Justification with Mapping	EST	27.4%	30.6%	31.0%	47.8%	24.4%	18.1%
	LST	28.7%	29.9%	32.1%	50.7%	26.3%	16.7%
	GRWC	27.1%	33.4%	38.0%	41.9%	21.5%	20.4%

Table B.6: Justification performance comparison for SRIP/max

B.4. Algorithm parameters

Two PSO parameters were tested: *nParticles* (number of swarm particles) and *Constriction Factor* value. For *nParticles*, *LST* priority rule was used with variable number of swarm particles and generated schedules; also *FBS & DJ* were alternatively used.

As shown in tables B.9 & B.10, the effect of changing the number of swarm particles was having different impact with the size and type of justification used; so, a detailed analysis was performed to decide the optimum number of particles to be adopted in the DDPSO analysis.

The results summarized in tables B.9 to B.10 & Charts B.1 to B.9 shows a trend that the larger the number of schedules to be generated the higher the need for larger number of particles to achieve better solutions. This trend is clearly visible with the small sized problems, but not necessarily true for large sized problems. So, for the purpose of generalizing a good number of particles to be selected for further DDPSO analysis, table B.7 was generated concluding the above results; taking into consideration that FBS & Justification are implemented.

N_{Sch}	No. of Particles			
	j-30	j-60	j-90	j-120
1,000	10/10	10/10	10/10	10/10
5,000	20/20	20/20	20/20	20/20
10,000	40/40	30/30	20/20	20/20
50,000	60/60	40/40	30/30	20/20

Table B.7: Best performing number of particles for different problems sized

N$_{Sch}$	DJ	Map.	N$_{Part}$	AD$_O$	AD$_{CP}$				Problems Solved to Optimality				
				j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
1,000 Schedules	No	No	10	1.39%	15.5%	15.5%	46.0%	**23.1%**	68.3%	63.5%	66.3%	19.2%	**54.3%**
	No	No	20	1.67%	15.7%	15.5%	46.1%	**23.2%**	67.3%	62.7%	66.0%	19.0%	**53.8%**
	No	No	30	1.65%	15.9%	15.5%	46.1%	**23.3%**	67.9%	62.9%	66.3%	19.0%	**54.0%**
	No	No	40	1.78%	15.7%	15.6%	46.1%	**23.3%**	66.3%	62.9%	65.8%	19.0%	**53.5%**
	No	No	50	1.74%	15.8%	15.5%	46.1%	**23.3%**	65.6%	62.9%	66.5%	19.0%	**53.5%**
	No	No	60	1.84%	15.9%	15.6%	46.2%	**23.4%**	65.4%	62.7%	66.3%	18.8%	**53.3%**
	Yes	No	10/10	1.09%	13.9%	13.6%	41.2%	**20.9%**	73.5%	69.6%	69.8%	25.0%	**59.5%**
	Yes	No	20/20	1.49%	14.2%	13.8%	41.6%	**21.3%**	67.7%	68.3%	68.8%	24.8%	**57.4%**
	Yes	No	30/30	2.33%	15.0%	14.3%	42.4%	**22.1%**	61.3%	64.4%	67.7%	23.0%	**54.1%**
	Yes	No	40/40	3.73%	15.9%	14.8%	43.7%	**23.2%**	54.8%	60.8%	66.5%	19.5%	**50.4%**
	Yes	No	50/50	3.73%	15.9%	14.8%	43.7%	**23.2%**	54.8%	60.8%	66.5%	19.5%	**50.4%**
	Yes	No	60/60	3.73%	15.9%	14.8%	43.7%	**23.2%**	54.8%	60.8%	66.5%	19.5%	**50.4%**
	Yes	Yes	10/10	1.20%	13.7%	13.3%	40.4%	**20.6%**	71.3%	69.6%	70.0%	25.8%	**59.2%**
	Yes	Yes	20/20	1.62%	14.2%	13.7%	41.1%	**21.2%**	66.0%	67.1%	68.5%	24.8%	**56.6%**
	Yes	Yes	30/30	2.31%	14.8%	14.1%	41.9%	**21.9%**	61.7%	64.8%	68.1%	22.8%	**54.4%**
	Yes	Yes	40/40	3.68%	15.7%	14.7%	43.2%	**23.0%**	55.0%	61.3%	66.5%	19.7%	**50.6%**
	Yes	Yes	50/50	3.68%	15.7%	14.7%	43.2%	**23.0%**	55.0%	61.3%	66.5%	19.7%	**50.6%**
	Yes	Yes	60/60	3.68%	15.7%	14.7%	43.2%	**23.0%**	55.0%	61.3%	66.5%	19.7%	**50.6%**
5,000 Schedules	No	No	10	0.98%	14.2%	14.5%	44.6%	**22.0%**	73.5%	67.9%	68.3%	21.3%	**57.8%**
	No	No	20	0.90%	14.6%	15.0%	45.5%	**22.4%**	75.0%	66.0%	67.3%	20.0%	**57.1%**
	No	No	30	0.91%	14.8%	15.1%	45.6%	**22.5%**	74.4%	65.2%	67.3%	19.7%	**56.6%**
	No	No	40	0.89%	14.8%	15.1%	45.6%	**22.5%**	72.9%	66.0%	66.9%	20.2%	**56.5%**
	No	No	50	0.99%	14.8%	15.1%	45.6%	**22.6%**	72.5%	65.2%	66.9%	19.8%	**56.1%**
	No	No	60	0.95%	15.0%	15.1%	45.6%	**22.6%**	73.8%	64.8%	67.3%	20.7%	**56.6%**
	Yes	No	10/10	0.47%	13.0%	12.9%	39.7%	**19.9%**	82.5%	72.5%	73.3%	28.2%	**64.1%**
	Yes	No	20/20	0.46%	13.0%	13.0%	39.9%	**20.0%**	83.8%	73.1%	72.9%	27.7%	**64.4%**
	Yes	No	30/30	0.51%	13.0%	13.0%	39.9%	**20.0%**	81.9%	72.7%	72.3%	28.0%	**63.7%**
	Yes	No	40/40	0.62%	13.2%	13.1%	39.9%	**20.1%**	79.6%	71.3%	71.9%	28.0%	**62.7%**
	Yes	No	50/50	0.60%	13.2%	13.1%	40.0%	**20.1%**	79.8%	71.7%	71.5%	27.7%	**62.6%**
	Yes	No	60/60	0.71%	13.3%	13.2%	40.1%	**20.2%**	78.5%	72.1%	72.3%	27.7%	**62.6%**
	Yes	Yes	10/10	0.39%	12.5%	12.5%	38.5%	**19.4%**	86.5%	73.8%	73.8%	29.7%	**65.9%**
	Yes	Yes	20/20	0.35%	12.5%	12.6%	38.7%	**19.4%**	87.3%	73.3%	73.8%	30.2%	**66.1%**
	Yes	Yes	30/30	0.43%	12.6%	12.6%	38.7%	**19.5%**	83.5%	74.2%	73.3%	29.7%	**65.2%**
	Yes	Yes	40/40	0.51%	12.8%	12.7%	38.9%	**19.6%**	82.5%	72.1%	72.1%	28.8%	**63.9%**
	Yes	Yes	50/50	0.59%	12.9%	12.7%	39.3%	**19.8%**	80.4%	72.7%	72.3%	29.0%	**63.6%**
	Yes	Yes	60/60	0.63%	13.0%	12.9%	39.4%	**19.9%**	78.1%	72.3%	72.1%	28.8%	**62.8%**

N_{Sch}	DJ	Map.	N_{Part}	AD_O	AD_{CP}				Problems Solved to Optimality				
				j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
10,000 Schedules	No	No	10	0.86%	13.9%	14.1%	42.9%	**21.3%**	74.6%	69.0%	69.0%	22.8%	**58.8%**
	No	No	20	0.69%	14.3%	14.4%	44.0%	**21.8%**	76.3%	68.1%	67.7%	21.7%	**58.4%**
	No	No	30	0.74%	14.2%	14.6%	45.0%	**22.0%**	76.5%	66.7%	68.3%	20.7%	**58.0%**
	No	No	40	0.67%	14.5%	14.9%	45.2%	**22.2%**	77.1%	66.9%	67.9%	20.5%	**58.1%**
	No	No	50	0.66%	14.5%	14.9%	45.3%	**22.3%**	77.1%	65.8%	67.3%	20.2%	**57.6%**
	No	No	60	0.80%	14.6%	15.0%	45.4%	**22.4%**	74.8%	66.3%	67.5%	20.2%	**57.2%**
	Yes	No	10/10	0.37%	12.8%	12.8%	39.2%	**19.7%**	85.0%	73.3%	73.3%	28.7%	**65.1%**
	Yes	No	20/20	0.32%	12.8%	12.8%	39.4%	**19.7%**	86.7%	73.1%	73.3%	29.0%	**65.5%**
	Yes	No	30/30	0.31%	12.8%	12.8%	39.4%	**19.7%**	87.1%	72.7%	72.9%	28.7%	**65.3%**
	Yes	No	40/40	0.38%	12.8%	12.8%	39.4%	**19.7%**	84.6%	73.1%	72.9%	28.7%	**64.8%**
	Yes	No	50/50	0.36%	12.8%	12.8%	39.5%	**19.7%**	85.6%	73.3%	73.1%	28.3%	**65.1%**
	Yes	No	60/60	0.46%	12.9%	12.9%	39.5%	**19.8%**	83.1%	72.3%	73.1%	28.8%	**64.3%**
	Yes	Yes	10/10	0.29%	12.2%	12.3%	38.0%	**19.1%**	88.1%	74.6%	74.4%	31.2%	**67.1%**
	Yes	Yes	20/20	0.26%	12.2%	12.4%	38.0%	**19.1%**	88.3%	73.8%	74.2%	31.2%	**66.9%**
	Yes	Yes	30/30	0.28%	12.2%	12.3%	38.1%	**19.1%**	87.9%	73.8%	74.6%	31.2%	**66.9%**
	Yes	Yes	40/40	0.26%	12.3%	12.4%	38.2%	**19.2%**	89.2%	74.4%	74.4%	31.0%	**67.2%**
	Yes	Yes	50/50	0.29%	12.3%	12.4%	38.3%	**19.2%**	87.5%	73.5%	74.4%	30.5%	**66.5%**
	Yes	Yes	60/60	0.36%	12.4%	12.4%	38.3%	**19.2%**	86.0%	74.2%	73.5%	30.2%	**66.0%**
50,000 Schedules	No	No	10	0.73%	13.5%	13.7%	42.2%	**20.9%**	77.9%	70.0%	70.0%	24.0%	**60.5%**
	No	No	20	0.53%	13.5%	13.8%	42.2%	**20.9%**	81.9%	69.0%	69.8%	24.3%	**61.2%**
	No	No	30	0.47%	13.6%	13.9%	42.3%	**21.0%**	81.7%	69.4%	69.4%	24.3%	**61.2%**
	No	No	40	0.50%	13.7%	13.9%	42.4%	**21.0%**	81.0%	69.2%	69.2%	24.3%	**60.9%**
	No	No	50	0.46%	13.7%	14.0%	42.6%	**21.1%**	80.6%	68.3%	69.4%	24.0%	**60.6%**
	No	No	60	0.46%	13.8%	14.1%	42.6%	**21.1%**	81.5%	69.8%	68.5%	23.8%	**60.9%**
	Yes	No	10/10	0.20%	12.4%	12.4%	38.3%	**19.2%**	90.4%	74.4%	74.2%	30.2%	**67.3%**
	Yes	No	20/20	0.19%	12.3%	12.4%	38.3%	**19.2%**	91.3%	74.2%	73.8%	30.7%	**67.5%**
	Yes	No	30/30	0.17%	12.3%	12.4%	38.3%	**19.2%**	91.5%	74.8%	74.6%	30.8%	**67.9%**
	Yes	No	40/40	0.18%	12.3%	12.4%	38.4%	**19.2%**	91.5%	74.2%	74.0%	30.2%	**67.4%**
	Yes	No	50/50	0.19%	12.3%	12.4%	38.5%	**19.2%**	90.4%	74.6%	74.6%	30.0%	**67.4%**
	Yes	No	60/60	0.18%	12.3%	12.4%	38.6%	**19.2%**	91.0%	74.0%	74.6%	30.0%	**67.4%**
	Yes	Yes	10/10	0.14%	11.8%	11.9%	36.9%	**18.5%**	92.5%	75.8%	76.3%	33.7%	**69.6%**
	Yes	Yes	20/20	0.12%	11.8%	11.9%	37.0%	**18.5%**	94.0%	75.6%	76.0%	33.2%	**69.7%**
	Yes	Yes	30/30	0.13%	11.8%	11.9%	36.9%	**18.6%**	92.1%	75.2%	75.6%	32.8%	**68.9%**
	Yes	Yes	40/40	0.11%	11.8%	11.9%	37.0%	**18.6%**	93.3%	75.4%	76.5%	32.5%	**69.4%**
	Yes	Yes	50/50	0.13%	11.8%	11.9%	37.1%	**18.6%**	93.5%	75.2%	75.8%	33.0%	**69.4%**
	Yes	Yes	60/60	0.09%	11.8%	11.9%	37.0%	**18.6%**	94.6%	75.6%	75.6%	33.7%	**69.9%**

Table B.8: Number of particles performance comparison for SRCPSP
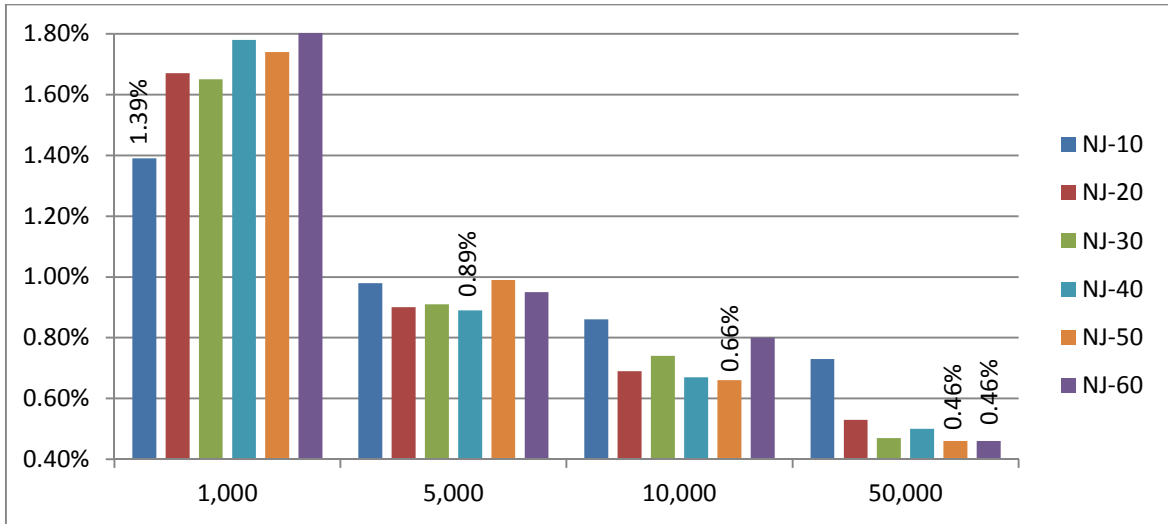
Figure B.1: No. of particles performance for RCPSP j-30 AD_O (no justification)
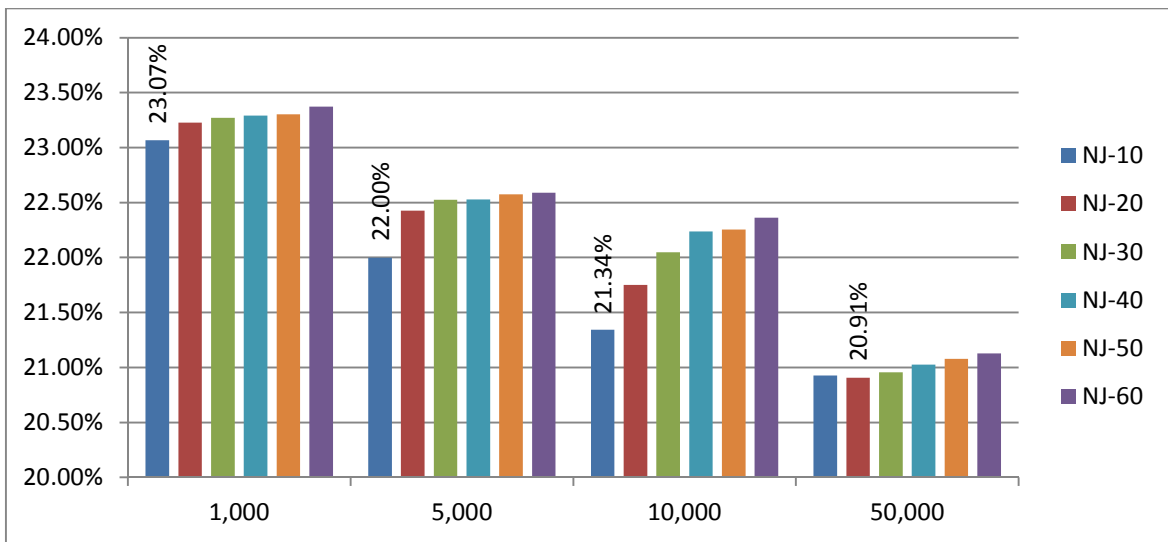
Figure B.2: No. of particles performance for RCPSP j60-j120 AD_{CP} (no justification)
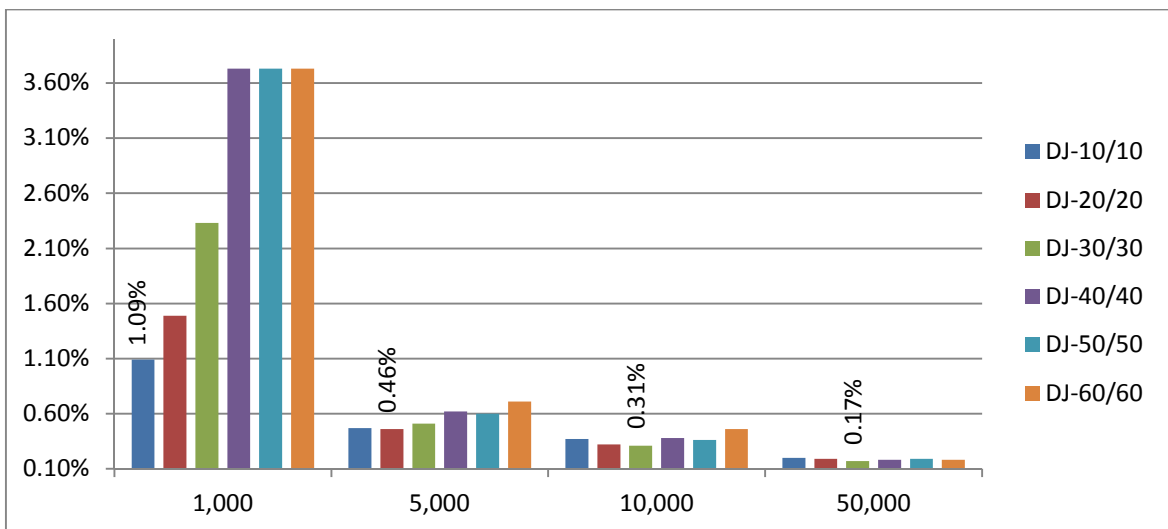
Figure B.3: No. of particles performance for RCPSP j30 AD_O (with DJ)
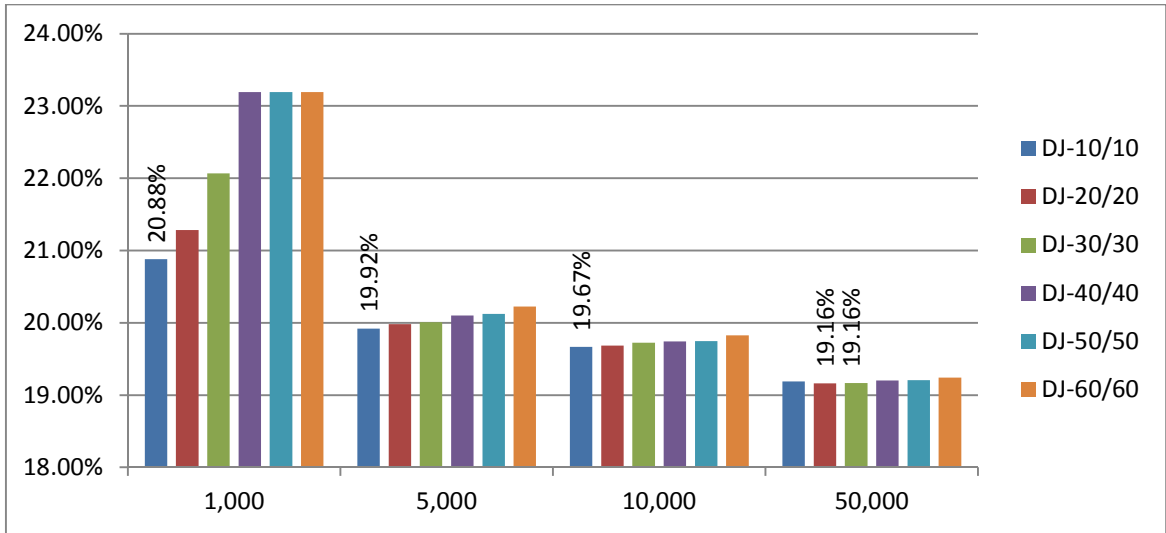
Figure B.4: No. of particles performance for RCPSP j60-j120 AD_{CP} (with DJ)
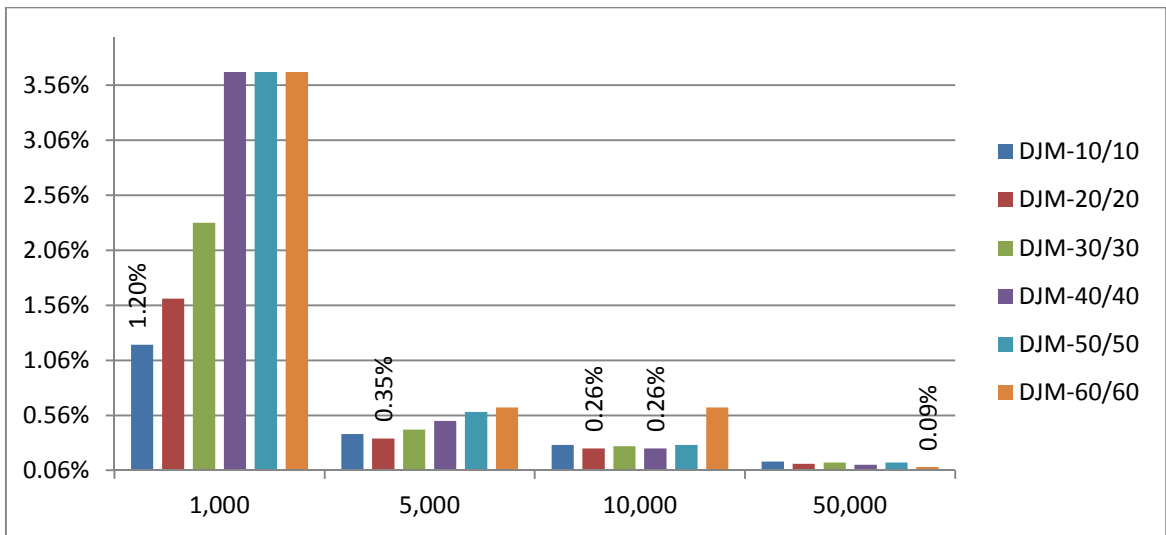
Figure B.5: No. of particles performance for RCPSP j30 AD_O (with DJ & mapping)
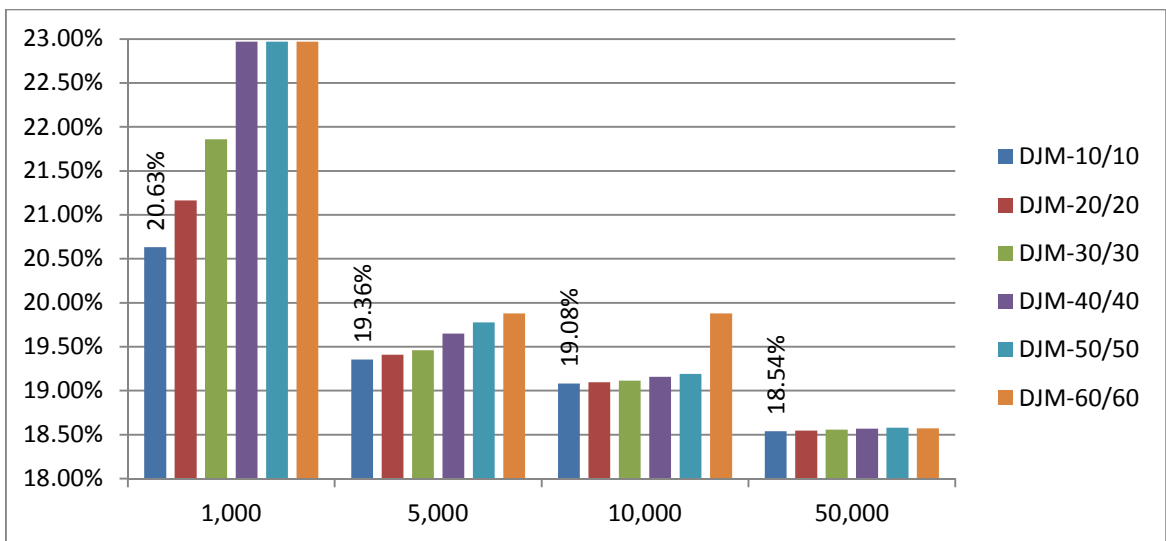
Figure B.6: No. of particles performance for RCPSP j60-120 AD_{CP} (with DJ & mapping)

N_{Sch}	DJ	Map.	N_{Part}	Average Cost Saving (ACS)				Problems Solved to Optimality			
				j-10	j-20	j-30	Aver.	j-10	j-20	j-30	Aver.
1,000 Schedules	No	No	10	29.1%	33.9%	29.6%	**30.9%**	46.7%	22.6%	14.4%	**27.9%**
	No	No	20	29.2%	33.7%	32.0%	**31.6%**	48.1%	23.0%	14.1%	**28.4%**
	No	No	30	29.4%	33.5%	31.9%	**31.6%**	47.0%	22.2%	14.1%	**27.8%**
	No	No	40	28.9%	33.6%	30.2%	**30.9%**	46.3%	23.3%	14.1%	**27.9%**
	No	No	50	29.0%	33.4%	29.7%	**30.7%**	45.9%	24.1%	15.2%	**28.4%**
	No	No	60	29.4%	33.6%	29.5%	**30.8%**	48.1%	24.4%	14.8%	**29.1%**
	Yes	No	10/10	30.3%	36.7%	32.9%	**33.3%**	56.3%	28.9%	24.4%	**36.5%**
	Yes	No	20/20	29.5%	33.0%	27.6%	**30.1%**	53.0%	29.6%	22.6%	**35.1%**
	Yes	No	30/30	28.0%	30.5%	25.9%	**28.1%**	50.0%	27.8%	18.5%	**32.1%**
	Yes	No	40/40	26.8%	27.6%	22.9%	**25.7%**	42.2%	21.9%	13.3%	**25.8%**
	Yes	No	50/50	26.8%	27.6%	22.9%	**25.7%**	42.2%	21.9%	13.3%	**25.8%**
	Yes	No	60/60	26.8%	27.6%	22.9%	**25.7%**	42.2%	21.9%	13.3%	**25.8%**
	Yes	Yes	10/10	30.5%	35.7%	31.3%	**32.5%**	54.4%	31.5%	24.1%	**36.7%**
	Yes	Yes	20/20	29.2%	33.3%	28.1%	**30.2%**	54.8%	30.4%	23.0%	**36.0%**
	Yes	Yes	30/30	28.4%	30.4%	26.0%	**28.3%**	49.6%	24.1%	17.0%	**30.2%**
	Yes	Yes	40/40	26.8%	27.6%	22.9%	**25.7%**	42.2%	21.9%	13.3%	**25.8%**
	Yes	Yes	50/50	26.8%	27.6%	22.9%	**25.7%**	42.2%	21.9%	13.3%	**25.8%**
	Yes	Yes	60/60	26.8%	27.6%	22.9%	**25.7%**	42.2%	21.9%	13.3%	**25.8%**
5,000 Schedules	No	No	10	28.9%	34.0%	33.5%	**32.1%**	47.0%	23.7%	14.8%	**28.5%**
	No	No	20	29.7%	34.5%	32.7%	**32.3%**	48.5%	23.7%	15.9%	**29.4%**
	No	No	30	29.3%	34.1%	32.7%	**32.0%**	48.9%	23.7%	15.2%	**29.3%**
	No	No	40	29.4%	34.4%	33.6%	**32.5%**	47.8%	23.3%	14.1%	**28.4%**
	No	No	50	29.2%	34.9%	32.5%	**32.2%**	46.7%	24.1%	14.8%	**28.5%**
	No	No	60	29.6%	34.4%	32.7%	**32.2%**	47.0%	24.4%	13.7%	**28.4%**
	Yes	No	10/10	31.3%	36.9%	37.2%	**35.1%**	57.0%	31.5%	28.9%	**39.1%**
	Yes	No	20/20	31.0%	38.3%	36.1%	**35.1%**	56.3%	34.1%	27.4%	**39.3%**
	Yes	No	30/30	31.2%	37.1%	35.5%	**34.6%**	54.8%	31.1%	27.8%	**37.9%**
	Yes	No	40/40	31.1%	37.7%	35.4%	**34.7%**	57.0%	33.7%	25.9%	**38.9%**
	Yes	No	50/50	30.7%	37.0%	35.4%	**34.4%**	55.6%	33.7%	25.6%	**38.3%**
	Yes	No	60/60	30.7%	37.5%	35.7%	**34.7%**	55.9%	31.9%	27.4%	**38.4%**
	Yes	Yes	10/10	30.9%	37.4%	37.9%	**35.4%**	54.8%	31.9%	26.3%	**37.7%**
	Yes	Yes	20/20	31.3%	38.0%	36.1%	**35.1%**	57.4%	33.0%	30.0%	**40.1%**
	Yes	Yes	30/30	31.2%	37.8%	34.9%	**34.6%**	54.8%	32.2%	25.9%	**37.7%**
	Yes	Yes	40/40	30.6%	38.0%	36.4%	**35.0%**	55.6%	32.6%	28.1%	**38.8%**
	Yes	Yes	50/50	30.7%	37.1%	36.1%	**34.6%**	56.3%	31.5%	27.4%	**38.4%**
	Yes	Yes	60/60	30.7%	37.7%	34.4%	**34.3%**	55.2%	33.3%	25.9%	**38.1%**

N$_{Sch}$	DJ	Map.	N$_{Part}$	Average Cost Saving (ACS)				Problems Solved to Optimality			
				j-10	j-20	j-30	Aver.	j-10	j-20	j-30	Aver.
10,000 Schedules	No	No	10	29.3%	34.5%	33.0%	**32.3%**	46.3%	23.0%	14.1%	**27.8%**
	No	No	20	29.2%	34.2%	32.0%	**31.8%**	46.7%	23.7%	14.1%	**28.1%**
	No	No	30	29.4%	34.3%	32.7%	**32.1%**	47.0%	24.4%	15.2%	**28.9%**
	No	No	40	29.8%	34.6%	33.2%	**32.5%**	49.3%	23.3%	15.2%	**29.3%**
	No	No	50	29.6%	34.2%	33.4%	**32.4%**	49.3%	24.1%	15.2%	**29.5%**
	No	No	60	29.7%	34.4%	33.9%	**32.6%**	47.4%	25.2%	14.4%	**29.0%**
	Yes	No	10/10	31.4%	38.0%	37.1%	**35.5%**	57.0%	32.2%	28.5%	**39.3%**
	Yes	No	20/20	31.7%	38.1%	37.1%	**35.7%**	57.4%	31.9%	27.8%	**39.0%**
	Yes	No	30/30	31.4%	39.3%	37.5%	**36.1%**	57.4%	35.9%	28.1%	**40.5%**
	Yes	No	40/40	31.3%	37.8%	37.7%	**35.6%**	54.8%	34.1%	27.8%	**38.9%**
	Yes	No	50/50	31.2%	38.3%	37.7%	**35.7%**	58.1%	33.0%	28.9%	**40.0%**
	Yes	No	60/60	31.2%	38.8%	38.4%	**36.1%**	56.7%	34.4%	29.3%	**40.1%**
	Yes	Yes	10/10	31.0%	37.9%	37.2%	**35.4%**	56.7%	34.4%	31.1%	**40.7%**
	Yes	Yes	20/20	31.2%	37.6%	37.6%	**35.5%**	55.6%	32.6%	30.0%	**39.4%**
	Yes	Yes	30/30	31.0%	38.5%	36.7%	**35.4%**	56.3%	34.1%	26.7%	**39.0%**
	Yes	Yes	40/40	31.4%	38.9%	37.5%	**35.9%**	57.0%	35.6%	30.7%	**41.1%**
	Yes	Yes	50/50	31.3%	38.4%	37.4%	**35.7%**	57.4%	33.3%	29.3%	**40.0%**
	Yes	Yes	60/60	31.2%	37.8%	37.0%	**35.3%**	55.6%	32.2%	30.0%	**39.3%**
50,000 Schedules	No	No	10	29.1%	34.6%	32.8%	**32.2%**	47.4%	24.1%	15.2%	**28.9%**
	No	No	20	30.0%	34.8%	31.7%	**32.2%**	47.8%	24.1%	14.1%	**28.6%**
	No	No	30	29.8%	34.8%	33.0%	**32.5%**	47.4%	23.3%	15.6%	**28.8%**
	No	No	40	29.4%	34.5%	32.1%	**32.0%**	47.8%	24.8%	14.1%	**28.9%**
	No	No	50	29.7%	34.3%	32.0%	**32.0%**	48.5%	24.4%	14.1%	**29.0%**
	No	No	60	29.6%	34.5%	33.4%	**32.5%**	47.0%	23.3%	15.6%	**28.6%**
	Yes	No	10/10	31.4%	38.6%	37.5%	**35.8%**	58.5%	34.1%	30.0%	**40.9%**
	Yes	No	20/20	31.4%	38.2%	36.6%	**35.4%**	56.3%	33.3%	30.4%	**40.0%**
	Yes	No	30/30	31.5%	38.7%	37.7%	**36.0%**	57.4%	33.3%	29.6%	**40.1%**
	Yes	No	40/40	31.5%	39.2%	39.0%	**36.5%**	57.0%	33.7%	29.6%	**40.1%**
	Yes	No	50/50	31.2%	38.5%	37.7%	**35.8%**	55.9%	33.3%	27.8%	**39.0%**
	Yes	No	60/60	30.8%	38.5%	38.9%	**36.0%**	57.0%	32.6%	28.5%	**39.4%**
	Yes	Yes	10/10	31.5%	38.7%	39.0%	**36.4%**	54.8%	33.3%	29.3%	**39.1%**
	Yes	Yes	20/20	31.0%	38.7%	38.2%	**36.0%**	54.1%	31.1%	29.6%	**38.3%**
	Yes	Yes	30/30	31.8%	39.4%	37.1%	**36.1%**	57.4%	34.1%	30.0%	**40.5%**
	Yes	Yes	40/40	31.6%	38.2%	37.1%	**35.6%**	56.7%	32.6%	29.3%	**39.5%**
	Yes	Yes	50/50	31.4%	37.7%	38.5%	**35.8%**	57.8%	32.6%	31.1%	**40.5%**
	Yes	Yes	60/60	31.2%	38.9%	37.7%	**35.9%**	56.7%	33.0%	32.2%	**40.6%**

Table B.9: Number of particles performance comparison for SRIP/max
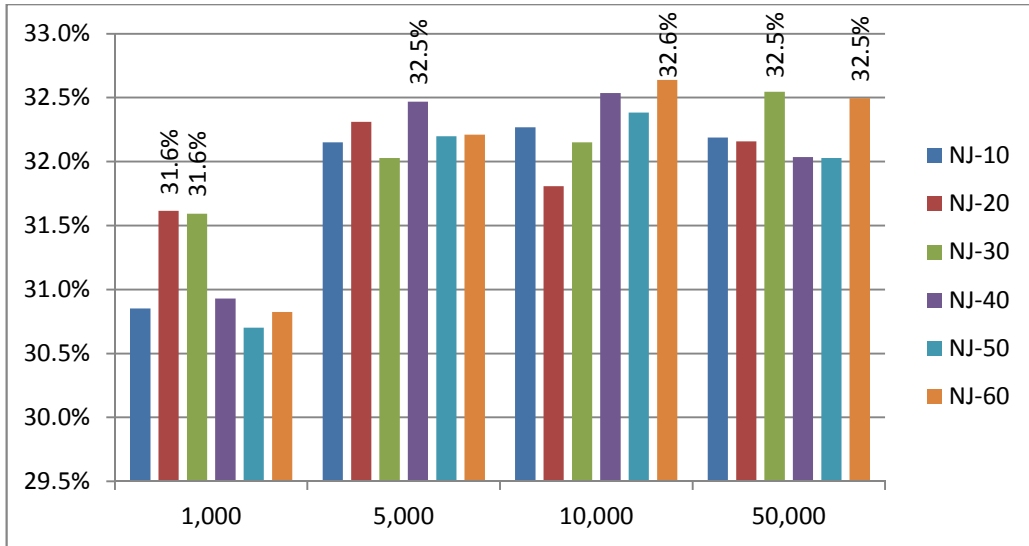
Figure B.7: No. of particles performance for SRIP/max *ACS* (no justification)
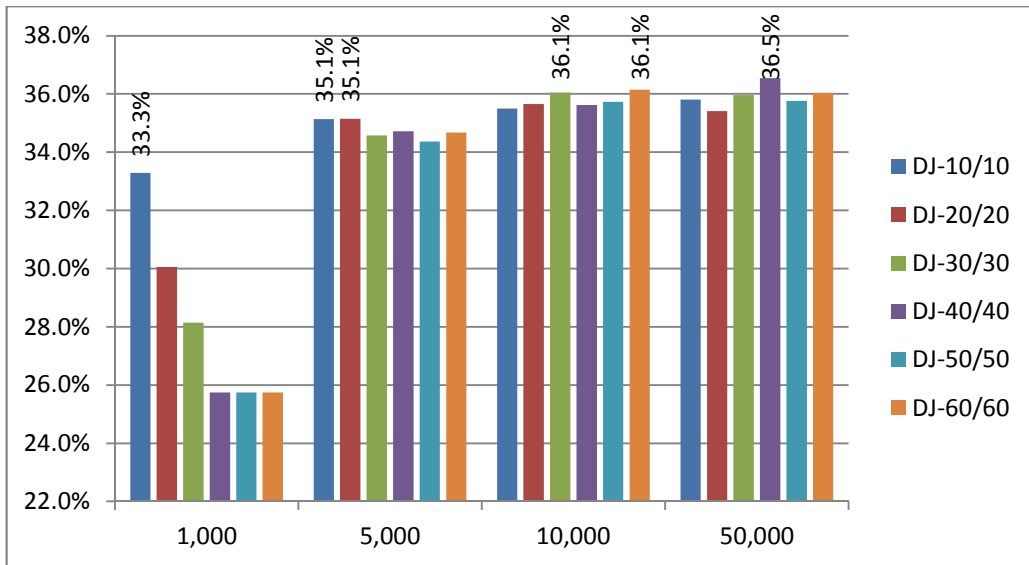
Figure B.8: No. of particles performance for SRIP/max *ACS* (with DJ)
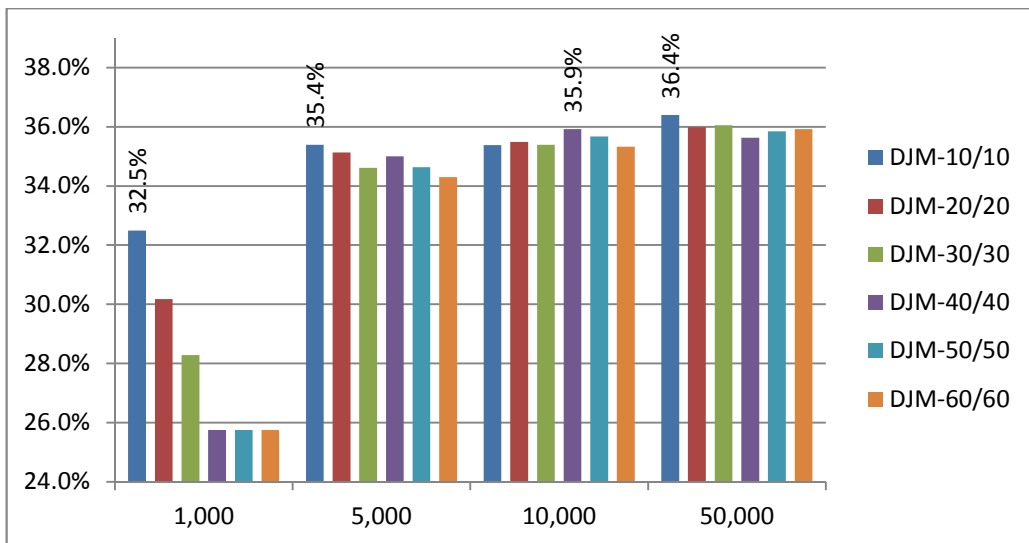
Figure B.9: No. of particles performance for SRIP/max *ACS* (with DJ & mapping)

And finally for *Constriction Factor* value, *Standard PSO* was used, with 20 single density forward particles, *LFT* priority rule for RCPSP (*LST* for TCPSP), and *DJ*. Stopping condition was tested for 1000, 5000 & 10000 generated schedules.

N_{Sch}	Schedule Generation Direction	AD_O	Average CP Deviation (AD_{CP})				Problems Solved to Optimality			
		j-30	j-30	j-60	j-90	j-120	j-30	j-60	j-90	j-120
1,000	χ = 1.0	1.32%	15.2%	14.0%	13.7%	41.3%	70.8%	69.4%	70.6%	25.7%
	χ = 0.9	1.27%	15.2%	14.0%	13.7%	41.3%	71.3%	68.3%	70.2%	26.2%
	χ = 0.8	1.30%	15.2%	14.0%	13.6%	41.2%	69.8%	69.2%	70.4%	25.7%
	χ = 0.73	1.32%	15.2%	14.0%	13.7%	41.2%	68.8%	69.2%	70.2%	25.3%
	χ = 0.6	1.39%	15.3%	14.1%	13.6%	41.1%	69.2%	69.4%	69.0%	25.7%
	χ = 0.5	1.61%	15.6%	14.1%	13.7%	41.1%	68.3%	67.9%	70.0%	25.5%
	χ = 0.4	1.69%	15.7%	14.1%	13.6%	41.1%	65.2%	70.0%	69.6%	24.2%
5,000	χ = 1.0	0.52%	14.1%	13.2%	13.1%	40.1%	81.7%	72.7%	72.1%	27.5%
	χ = 0.9	0.54%	14.1%	13.1%	13.1%	40.0%	82.7%	72.3%	72.3%	27.5%
	χ = 0.8	0.60%	14.2%	12.9%	12.9%	39.6%	80.4%	72.9%	73.1%	28.0%
	χ = 0.73	0.74%	14.4%	12.9%	12.8%	39.4%	76.0%	71.7%	73.1%	28.2%
	χ = 0.6	1.00%	14.8%	13.1%	12.8%	38.8%	73.3%	70.8%	71.7%	28.2%
	χ = 0.5	1.08%	14.9%	13.2%	12.8%	39.1%	72.9%	70.4%	71.5%	27.5%
	χ = 0.4	1.27%	15.2%	13.4%	12.9%	39.1%	69.8%	70.0%	70.6%	28.5%
10,000	χ = 1.0	0.45%	14.0%	13.0%	13.0%	39.8%	83.1%	72.7%	73.1%	27.7%
	χ = 0.9	0.38%	13.9%	12.9%	12.9%	39.7%	84.8%	72.9%	72.7%	28.2%
	χ = 0.8	0.48%	14.0%	12.7%	12.7%	39.2%	82.3%	72.7%	73.8%	28.5%
	χ = 0.73	0.54%	14.1%	12.6%	12.5%	38.7%	80.6%	72.5%	73.3%	29.7%
	χ = 0.6	0.89%	14.6%	12.9%	12.5%	38.3%	75.4%	71.7%	72.5%	28.7%
	χ = 0.5	1.06%	14.8%	13.1%	12.7%	38.6%	71.0%	71.7%	71.5%	27.7%
	χ = 0.4	1.15%	15.0%	13.4%	12.8%	38.9%	71.0%	70.4%	70.6%	26.8%

Table B.10: Constriction Factor performance comparison for SRCPSP

For testing different *Constriction Factor (CF)* values, the results shows a general trend that the larger the problem size and the number of schedules generated the higher the need for smaller value for *CF* for reaching better solutions. This trend appears clearly in the RCPSP problems (table B.10); while for TCPSP (table B.11), the maximum size of 30 activities was not sufficient to make this trend clear for smaller number of schedules, but it started to be visible on the 10000 schedules test results. This trend is mainly because the *CF* serves for the solutions space exploration; so, for large size problems, lower *CF* values allows higher exploration, and accordingly better solutions can be achieved. Consequently, the following conclusion can be established: if the purpose of the analysis is to get quick optimized solution

(i.e. lower number of schedules to be generated), then large *CF* should be selected (0.8-0.9); otherwise, the *CF* value should be lowered with the increase of analysis time (0.7-0.8 for 5000 schedules, 0.6-0.7 for 10000 schedules, and even lower values for larger number of schedules to be generated).

N_{Sch}	Schedule Generation Direction	Average Cost Saving (ACS)			Problems Solved to Optimality		
		j-10	j-20	j-30	j-10	j-20	j-30
1,000	χ = 1.0	30.4%	36.3%	31.8%	55.9%	34.4%	22.2%
	χ = 0.9	30.5%	36.3%	31.4%	55.2%	30.4%	21.9%
	χ = 0.8	30.3%	35.7%	32.3%	54.4%	32.2%	24.8%
	χ = 0.73	30.1%	35.2%	29.8%	56.3%	31.5%	24.8%
	χ = 0.6	30.6%	34.9%	31.6%	55.9%	30.0%	23.7%
	χ = 0.5	29.5%	35.4%	30.5%	53.0%	29.6%	22.2%
	χ = 0.4	29.2%	33.5%	30.5%	51.5%	30.4%	24.1%
5,000	χ = 1.0	31.2%	37.4%	35.4%	55.9%	34.1%	27.8%
	χ = 0.9	31.3%	38.7%	36.7%	57.0%	34.1%	26.3%
	χ = 0.8	31.3%	37.1%	35.1%	55.9%	31.9%	26.3%
	χ = 0.73	30.3%	36.2%	35.2%	54.8%	31.5%	25.2%
	χ = 0.6	30.4%	35.9%	32.9%	54.1%	31.9%	25.2%
	χ = 0.5	30.1%	34.7%	32.5%	54.1%	29.3%	23.3%
	χ = 0.4	30.0%	34.6%	30.6%	52.6%	32.6%	23.7%
10,000	χ = 1.0	31.5%	38.8%	37.4%	56.7%	33.3%	28.1%
	χ = 0.9	31.1%	38.1%	36.9%	54.8%	32.6%	27.8%
	χ = 0.8	31.2%	37.1%	36.2%	55.2%	33.3%	27.0%
	χ = 0.73	31.2%	37.5%	36.0%	56.7%	33.0%	28.5%
	χ = 0.6	29.9%	37.1%	34.4%	53.7%	28.9%	25.2%
	χ = 0.5	29.7%	36.5%	32.1%	53.7%	30.7%	23.3%
	χ = 0.4	30.0%	36.2%	32.2%	53.0%	31.1%	25.2%

Table B.11: Constriction Factor performance comparison for SRIP/max

Appendix C: Detailed DDPSO test results

This appendix contains the full detailed testing for the proposed *DDPSO* algorithm and its elements. The experimental results were performed on 2850 problem (2040 for SRCPSP & 810 for RIP/max), with a detailed testing for more than 2000 different conditions (different elements & parameter values; resulting to about 6 million problem solving cycles, which corresponds to about 10,500 run-time hours for a single core PC (or about 1,900 run-time hours for the PC used in the analysis [2.4GHz-6cores]).

C.1. RCPSP justification schemes

C.1.1. Justification schemes comparison

N_{Sch}	Justification Scheme	Priority Rule	AD_O j-30	AD_{CP} j-30	j-60	j-90	j-120	Aver.	Problems Solved to Optimality j-30	j-60	j-90	j-120	Aver.
1,000 Schedules (10F/10B Particles)	NJ (No Justification)	LST	1.34	15.23	14.81	14.95	45.02	**22.50**	70.42	64.38	66.67	19.17	**55.16**
		LFT	1.33	15.16	14.98	15.11	45.62	**22.72**	68.33	63.75	65.21	18.17	**53.86**
		MTS	1.18	14.99	14.41	14.46	44.03	**21.97**	70.63	64.38	65.83	16.00	**54.21**
		CPR	0.90	14.61	14.54	14.65	44.03	**21.96**	74.38	66.46	68.33	21.17	**57.58**
	DJ (Double Justification)	LST	1.02	14.85	13.16	12.83	39.10	**19.99**	72.29	71.04	71.88	28.33	**60.89**
		LFT	1.00	14.80	13.13	12.85	39.11	**19.97**	74.38	72.29	71.67	28.33	**61.67**
		MTS	0.75	14.48	13.02	12.81	39.11	**19.85**	76.25	70.63	71.67	28.00	**61.64**
		CPR	0.51	14.12	12.89	12.76	38.81	**19.64**	82.29	72.71	72.08	28.83	**63.98**
	SJ (Stacking Justification)	LST	0.70	14.36	13.08	13.11	40.04	**20.15**	76.67	69.79	68.96	23.17	**59.65**
		LFT	0.64	14.28	13.07	13.11	40.20	**20.17**	78.33	70.42	69.38	23.17	**60.32**
		MTS	0.63	14.27	13.12	13.03	39.73	**20.04**	79.17	70.21	69.17	22.83	**60.34**
		CPR	0.46	14.04	13.03	12.86	39.20	**19.78**	82.50	71.04	70.42	26.00	**62.49**
	SDJ (Stacking & Double Justification)	LST	0.76	14.47	12.59	12.33	37.86	**19.31**	79.38	73.13	72.29	29.50	**63.57**
		LFT	0.66	14.33	12.66	12.36	37.83	**19.29**	79.38	72.29	72.50	29.00	**63.29**
		MTS	0.63	14.30	12.61	12.28	37.49	**19.17**	78.96	71.25	72.71	29.83	**63.19**
		CPR	0.45	14.06	12.55	12.24	37.44	**19.07**	84.79	73.33	72.92	30.17	**65.30**
	ASDJ (Alternating SJ & DJ)	LST	0.53	14.14	12.96	12.84	39.33	**19.82**	81.04	73.13	71.67	27.67	**63.38**
		LFT	0.59	14.23	13.10	12.80	39.41	**19.88**	80.21	71.88	71.88	28.00	**62.99**
		MTS	0.58	14.23	12.99	12.78	38.95	**19.74**	80.00	71.67	71.25	27.50	**62.60**
		CPR	0.42	14.00	12.88	12.78	39.05	**19.68**	83.33	72.71	72.50	29.00	**64.39**
5,000 Schedules (10F/10B Particles)	NJ (No Justification)	LST	0.70	14.34	13.79	14.25	43.59	**21.49**	76.88	68.33	68.33	20.67	**58.55**
		LFT	0.66	14.30	13.90	14.21	43.87	**21.57**	78.33	67.50	66.46	20.67	**58.24**
		MTS	0.57	14.17	13.65	13.95	42.75	**21.13**	80.42	68.13	67.08	19.33	**58.74**
		CPR	0.63	14.26	13.57	13.98	43.22	**21.26**	78.75	69.17	69.38	21.83	**59.78**
	DJ (Double Justification)	LST	0.21	13.69	12.06	11.97	37.13	**18.71**	90.21	75.42	75.63	32.83	**68.52**
		LFT	0.20	13.68	12.05	12.00	37.19	**18.73**	90.83	75.21	75.42	33.17	**68.66**
		MTS	0.18	13.65	12.06	11.93	37.07	**18.68**	90.63	75.42	75.21	32.67	**68.48**
		CPR	0.16	13.61	11.98	11.93	36.95	**18.62**	91.46	75.21	76.04	33.00	**68.93**

5,000 Schedules (10F/10B Particles)	SJ (Stacking Justification)	LST	0.13	13.56	12.13	12.26	38.07	**19.01**	93.13	73.54	73.33	28.33	**67.08**
		LFT	0.14	13.59	12.18	12.27	38.22	**19.07**	91.88	73.96	74.17	28.33	**67.08**
		MTS	0.13	13.57	12.15	12.26	38.07	**19.01**	93.33	73.75	73.75	28.33	**67.29**
		CPR	0.13	13.56	12.15	12.19	37.96	**18.96**	93.13	73.96	73.13	28.83	**67.26**
	SDJ (Stacking & Double Justification)	LST	0.11	13.56	11.73	11.60	36.13	**18.26**	94.17	76.67	75.83	33.50	**70.04**
		LFT	0.09	13.51	11.64	11.57	36.04	**18.19**	94.79	78.13	75.83	33.17	**70.48**
		MTS	0.09	13.51	11.71	11.60	36.04	**18.21**	94.79	77.08	76.67	33.83	**70.59**
		CPR	0.08	13.49	11.63	11.59	36.02	**18.18**	95.00	77.29	75.21	33.17	**70.17**
	ASDJ (Alternating SJ & DJ)	LST	0.14	13.58	12.04	12.13	37.37	**18.78**	92.50	75.42	74.58	31.67	**68.54**
		LFT	0.14	13.58	12.07	12.07	37.38	**18.78**	92.50	76.25	74.79	31.67	**68.80**
		MTS	0.09	13.52	12.10	12.09	37.39	**18.78**	95.00	75.00	74.58	31.50	**69.02**
		CPR	0.13	13.57	12.05	12.06	37.29	**18.74**	93.13	75.21	75.21	31.33	**68.72**
50,000 Schedules (20F/20B Particles)	NJ (No Justification)	LST	0.36	13.88	12.77	13.16	41.00	**20.21**	85.00	71.04	69.58	23.00	**62.16**
		LFT	0.26	13.74	12.57	12.91	40.63	**19.96**	87.29	71.67	70.00	23.50	**63.11**
		MTS	0.21	13.67	12.50	12.79	39.74	**19.68**	89.38	72.29	71.04	23.67	**64.09**
		CPR	0.30	13.79	12.49	12.78	39.92	**19.75**	85.83	72.29	71.25	26.83	**64.05**
	DJ (Double Justification)	LST	0.07	13.48	11.40	11.40	35.57	**17.97**	95.83	79.38	77.50	36.00	**72.18**
		LFT	0.08	13.49	11.43	11.44	35.65	**18.00**	95.63	78.54	77.29	36.33	**71.95**
		MTS	0.06	13.47	11.44	11.40	35.68	**18.00**	96.25	78.96	77.50	35.83	**72.14**
		CPR	0.06	13.45	11.40	11.37	35.61	**17.96**	96.25	79.17	77.29	36.33	**72.26**
	SJ (Stacking Justification)	LST	0.04	13.43	11.53	11.70	36.71	**18.34**	97.08	76.46	74.17	31.33	**69.76**
		LFT	0.06	13.46	11.52	11.71	36.67	**18.34**	96.46	77.50	74.58	31.50	**70.01**
		MTS	0.06	13.46	11.62	11.66	36.63	**18.34**	96.46	76.25	74.79	31.33	**69.71**
		CPR	0.06	13.46	11.59	11.68	36.62	**18.34**	96.46	76.04	75.21	31.67	**69.84**
	SDJ (Stacking & Double Justification)	LST	0.03	13.42	11.17	11.15	34.89	**17.66**	98.33	82.08	77.08	36.17	**73.42**
		LFT	0.02	13.41	11.19	11.14	34.93	**17.66**	98.54	80.63	77.08	36.00	**73.06**
		MTS	0.03	13.41	11.19	11.11	34.94	**17.66**	98.13	81.04	77.29	36.17	**73.16**
		CPR	0.03	13.42	11.21	11.13	34.90	**17.66**	98.33	80.83	77.29	36.50	**73.24**
	ASDJ (Alternating SJ & DJ)	LST	0.06	13.45	11.49	11.52	35.99	**18.11**	96.25	78.33	77.08	33.83	**71.38**
		LFT	0.05	13.44	11.48	11.53	36.00	**18.11**	96.88	78.54	77.08	34.33	**71.71**
		MTS	0.05	13.44	11.51	11.57	36.00	**18.13**	96.67	77.50	76.46	35.00	**71.41**
		CPR	0.03	13.43	11.50	11.50	35.92	**18.09**	97.71	77.92	77.29	34.33	**71.81**
1,000 Sched. (10F/10B)	NJ	Best of LST, LFT, MTS & CPR	0.90	14.61	14.41	14.46	44.03	**21.96**	74.38	66.46	68.33	21.17	**57.58**
	DJ		0.51	14.12	12.89	12.76	38.81	**19.64**	82.29	72.71	72.08	28.83	**63.98**
	SJ		0.46	14.04	13.03	12.86	39.20	**19.78**	82.50	71.04	70.42	26.00	**62.49**
	SDJ		0.45	14.06	12.55	12.24	37.44	**19.07**	84.79	73.33	72.92	30.17	**65.30**
	ASDJ		0.42	14.00	12.88	12.78	38.95	**19.68**	83.33	73.13	72.50	29.00	**64.39**
5,000 Sched. (10F/10B)	NJ	Best of LST, LFT, MTS & CPR	0.57	14.17	13.57	13.95	42.75	**21.13**	80.42	69.17	69.38	21.83	**59.78**
	DJ		0.16	13.61	11.98	11.93	36.95	**18.62**	91.46	75.42	76.04	33.17	**68.93**
	SJ		0.13	13.56	12.13	12.19	37.96	**18.96**	93.33	73.96	74.17	28.83	**67.29**
	SDJ		0.08	13.49	11.63	11.57	36.02	**18.18**	95.00	78.13	76.67	33.83	**70.59**
	ASDJ		0.09	13.52	12.04	12.06	37.29	**18.74**	95.00	76.25	75.21	31.67	**69.02**
50,000 Sched. (20F/20B)	NJ	Best of LST, LFT, MTS & CPR	0.21	13.67	12.49	12.78	39.74	**19.68**	89.38	72.29	71.25	26.83	**64.09**
	DJ		0.06	13.45	11.40	11.37	35.57	**17.96**	96.25	79.38	77.50	36.33	**72.26**
	SJ		0.04	13.43	11.52	11.66	36.62	**18.34**	97.08	77.50	75.21	31.67	**70.01**
	SDJ		0.02	13.41	11.17	11.11	34.89	**17.66**	98.54	82.08	77.29	36.50	**73.42**
	ASDJ		0.03	13.43	11.48	11.50	35.92	**18.09**	97.71	78.54	77.29	35.00	**71.81**

Table C.1: Test results for different RCPSP justification schemes

C.1.2. Stacking Justification detailed testing

N_{Sch}	C.F. (χ)	Priority Rule	AD_O j-30	AD_{CP} j-30	j-60	j-90	j-120	Aver.	Problems Solved to Optimality j-30	j-60	j-90	j-120	Aver.
1,000 Schedules (10F/10B Particles)	0.73	LST	0.76	14.47	12.59	12.33	37.86	**19.31**	79.38	73.13	72.29	29.50	**63.57**
		LFT	0.66	14.33	12.66	12.36	37.83	**19.29**	79.38	72.29	72.50	29.00	**63.29**
		MTS	0.63	14.30	12.61	12.28	37.49	**19.17**	78.96	71.25	72.71	29.83	**63.19**
		CPR	0.45	14.06	12.55	12.24	37.44	**19.07**	84.79	73.33	72.92	30.17	**65.30**
	0.6	LST	0.36	13.93	12.35	12.23	37.53	**19.01**	85.21	74.17	73.13	30.33	**65.71**
		LFT	0.44	14.03	12.44	12.18	37.49	**19.04**	83.75	73.75	73.33	30.83	**65.42**
		MTS	0.45	14.06	12.36	12.17	37.28	**18.97**	84.79	73.75	73.13	30.50	**65.54**
		CPR	0.31	13.84	12.40	12.16	37.25	**18.91**	87.71	73.54	74.17	29.67	**66.27**
	0.5	LST	0.35	13.89	12.21	12.01	37.01	**18.78**	85.42	74.38	73.54	31.33	**66.17**
		LFT	0.32	13.86	12.17	12.01	37.06	**18.77**	87.08	75.00	73.54	31.17	**66.70**
		MTS	0.35	13.90	12.22	12.00	36.96	**18.77**	85.83	74.79	74.58	31.33	**66.64**
		CPR	0.28	13.80	12.16	11.95	36.79	**18.68**	88.13	75.00	74.38	31.50	**67.25**
	0.4	LST	0.35	13.90	12.01	11.74	36.38	**18.51**	85.00	74.79	74.38	32.00	**66.54**
		LFT	0.35	13.89	12.03	11.81	36.39	**18.53**	86.04	74.38	74.79	32.33	**66.89**
		MTS	0.44	14.01	12.07	11.78	36.42	**18.57**	84.58	74.58	74.58	31.50	**66.31**
		CPR	0.25	13.75	12.01	11.73	36.22	**18.43**	89.58	75.63	75.00	32.33	**68.14**
	0.3	LST	0.45	14.05	11.88	11.50	36.02	**18.36**	83.96	75.00	75.63	33.00	**66.90**
		LFT	0.39	13.96	11.97	11.65	35.96	**18.39**	85.42	74.38	75.21	32.33	**66.83**
		MTS	0.53	14.11	11.99	11.65	35.92	**18.42**	84.58	74.38	75.21	32.67	**66.71**
		CPR	0.26	13.77	11.88	11.54	35.83	**18.26**	88.75	75.42	75.83	32.67	**68.17**
	0.2	LST	0.51	14.12	12.02	11.60	35.69	**18.36**	81.04	74.79	75.63	33.00	**66.11**
		LFT	0.51	14.11	12.06	11.59	35.80	**18.39**	83.13	73.96	75.42	32.83	**66.33**
		MTS	0.69	14.31	12.03	11.53	35.67	**18.38**	81.04	73.75	74.79	32.67	**65.56**
		CPR	0.28	13.81	11.94	11.54	35.65	**18.24**	89.17	75.00	75.21	32.83	**68.05**
	0.1	LST	0.69	14.40	12.22	11.69	35.91	**18.55**	79.58	74.17	74.58	31.50	**64.96**
		LFT	0.78	14.52	12.22	11.68	35.91	**18.58**	80.00	73.54	73.75	32.17	**64.86**
		MTS	0.92	14.63	12.19	11.65	35.78	**18.56**	76.04	73.13	74.58	31.17	**63.73**
		CPR	0.38	13.89	12.15	11.61	35.76	**18.35**	86.67	73.54	74.79	32.17	**66.79**
5,000 Schedules (10F/10B Particles)	0.73	LST	0.11	13.56	11.73	11.60	36.13	**18.26**	94.17	76.67	75.83	33.50	**70.04**
		LFT	0.09	13.51	11.64	11.57	36.04	**18.19**	94.79	78.13	75.83	33.17	**70.48**
		MTS	0.09	13.51	11.71	11.60	36.04	**18.22**	94.79	77.08	76.67	33.83	**70.59**
		CPR	0.08	13.49	11.63	11.59	36.02	**18.18**	95.00	77.29	75.21	33.17	**70.17**
	0.6	LST	0.09	13.51	11.39	11.39	35.46	**17.94**	94.58	78.96	77.29	34.67	**71.38**
		LFT	0.10	13.52	11.42	11.42	35.53	**17.97**	94.58	78.54	76.67	34.50	**71.07**
		MTS	0.08	13.49	11.46	11.38	35.50	**17.96**	95.42	78.33	77.29	34.33	**71.34**
		CPR	0.08	13.50	11.43	11.33	35.53	**17.95**	94.79	78.54	76.88	34.67	**71.22**
	0.5	LST	0.11	13.55	11.31	11.12	34.85	**17.71**	93.54	78.75	76.88	37.17	**71.58**
		LFT	0.15	13.60	11.29	11.07	34.84	**17.70**	92.08	78.96	77.08	36.17	**71.07**
		MTS	0.12	13.56	11.32	11.12	34.94	**17.73**	94.38	78.75	76.88	35.33	**71.33**
		CPR	0.09	13.52	11.24	11.05	34.80	**17.65**	94.79	79.58	77.08	36.33	**71.95**
	0.4	LST	0.22	13.71	11.25	10.84	34.18	**17.49**	90.00	78.33	76.88	36.50	**70.43**
		LFT	0.20	13.68	11.31	10.88	34.18	**17.51**	90.42	77.50	76.67	35.67	**70.06**
		MTS	0.20	13.68	11.27	10.88	34.21	**17.51**	90.63	77.29	77.08	35.50	**70.13**
		CPR	0.12	13.56	11.19	10.84	34.09	**17.42**	92.92	79.17	76.46	37.33	**71.47**
	0.3	LST	0.30	13.83	11.28	10.79	33.82	**17.43**	88.13	77.50	76.25	36.67	**69.64**
		LFT	0.26	13.76	11.31	10.79	33.83	**17.42**	86.25	76.67	76.46	37.00	**69.09**
		MTS	0.39	13.90	11.31	10.80	33.88	**17.47**	86.46	77.08	76.46	36.00	**69.00**
		CPR	0.17	13.64	11.29	10.86	33.91	**17.43**	91.67	77.29	76.67	36.33	**70.49**
	0.2	LST	0.31	13.84	11.37	10.82	33.88	**17.48**	86.67	76.67	76.25	35.67	**68.81**

Group		Method											
		LFT	0.35	13.90	11.37	10.85	33.82	**17.48**	85.42	76.25	76.67	35.50	**68.46**
		MTS	0.61	14.19	11.41	10.87	33.87	**17.59**	83.96	76.67	76.04	36.17	**68.21**
		CPR	0.26	13.77	11.29	10.81	33.84	**17.43**	88.13	77.29	76.88	35.17	**69.36**
	0.1	LST	0.46	14.06	11.61	11.07	34.28	**17.75**	83.96	75.83	75.83	36.00	**67.91**
		LFT	0.39	13.96	11.55	11.04	34.31	**17.71**	84.58	76.88	76.46	35.17	**68.27**
		MTS	0.65	14.25	11.61	11.05	34.26	**17.79**	82.92	75.42	77.08	35.33	**67.69**
		CPR	0.28	13.80	11.55	11.02	34.19	**17.64**	87.50	77.29	76.25	35.50	**69.14**
5,000 Schedules (20F/20B Particles)	0.73	LST	0.11	13.54	11.78	11.70	36.32	**18.33**	93.96	76.88	75.42	32.50	**69.69**
		LFT	0.10	13.52	11.81	11.66	36.29	**18.32**	94.17	76.88	76.04	32.67	**69.94**
		MTS	0.08	13.49	11.75	11.69	36.19	**18.28**	95.00	76.25	75.83	32.50	**69.90**
		CPR	0.12	13.55	11.78	11.66	36.17	**18.29**	93.75	76.04	75.42	33.17	**69.59**
	0.6	LST	0.07	13.47	11.55	11.43	35.70	**18.04**	96.25	77.29	76.67	34.17	**71.09**
		LFT	0.05	13.46	11.49	11.50	35.66	**18.03**	96.67	78.54	76.46	34.17	**71.46**
		MTS	0.08	13.50	11.53	11.49	35.75	**18.07**	95.00	77.50	76.25	34.00	**70.69**
		CPR	0.07	13.48	11.50	11.43	35.61	**18.01**	95.83	78.96	76.88	34.17	**71.46**
	0.5	LST	0.11	13.54	11.34	11.15	34.99	**17.75**	94.58	79.79	76.88	36.00	**71.81**
		LFT	0.11	13.53	11.37	11.18	35.02	**17.78**	93.75	78.75	76.88	36.00	**71.34**
		MTS	0.08	13.50	11.34	11.18	34.95	**17.74**	95.21	78.75	77.08	36.67	**71.93**
		CPR	0.07	13.49	11.27	11.13	34.99	**17.72**	95.21	80.21	77.29	35.67	**72.09**
	0.4	LST	0.14	13.60	11.19	10.95	34.40	**17.54**	92.50	78.75	76.67	36.67	**71.15**
		LFT	0.12	13.55	11.24	10.86	34.34	**17.50**	93.96	78.13	77.71	36.67	**71.61**
		MTS	0.12	13.56	11.32	10.97	34.40	**17.56**	93.75	78.75	77.08	36.17	**71.44**
		CPR	0.07	13.49	11.25	10.94	34.34	**17.51**	95.63	79.58	76.88	37.50	**72.40**
	0.3	LST	0.14	13.60	11.22	10.86	33.97	**17.41**	92.71	77.92	77.71	37.17	**71.38**
		LFT	0.16	13.61	11.21	10.80	33.99	**17.40**	91.88	78.96	77.29	37.33	**71.36**
		MTS	0.29	13.76	11.23	10.84	34.05	**17.47**	89.79	80.21	77.71	37.00	**71.18**
		CPR	0.14	13.59	11.22	10.85	34.01	**17.42**	92.71	77.92	77.29	37.00	**71.23**
	0.2	LST	0.19	13.66	11.35	10.96	34.15	**17.53**	90.63	78.13	76.46	35.67	**70.22**
		LFT	0.15	13.60	11.34	10.93	34.10	**17.49**	92.50	78.54	76.46	36.83	**71.08**
		MTS	0.34	13.82	11.45	10.92	34.15	**17.59**	88.96	76.88	76.67	35.83	**69.58**
		CPR	0.15	13.60	11.29	10.91	34.03	**17.46**	92.29	78.75	77.08	36.50	**71.16**
	0.1	LST	0.24	13.74	11.57	11.13	34.46	**17.72**	89.38	76.88	76.67	35.33	**69.56**
		LFT	0.27	13.78	11.59	11.14	34.50	**17.75**	88.96	76.25	76.46	34.83	**69.13**
		MTS	0.40	13.92	11.65	11.14	34.46	**17.79**	87.29	76.46	76.88	35.17	**68.95**
		CPR	0.13	13.57	11.60	11.10	34.41	**17.67**	93.33	76.67	77.08	36.17	**70.81**
50,000 Schedules (20F/20B Particles)	0.73	LST	0.03	13.42	11.17	11.15	34.89	**17.66**	98.33	82.08	77.08	36.17	**73.42**
		LFT	0.02	13.41	11.19	11.14	34.93	**17.67**	98.54	80.63	77.08	36.00	**73.06**
		MTS	0.03	13.41	11.19	11.11	34.94	**17.66**	98.13	81.04	77.29	36.17	**73.16**
		CPR	0.03	13.42	11.21	11.13	34.90	**17.67**	98.33	80.83	77.29	36.50	**73.24**
	0.6	LST	0.03	13.42	11.02	10.95	34.44	**17.46**	98.33	82.29	77.92	38.83	**74.34**
		LFT	0.02	13.40	10.98	10.94	34.46	**17.44**	98.75	83.54	77.71	37.67	**74.42**
		MTS	0.03	13.41	11.01	10.92	34.49	**17.46**	98.13	82.71	77.71	38.00	**74.14**
		CPR	0.02	13.40	10.99	10.95	34.45	**17.45**	98.75	83.33	77.71	37.50	**74.32**
	0.5	LST	0.04	13.43	10.92	10.66	33.73	**17.19**	97.50	82.92	78.13	39.00	**74.39**
		LFT	0.04	13.45	10.89	10.61	33.78	**17.18**	97.50	83.75	78.54	39.17	**74.74**
		MTS	0.04	13.44	10.85	10.65	33.83	**17.19**	97.50	84.17	78.75	39.67	**75.02**
		CPR	0.03	13.41	10.89	10.65	33.71	**17.16**	98.13	82.71	78.13	39.50	**74.61**
	0.4	LST	0.06	13.47	10.92	10.38	32.96	**16.93**	96.04	81.46	78.33	39.33	**73.79**
		LFT	0.07	13.49	10.97	10.39	32.94	**16.95**	95.63	80.42	78.75	39.50	**73.57**
		MTS	0.08	13.50	10.99	10.45	33.02	**16.99**	95.42	81.46	78.13	37.83	**73.21**
		CPR	0.07	13.47	10.93	10.42	32.85	**16.92**	95.83	81.25	78.33	40.17	**73.90**
	0.3	LST	0.16	13.61	11.07	10.38	32.57	**16.91**	91.88	78.54	77.92	39.00	**71.83**
		LFT	0.12	13.57	11.07	10.37	32.59	**16.90**	93.96	78.54	78.54	39.33	**72.59**

	C.F	Priority Rule	AD_O j-30	ADcp j-30	j-60	j-90	j-120	Aver.	Opt j-30	j-60	j-90	j-120	Aver.
		MTS	0.14	13.59	11.04	10.41	32.57	**16.90**	92.71	80.00	77.71	38.67	**72.27**
		CPR	0.09	13.52	11.04	10.35	32.54	**16.86**	94.58	80.83	77.08	39.33	**72.96**
	0.2	LST	0.14	13.59	11.07	10.36	32.46	**16.87**	92.29	79.79	77.71	38.50	**72.07**
	0.2	LFT	0.13	13.57	11.07	10.36	32.43	**16.86**	92.71	78.13	78.13	39.00	**71.99**
	0.2	MTS	0.26	13.72	11.08	10.35	32.50	**16.91**	91.88	79.17	77.71	38.17	**71.73**
	0.2	*CPR*	0.11	13.54	11.03	10.37	32.44	**16.85**	93.96	78.75	77.92	40.00	**72.66**
	0.1	LST	0.17	13.63	11.05	10.42	32.78	**16.97**	91.88	80.00	78.13	39.17	**72.29**
	0.1	LFT	0.16	13.63	11.05	10.42	32.78	**16.97**	92.08	79.17	78.13	39.00	**72.09**
	0.1	MTS	0.31	13.77	11.09	10.44	32.75	**17.01**	90.21	78.96	77.71	40.33	**71.80**
	0.1	*CPR*	0.14	13.60	11.02	10.40	32.75	**16.94**	92.50	79.17	77.92	39.17	**72.19**
1,000 Sched. (10F/10B)	0.73	Best of LST, LFT, MTS & CPR	0.45	14.06	12.55	12.24	37.44	**19.07**	84.79	73.33	72.92	30.17	**65.30**
	0.6		0.31	13.84	12.35	12.16	37.25	**18.91**	87.71	74.17	74.17	30.83	**66.27**
	0.5		0.28	13.80	12.16	11.95	36.79	**18.68**	88.13	75.00	74.58	31.50	**67.25**
	0.4		0.25	13.75	12.01	11.73	36.22	**18.43**	89.58	75.63	75.00	32.33	**68.14**
	0.3		0.26	13.77	11.88	11.50	35.83	**18.26**	88.75	75.42	75.83	33.00	**68.17**
	0.2		0.28	13.81	11.94	11.53	35.65	**18.24**	89.17	75.00	75.63	33.00	**68.05**
	0.1		0.38	13.89	12.15	11.61	35.76	**18.35**	86.67	74.17	74.79	32.17	**66.79**
5,000 Sched. (10F/10B)	0.73	Best of LST, LFT, MTS & CPR	0.08	13.49	11.63	11.57	36.02	**18.18**	95.00	78.13	76.67	33.83	**70.59**
	0.6		0.08	13.49	11.39	11.33	35.46	**17.94**	95.42	78.96	77.29	34.67	**71.38**
	0.5		0.09	13.52	11.24	11.05	34.80	**17.65**	94.79	79.58	77.08	37.17	**71.95**
	0.4		0.12	13.56	11.19	10.84	34.09	**17.42**	92.92	79.17	77.08	37.33	**71.47**
	0.3		0.17	13.64	11.28	10.79	33.82	**17.42**	91.67	77.50	76.67	37.00	**70.49**
	0.2		0.26	13.77	11.29	10.81	33.82	**17.43**	88.13	77.29	76.88	36.17	**69.36**
	0.1		0.28	13.80	11.55	11.02	34.19	**17.64**	87.50	77.29	77.08	36.00	**69.14**
5,000 Sched. (20F/20B)	0.73	Best of LST, LFT, MTS & CPR	0.08	13.49	11.75	11.66	36.17	**18.28**	95.00	76.88	76.04	33.17	**69.94**
	0.6		0.05	13.46	11.49	11.43	35.61	**18.01**	96.67	78.96	76.88	34.17	**71.46**
	0.5		0.07	13.49	11.27	11.13	34.95	**17.72**	95.21	80.21	77.29	36.67	**72.09**
	0.4		0.07	13.49	11.19	10.86	34.34	**17.50**	95.63	79.58	77.71	37.50	**72.40**
	0.3		0.14	13.59	11.21	10.80	33.97	**17.40**	92.71	80.21	77.71	37.33	**71.38**
	0.2		0.15	13.60	11.29	10.91	34.03	**17.46**	92.50	78.75	77.08	36.83	**71.16**
	0.1		0.13	13.57	11.57	11.10	34.41	**17.67**	93.33	76.88	77.08	36.17	**70.81**
50,000 Sched. (20F/20B)	0.73	Best of LST, LFT, MTS & CPR	0.02	13.41	11.17	11.11	34.89	**17.66**	98.54	82.08	77.29	36.50	**73.42**
	0.6		0.02	13.40	10.98	10.92	34.44	**17.44**	98.75	83.54	77.92	38.83	**74.42**
	0.5		0.03	13.41	10.85	10.61	33.71	**17.16**	98.13	84.17	78.75	39.67	**75.02**
	0.4		0.06	13.47	10.92	10.38	32.85	**16.92**	96.04	81.46	78.75	40.17	**73.90**
	0.3		0.09	13.52	11.04	10.35	32.54	**16.86**	94.58	80.83	78.54	39.33	**72.96**
	0.2		0.11	13.54	11.03	10.35	32.43	**16.85**	93.96	79.79	78.13	40.00	**72.66**
	0.1		0.14	13.60	11.02	10.40	32.75	**16.94**	92.50	80.00	78.13	40.33	**72.29**

Table C.2: Test results for SDJ under different constriction factor values

PSO Topology	C.F (χ)	Priority Rule	AD_O j-30	AD_CP j-30	j-60	j-90	j-120	Aver.	Problems Solved to Optimality j-30	j-60	j-90	j-120	Aver.
gbest (GR = 1.0)	0.6	LST	0.36	13.93	12.35	12.23	37.53	**19.01**	85.21	74.17	73.13	30.33	**65.71**
	0.6	LFT	0.44	14.03	12.44	12.18	37.49	**19.04**	83.75	73.75	73.33	30.83	**65.42**
	0.6	MTS	0.45	14.06	12.36	12.17	37.28	**18.97**	84.79	73.75	73.13	30.50	**65.54**
	0.6	CPR	0.31	13.84	12.40	12.16	37.25	**18.91**	87.71	73.54	74.17	29.67	**66.27**
	0.5	LST	0.35	13.89	12.21	12.01	37.01	**18.78**	85.42	74.38	73.54	31.33	**66.17**
	0.5	LFT	0.32	13.86	12.17	12.01	37.06	**18.77**	87.08	75.00	73.54	31.17	**66.70**
	0.5	MTS	0.35	13.90	12.22	12.00	36.96	**18.77**	85.83	74.79	74.58	31.33	**66.64**
	0.5	CPR	0.28	13.80	12.16	11.95	36.79	**18.68**	88.13	75.00	74.38	31.50	**67.25**

		Method											
	0.4	LST	0.35	13.90	12.01	11.74	36.38	**18.51**	85.00	74.79	74.38	32.00	**66.54**
		LFT	0.35	13.89	12.03	11.81	36.39	**18.53**	86.04	74.38	74.79	32.33	**66.89**
		MTS	0.44	14.01	12.07	11.78	36.42	**18.57**	84.58	74.58	74.58	31.50	**66.31**
		CPR	0.25	13.75	12.01	11.73	36.22	**18.43**	89.58	75.63	75.00	32.33	**68.14**
	0.3	LST	0.45	14.05	11.88	11.50	36.02	**18.36**	83.96	75.00	75.63	33.00	**66.90**
		LFT	0.39	13.96	11.97	11.65	35.96	**18.39**	85.42	74.38	75.21	32.33	**66.83**
		MTS	0.53	14.11	11.99	11.65	35.92	**18.42**	84.58	74.38	75.21	32.67	**66.71**
		CPR	0.26	13.77	11.88	11.54	35.83	**18.26**	88.75	75.42	75.83	32.67	**68.17**
	0.2	LST	0.51	14.12	12.02	11.60	35.69	**18.36**	81.04	74.79	75.63	33.00	**66.11**
		LFT	0.51	14.11	12.06	11.59	35.80	**18.39**	83.13	73.96	75.42	32.83	**66.33**
		MTS	0.69	14.31	12.03	11.53	35.67	**18.35**	81.04	73.75	74.79	32.67	**65.56**
		CPR	0.28	13.81	11.94	11.54	35.65	**18.24**	89.17	75.00	75.21	32.83	**68.05**
neighboring (GR = 0.75)	0.6	LST	0.48	14.09	12.45	12.20	37.49	**19.06**	83.96	75.00	72.71	30.00	**65.42**
		LFT	0.41	14.00	12.45	12.19	37.46	**19.03**	85.21	73.75	73.75	30.50	**65.80**
		MTS	0.36	13.92	12.39	12.14	37.29	**18.94**	85.21	74.38	73.96	30.17	**65.93**
		CPR	0.28	13.81	12.37	12.11	37.24	**18.88**	87.71	73.33	73.75	30.00	**66.20**
	0.5	LST	0.30	13.83	12.18	12.01	37.00	**18.76**	87.71	75.21	74.38	31.17	**67.11**
		LFT	0.33	13.88	12.23	11.98	37.01	**18.77**	86.88	73.96	74.38	31.33	**66.64**
		MTS	0.33	13.86	12.31	12.01	36.96	**18.79**	85.83	73.75	73.75	31.33	**66.17**
		CPR	0.24	13.73	12.17	11.97	36.79	**18.67**	89.17	74.79	73.96	31.50	**67.35**
	0.4	LST	0.36	13.91	12.04	11.75	36.38	**18.52**	86.25	74.58	75.21	32.00	**67.01**
		LFT	0.35	13.89	12.07	11.75	36.38	**18.52**	85.83	74.58	74.58	32.00	**66.75**
		MTS	0.38	13.93	12.02	11.80	36.42	**18.54**	86.04	73.96	74.17	32.17	**66.58**
		CPR	0.25	13.75	11.98	11.74	36.25	**18.43**	88.96	74.58	74.79	32.50	**67.71**
	0.3	LST	0.39	13.96	11.94	11.66	35.94	**18.37**	84.79	74.79	74.79	32.67	**66.76**
		LFT	0.36	13.90	11.97	11.59	35.93	**18.35**	84.79	74.58	75.42	33.00	**66.95**
		MTS	0.45	13.99	11.96	11.63	35.94	**18.38**	85.00	74.79	75.63	32.83	**67.06**
		CPR	0.22	13.72	11.88	11.53	35.89	**18.26**	90.00	74.79	75.42	33.50	**68.43**
	0.2	LST	0.45	14.12	12.11	11.60	35.86	**18.42**	82.29	74.38	74.38	32.33	**65.84**
		LFT	0.42	14.00	11.96	11.55	35.82	**18.33**	83.96	74.58	75.21	32.83	**66.65**
		MTS	0.78	14.43	11.98	11.58	35.75	**18.44**	80.21	73.54	74.79	32.33	**65.22**
		CPR	0.31	13.86	11.93	11.57	35.69	**18.26**	88.13	74.79	75.63	33.00	**67.89**
neighboring (GR = 0.5)	0.6	LST	0.43	14.01	12.45	12.14	37.46	**19.02**	83.75	73.75	73.75	30.33	**65.40**
		LFT	0.39	13.97	12.45	12.20	37.55	**19.04**	84.79	73.33	73.13	30.33	**65.40**
		MTS	0.39	13.95	12.50	12.16	37.32	**18.98**	84.38	73.75	73.13	30.33	**65.40**
		CPR	0.29	13.81	12.34	12.13	37.18	**18.87**	87.92	74.38	73.54	30.50	**66.58**
	0.5	LST	0.38	13.95	12.26	12.01	37.07	**18.82**	85.42	73.96	74.79	30.83	**66.25**
		LFT	0.36	13.93	12.27	11.95	36.99	**18.79**	85.21	73.75	75.00	31.83	**66.45**
		MTS	0.32	13.87	12.26	11.97	36.90	**18.75**	86.25	74.79	74.58	31.00	**66.66**
		CPR	0.29	13.82	12.19	11.98	36.84	**18.71**	88.13	74.79	75.00	31.17	**67.27**
	0.4	LST	0.32	13.86	12.11	11.79	36.37	**18.53**	86.25	74.17	74.79	31.83	**66.76**
		LFT	0.32	13.87	12.01	11.80	36.40	**18.52**	87.29	75.63	75.00	32.00	**67.48**
		MTS	0.37	13.90	12.11	11.84	36.47	**18.58**	85.21	73.96	75.00	31.50	**66.42**
		CPR	0.22	13.72	12.03	11.80	36.30	**18.46**	90.00	75.21	75.42	32.17	**68.20**
	0.3	LST	0.36	13.93	12.04	11.66	35.98	**18.40**	86.04	74.79	75.00	33.17	**67.25**
		LFT	0.43	14.01	11.98	11.59	36.01	**18.40**	83.96	75.00	75.42	33.17	**66.89**
		MTS	0.46	14.01	11.96	11.66	35.94	**18.39**	85.83	74.38	75.00	32.67	**66.97**
		CPR	0.23	13.74	11.86	11.62	35.87	**18.27**	89.79	75.83	75.21	32.83	**68.42**
	0.2	LST	0.42	14.06	12.05	11.62	35.93	**18.41**	82.71	75.00	74.79	32.33	**66.21**
		LFT	0.50	14.12	12.06	11.65	35.88	**18.43**	82.92	73.96	74.79	32.33	**66.00**

Group	Param	Rule											
		MTS	0.65	14.29	12.02	11.62	35.80	**18.43**	80.42	73.96	75.00	32.50	**65.47**
		CPR	0.29	13.82	11.94	11.57	35.75	**18.27**	88.13	75.21	75.42	33.17	**67.98**
neighboring (GR = 0.25)	0.6	LST	0.40	14.00	12.50	12.19	37.62	**19.08**	84.17	73.33	73.33	30.00	**65.21**
		LFT	0.39	13.95	12.45	12.19	37.58	**19.04**	84.17	73.75	73.33	30.50	**65.44**
		MTS	0.45	14.05	12.41	12.15	37.28	**18.97**	83.54	74.17	73.13	31.00	**65.46**
		CPR	0.36	13.91	12.41	12.15	37.18	**18.91**	84.17	74.58	74.17	30.17	**65.77**
	0.5	LST	0.36	13.91	12.30	12.00	37.05	**18.82**	85.21	74.38	74.38	31.00	**66.24**
		LFT	0.36	13.91	12.24	11.99	37.05	**18.80**	86.04	74.38	73.54	30.33	**66.07**
		MTS	0.34	13.89	12.25	12.04	37.00	**18.79**	85.63	74.17	73.96	30.33	**66.02**
		CPR	0.25	13.75	12.21	11.99	36.87	**18.71**	87.92	74.58	73.96	30.83	**66.82**
	0.4	LST	0.34	13.88	12.13	11.78	36.48	**18.57**	86.88	74.38	74.79	31.83	**66.97**
		LFT	0.32	13.85	12.08	11.82	36.47	**18.55**	87.50	75.00	75.21	31.83	**67.39**
		MTS	0.27	13.78	12.09	11.83	36.48	**18.55**	87.71	73.96	74.58	31.50	**66.94**
		CPR	0.24	13.74	12.07	11.80	36.39	**18.50**	88.75	75.42	75.42	31.50	**67.77**
	0.3	LST	0.33	13.88	12.01	11.64	36.08	**18.40**	87.71	73.54	75.21	33.00	**67.36**
		LFT	0.31	13.85	12.02	11.64	36.13	**18.41**	87.71	74.79	75.00	32.00	**67.38**
		MTS	0.55	14.14	12.09	11.69	36.09	**18.50**	83.75	74.17	75.42	32.33	**66.42**
		CPR	0.26	13.77	11.97	11.60	35.94	**18.32**	87.71	75.21	75.42	33.17	**67.88**
	0.2	LST	0.55	14.18	12.09	11.67	36.02	**18.49**	79.79	75.00	74.58	32.33	**65.43**
		LFT	0.43	14.00	12.03	11.65	35.92	**18.40**	83.33	74.38	75.42	32.67	**66.45**
		MTS	0.65	14.28	12.02	11.64	35.85	**18.45**	82.71	74.38	75.21	32.00	**66.07**
		CPR	0.28	13.81	11.98	11.58	35.81	**18.30**	87.71	75.00	76.04	32.33	**67.77**
lbest (GR = 0.0)	0.6	LST	0.39	13.96	12.51	12.18	37.60	**19.06**	85.21	74.17	73.75	30.33	**65.86**
		LFT	0.39	13.97	12.45	12.21	37.60	**19.06**	85.63	73.54	73.33	30.50	**65.75**
		MTS	0.41	13.99	12.44	12.15	37.36	**18.98**	84.79	73.33	73.13	30.17	**65.35**
		CPR	0.32	13.85	12.48	12.18	37.20	**18.93**	86.25	74.38	73.33	30.50	**66.11**
	0.5	LST	0.42	14.00	12.41	12.04	37.18	**18.91**	85.00	73.96	73.96	30.67	**65.90**
		LFT	0.37	13.93	12.33	12.12	37.09	**18.87**	85.21	74.38	73.96	30.83	**66.09**
		MTS	0.33	13.88	12.32	12.06	37.03	**18.82**	85.83	73.54	73.96	31.33	**66.17**
		CPR	0.27	13.80	12.32	12.02	36.95	**18.77**	88.54	74.58	73.75	31.33	**67.05**
	0.4	LST	0.36	13.92	12.15	11.87	36.57	**18.63**	85.63	74.17	74.58	32.17	**66.64**
		LFT	0.39	13.95	12.07	11.86	36.58	**18.61**	84.58	75.21	74.38	32.00	**66.54**
		MTS	0.36	13.90	12.15	11.84	36.54	**18.61**	87.50	74.38	74.79	31.33	**67.00**
		CPR	0.26	13.77	12.09	11.78	36.46	**18.52**	88.54	75.00	74.79	32.17	**67.63**
	0.3	LST	0.40	13.98	12.02	11.74	36.15	**18.47**	84.79	75.42	74.38	32.00	**66.65**
		LFT	0.41	13.99	11.98	11.76	36.22	**18.49**	84.79	74.38	75.21	32.33	**66.68**
		MTS	0.47	14.04	12.11	11.73	36.15	**18.51**	85.21	73.75	74.79	32.33	**66.52**
		CPR	0.25	13.76	12.02	11.65	36.09	**18.38**	88.33	74.79	75.42	32.83	**67.84**
	0.2	LST	0.46	14.05	12.07	11.73	36.09	**18.49**	83.75	73.96	75.21	32.00	**66.23**
		LFT	0.54	14.16	12.12	11.71	36.07	**18.51**	82.08	74.38	74.58	32.00	**65.76**
		MTS	0.66	14.28	12.12	11.64	35.95	**18.50**	81.04	74.38	75.00	32.00	**65.60**
		CPR	0.29	13.82	12.03	11.60	35.87	**18.33**	86.88	73.75	75.21	31.83	**66.92**

Table C.3: RCPSP test results for SDJ under different PSO topologies
(1,000 schedules – 10 forward/ 10 backward particles)

PSO Topology	C.F (χ)	Priority Rule	AD_O	AD_CP					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
gbest (GR = 1.0)	0.6	LST	0.09	13.51	11.39	11.39	35.46	**17.94**	94.58	78.96	77.29	34.67	**71.38**
		LFT	0.10	13.52	11.42	11.42	35.53	**17.97**	94.58	78.54	76.67	34.50	**71.07**
		MTS	0.10	13.53	11.48	11.34	35.44	**17.95**	94.58	77.50	76.46	34.33	**70.72**
		CPR	0.08	13.50	11.43	11.33	35.53	**17.95**	94.79	78.54	76.88	34.67	**71.22**
	0.5	LST	0.12	13.55	11.38	11.14	34.91	**17.74**	94.38	77.92	77.71	35.67	**71.42**
		LFT	0.10	13.53	11.49	11.13	34.94	**17.78**	94.79	77.92	76.67	35.00	**71.09**
		MTS	0.12	13.55	11.44	11.13	34.92	**17.76**	93.13	78.13	76.67	34.50	**70.60**
		CPR	0.10	13.52	11.42	11.09	34.85	**17.72**	94.79	78.33	77.29	35.83	**71.56**
	0.4	LST	0.20	13.67	11.41	10.94	34.26	**17.57**	90.00	76.46	76.67	35.83	**69.74**
		LFT	0.19	13.66	11.43	10.97	34.18	**17.56**	90.83	76.67	76.67	35.33	**69.88**
		MTS	0.20	13.67	11.36	10.98	34.23	**17.56**	90.63	77.29	77.08	35.50	**70.13**
		CPR	0.13	13.56	11.29	10.91	34.24	**17.50**	92.71	78.33	76.67	35.50	**70.80**
	0.3	LST	0.30	13.83	11.28	10.79	33.82	**17.43**	88.13	77.50	76.25	36.67	**69.64**
		LFT	0.26	13.76	11.31	10.79	33.83	**17.42**	86.25	76.67	76.46	37.00	**69.09**
		MTS	0.39	13.91	11.34	10.92	34.00	**17.54**	85.83	77.50	75.63	36.17	**68.78**
		CPR	0.17	13.64	11.29	10.86	33.91	**17.43**	91.67	77.29	76.67	36.33	**70.49**
	0.2	LST	0.31	13.84	11.37	10.82	33.88	**17.48**	86.67	76.67	76.25	35.67	**68.81**
		LFT	0.40	13.96	11.37	10.91	34.02	**17.56**	85.42	75.83	76.04	36.50	**68.45**
		MTS	0.67	14.29	11.50	10.90	33.96	**17.66**	81.67	74.38	75.63	37.00	**67.17**
		CPR	0.20	13.69	11.37	10.83	33.99	**17.47**	89.79	76.88	76.67	36.00	**69.83**
neighboring (GR = 0.75)	0.6	LFT	0.06	13.48	11.44	11.38	35.50	**17.95**	96.04	78.75	77.50	35.33	**71.91**
		CPR	0.09	13.52	11.42	11.34	35.46	**17.94**	94.58	78.33	77.29	34.83	**71.26**
	0.5	LFT	0.10	13.53	11.27	11.09	35.01	**17.72**	94.17	80.21	77.08	35.33	**71.70**
		CPR	0.08	13.50	11.24	11.14	34.90	**17.69**	95.63	79.17	76.88	36.00	**71.92**
	0.4	LFT	0.14	13.59	11.25	10.89	34.17	**17.48**	92.29	77.50	76.88	36.50	**70.79**
		CPR	0.09	13.52	11.23	10.85	34.19	**17.45**	93.75	78.54	77.08	36.67	**71.51**
	0.3	LFT	0.22	13.71	11.26	10.78	33.86	**17.40**	90.00	77.08	77.08	36.33	**70.13**
		CPR	0.15	13.62	11.27	10.75	33.78	**17.35**	92.50	78.75	77.29	37.00	**71.39**
	0.2	LFT	0.28	13.79	11.33	10.86	33.95	**17.48**	88.33	77.50	76.46	35.33	**69.41**
		CPR	0.17	13.64	11.31	10.82	33.80	**17.39**	92.08	77.08	77.08	35.83	**70.52**
neighboring (GR = 0.5)	0.6	LFT	0.09	13.52	11.48	11.36	35.49	**17.96**	94.79	77.08	76.04	34.33	**70.56**
		CPR	0.09	13.51	11.47	11.40	35.44	**17.95**	94.79	78.33	76.67	34.50	**71.07**
	0.5	LFT	0.07	13.49	11.27	11.14	34.95	**17.71**	95.63	79.79	77.29	36.50	**72.30**
		CPR	0.07	13.49	11.27	11.17	34.93	**17.72**	96.04	79.17	76.46	36.33	**72.00**
	0.4	LFT	0.12	13.56	11.19	10.90	34.29	**17.49**	93.75	79.58	77.50	36.83	**71.92**
		CPR	0.09	13.51	11.24	10.87	34.27	**17.47**	94.79	77.92	77.29	36.83	**71.71**
	0.3	LFT	0.15	13.60	11.27	10.83	33.88	**17.39**	92.71	77.50	76.67	37.00	**70.97**
		CPR	0.11	13.55	11.23	10.76	33.83	**17.34**	93.96	78.33	76.46	36.50	**71.31**
	0.2	LFT	0.22	13.69	11.33	10.86	33.99	**17.47**	89.79	77.08	76.88	36.17	**69.98**
		CPR	0.18	13.64	11.27	10.86	33.91	**17.42**	91.04	76.88	77.08	36.33	**70.33**
neighboring (GR = 0.25)	0.6	LFT	0.07	13.49	11.50	11.40	35.51	**17.97**	95.63	78.33	77.08	35.33	**71.59**
		CPR	0.07	13.47	11.44	11.37	35.47	**17.94**	96.04	78.75	76.88	35.33	**71.75**
	0.5	LFT	0.08	13.50	11.30	11.17	34.98	**17.74**	95.63	79.38	77.29	35.67	**71.99**
		CPR	0.06	13.47	11.27	11.17	34.93	**17.71**	96.25	79.58	76.46	35.33	**71.91**
	0.4	LFT	0.09	13.52	11.20	10.92	34.34	**17.49**	95.21	78.75	76.67	37.50	**72.03**
		CPR	0.07	13.48	11.25	10.91	34.21	**17.46**	96.04	78.13	77.29	37.83	**72.32**
	0.3	LFT	0.14	13.60	11.26	10.81	33.96	**17.41**	91.88	77.50	77.08	36.83	**70.82**
		CPR	0.10	13.52	11.21	10.79	33.93	**17.36**	94.58	79.17	77.29	37.00	**72.01**

	C.F (χ)	Priority Rule	AD$_O$ j-30	AD$_{CP}$ j-30	j-60	j-90	j-120	Aver.	Problems Solved to Optimality j-30	j-60	j-90	j-120	Aver.
	0.2	LFT	0.25	13.73	11.30	10.87	34.04	**17.48**	87.92	78.96	77.50	36.00	**70.09**
		CPR	0.16	13.62	11.31	10.85	34.02	**17.45**	92.08	78.13	77.50	35.67	**70.84**
lbest (GR = 0.0)	0.6	LFT	0.09	13.52	11.50	11.40	35.58	**18.00**	94.79	78.33	77.08	34.67	**71.22**
		CPR	0.06	13.47	11.48	11.41	35.56	**17.98**	96.04	78.33	77.08	34.83	**71.57**
	0.5	LFT	0.09	13.52	11.32	11.17	34.98	**17.74**	95.42	80.00	77.29	35.17	**71.97**
		CPR	0.09	13.51	11.33	11.17	35.02	**17.76**	95.21	79.17	77.08	35.83	**71.82**
	0.4	LFT	0.09	13.52	11.28	10.90	34.30	**17.50**	94.38	78.54	77.29	36.50	**71.68**
		CPR	0.07	13.48	11.22	10.93	34.32	**17.49**	95.63	80.21	77.08	36.67	**72.40**
	0.3	LFT	0.19	13.68	11.34	10.82	34.04	**17.47**	91.04	77.08	77.29	36.50	**70.48**
		CPR	0.14	13.56	11.25	10.78	33.99	**17.39**	93.75	79.17	77.29	36.50	**71.68**
	0.2	LFT	0.24	13.72	11.44	10.89	34.18	**17.56**	88.75	76.67	76.46	35.33	**69.30**
		CPR	0.19	13.67	11.36	10.91	34.08	**17.50**	90.21	77.50	76.67	35.83	**70.05**

Table C.4: RCPSP test results for SDJ under different PSO topologies
(5,000 schedules – 10 forward/ 10 backward particles)

PSO Topology	C.F (χ)	Priority Rule	AD$_O$ j-30	AD$_{CP}$ j-30	j-60	j-90	j-120	Aver.	Problems Solved to Optimality j-30	j-60	j-90	j-120	Aver.
gbest (GR = 1.0)	0.6	LST	0.08	13.50	11.55	11.43	35.53	**18.00**	95.42	77.50	77.08	34.67	**71.17**
		LFT	0.08	13.50	11.54	11.39	35.55	**18.00**	96.04	77.29	76.88	34.83	**71.26**
		MTS	0.10	13.53	11.55	11.41	35.53	**18.00**	94.38	78.33	76.46	33.67	**70.71**
		CPR	0.07	13.48	11.50	11.43	35.61	**18.01**	95.83	78.96	76.88	34.17	**71.46**
	0.5	LST	0.11	13.54	11.39	11.15	35.01	**17.77**	94.38	78.96	76.88	35.50	**71.43**
		LFT	0.10	13.52	11.40	11.21	35.03	**17.79**	94.58	77.71	77.29	35.00	**71.15**
		MTS	0.11	13.54	11.42	11.16	35.01	**17.78**	93.96	78.13	76.88	35.67	**71.16**
		CPR	0.09	13.51	11.41	11.20	34.99	**17.78**	95.42	78.54	76.88	35.83	**71.67**
	0.4	LST	0.15	13.60	11.32	11.00	34.42	**17.59**	92.92	78.54	76.67	36.17	**71.07**
		LFT	0.12	13.55	11.29	10.98	34.40	**17.56**	94.38	78.33	77.29	35.83	**71.46**
		MTS	0.12	13.55	11.29	10.99	34.48	**17.58**	93.75	79.58	77.71	36.67	**71.93**
		CPR	0.11	13.55	11.30	11.00	34.38	**17.56**	93.75	77.71	76.67	35.67	**70.95**
	0.3	LST	0.18	13.64	11.27	10.95	34.13	**17.50**	91.25	78.13	76.67	36.50	**70.64**
		LFT	0.17	13.63	11.31	10.94	34.15	**17.51**	90.83	78.54	76.25	36.00	**70.41**
		MTS	0.27	13.76	11.30	10.85	34.15	**17.51**	88.75	77.50	77.08	36.50	**69.96**
		CPR	0.14	13.59	11.22	10.85	34.01	**17.42**	92.71	77.92	77.29	37.00	**71.23**
	0.2	LST	0.23	13.71	11.37	10.97	34.20	**17.56**	88.54	77.71	76.88	36.00	**69.78**
		LFT	0.20	13.69	11.32	10.94	34.18	**17.53**	90.42	77.92	77.08	36.83	**70.56**
		MTS	0.42	13.94	11.37	10.97	34.29	**17.64**	87.29	78.13	77.08	36.17	**69.67**
		CPR	0.14	13.60	11.33	10.93	34.18	**17.51**	92.71	77.71	76.88	36.67	**70.99**
neighboring (GR = 0.75)	0.6	LFT	0.09	13.52	11.56	11.50	35.71	**18.07**	94.79	78.33	76.04	34.17	**70.83**
		CPR	0.08	13.49	11.55	11.43	35.63	**18.02**	94.79	78.75	76.67	35.33	**71.39**
	0.5	LFT	0.13	13.58	11.36	11.22	35.06	**17.80**	93.13	78.96	77.29	36.00	**71.34**
		CPR	0.08	13.50	11.31	11.17	35.08	**17.76**	95.83	79.79	77.71	35.17	**72.13**
	0.4	LFT	0.12	13.56	11.24	10.94	34.43	**17.54**	93.75	79.17	77.29	35.83	**71.51**
		CPR	0.09	13.51	11.24	10.96	34.42	**17.53**	95.42	78.33	77.08	36.50	**71.83**
	0.3	LFT	0.16	13.61	11.25	10.88	34.11	**17.46**	91.88	78.54	77.08	36.83	**71.08**
		CPR	0.15	13.59	11.22	10.90	34.12	**17.46**	92.08	78.54	77.08	37.33	**71.26**
	0.2	LFT	0.22	13.71	11.38	10.97	34.20	**17.56**	89.17	77.92	76.88	35.83	**69.95**
		CPR	0.14	13.58	11.33	10.92	34.16	**17.50**	92.29	78.96	76.88	35.67	**70.95**

			AD_O	AD_CP					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
neighboring (GR = 0.5)	0.6	LFT	0.08	13.49	11.58	11.51	35.71	**18.07**	95.21	77.92	76.67	34.17	**70.99**
		CPR	0.05	13.44	11.58	11.46	35.64	**18.03**	96.67	78.33	77.29	34.83	**71.78**
	0.5	LFT	0.08	13.49	11.40	11.21	35.12	**17.81**	95.63	79.17	77.50	36.17	**72.11**
		CPR	0.05	13.46	11.41	11.22	35.11	**17.80**	96.88	79.58	77.50	36.50	**72.61**
	0.4	LFT	0.10	13.53	11.30	10.99	34.58	**17.60**	95.00	79.17	77.08	37.17	**72.10**
		CPR	0.08	13.50	11.28	11.04	34.53	**17.59**	94.79	79.38	77.50	37.00	**72.17**
	0.3	LFT	0.16	13.62	11.25	10.99	34.24	**17.52**	91.04	77.92	77.08	36.50	**70.64**
		CPR	0.10	13.53	11.24	10.91	34.26	**17.48**	94.17	78.96	77.29	36.33	**71.69**
	0.2	LFT	0.22	13.71	11.41	10.98	34.29	**17.60**	90.21	78.54	77.08	36.50	**70.58**
		CPR	0.15	13.62	11.39	10.96	34.28	**17.56**	92.71	78.33	76.88	36.67	**71.15**
neighboring (GR = 0.25)	0.6	LFT	0.07	13.50	11.63	11.48	35.80	**18.10**	95.83	77.71	77.29	33.67	**71.13**
		CPR	0.07	13.48	11.59	11.52	35.75	**18.09**	95.83	79.38	76.88	34.33	**71.60**
	0.5	LFT	0.10	13.51	11.43	11.30	35.21	**17.86**	94.79	79.38	77.29	36.00	**71.86**
		CPR	0.06	13.46	11.39	11.26	35.20	**17.83**	96.67	79.58	77.29	35.50	**72.26**
	0.4	LFT	0.10	13.52	11.33	11.06	34.67	**17.65**	94.58	78.75	77.29	37.00	**71.91**
		CPR	0.08	13.49	11.28	11.05	34.62	**17.61**	95.21	79.38	77.08	36.33	**72.00**
	0.3	LFT	0.14	13.58	11.31	10.97	34.40	**17.57**	92.29	77.92	76.88	36.50	**70.90**
		CPR	0.08	13.50	11.29	11.00	34.34	**17.53**	95.00	78.33	76.88	36.00	**71.55**
	0.2	LFT	0.24	13.75	11.46	11.03	34.45	**17.67**	88.13	77.08	77.08	35.83	**69.53**
		CPR	0.15	13.60	11.40	11.07	34.40	**17.62**	92.08	78.13	76.88	36.17	**70.81**
lbest (GR = 0.0)	0.6	LFT	0.09	13.52	11.61	11.58	35.84	**18.14**	95.00	77.50	76.67	34.17	**70.83**
		CPR	0.09	13.51	11.64	11.53	35.81	**18.12**	95.21	77.29	76.67	33.83	**70.75**
	0.5	LFT	0.08	13.51	11.48	11.28	35.28	**17.88**	95.63	77.50	76.88	35.00	**71.25**
		CPR	0.08	13.50	11.40	11.25	35.29	**17.86**	95.83	78.54	77.08	35.00	**71.61**
	0.4	LFT	0.09	13.51	11.36	11.07	34.72	**17.67**	94.58	78.96	77.08	35.83	**71.61**
		CPR	0.11	13.54	11.31	11.09	34.63	**17.64**	94.58	79.79	76.67	36.50	**71.89**
	0.3	LFT	0.19	13.66	11.40	10.99	34.45	**17.63**	90.63	78.33	76.46	36.17	**70.40**
		CPR	0.10	13.54	11.34	11.01	34.37	**17.57**	94.17	77.71	76.88	36.00	**71.19**
	0.2	LFT	0.28	13.80	11.53	11.11	34.56	**17.75**	87.29	76.67	76.88	36.00	**69.21**
		CPR	0.15	13.62	11.45	11.05	34.50	**17.65**	91.46	77.50	77.08	35.33	**70.34**

Table C.5: RCPSP test results for SDJ under different PSO topologies
(5,000 schedules – 20 forward/ 20 backward particles)

PSO Topo.	C.F (χ)	Priority Rule	AD_O	AD_CP					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
gbest (GR = 1.0)	0.6	LST	0.04	13.43	11.04	10.98	34.39	**17.46**	97.92	81.25	77.29	38.17	**73.66**
		LFT	0.03	13.43	11.08	10.94	34.45	**17.48**	97.92	81.88	77.50	37.33	**73.66**
		MTS	0.03	13.41	11.01	10.92	34.49	**17.46**	98.13	82.71	77.71	38.00	**74.14**
		CPR	0.03	13.41	11.07	10.94	34.42	**17.46**	98.13	82.50	77.92	38.00	**74.14**
	0.5	LST	0.04	13.43	10.92	10.66	33.73	**17.19**	97.50	82.92	78.13	39.00	**74.39**
		LFT	0.04	13.45	10.89	10.61	33.78	**17.18**	97.50	83.75	78.54	39.17	**74.74**
		MTS	0.04	13.44	10.85	10.65	33.83	**17.19**	97.50	84.17	78.75	39.67	**75.02**
		CPR	0.03	13.41	10.95	10.70	33.78	**17.21**	98.13	82.71	78.13	39.00	**74.49**
	0.4	LST	0.06	13.47	10.92	10.38	32.96	**16.93**	96.04	81.46	78.33	39.33	**73.79**
		LFT	0.09	13.51	10.99	10.51	33.01	**17.00**	95.00	81.04	78.54	39.83	**73.60**
		MTS	0.08	13.50	10.99	10.45	33.02	**16.99**	95.42	81.46	78.13	37.83	**73.21**
		CPR	0.07	13.47	10.93	10.42	32.85	**16.92**	95.83	81.25	78.33	40.17	**73.90**
	0.3	LST	0.16	13.61	11.07	10.38	32.57	**16.91**	91.88	78.54	77.92	39.00	**71.83**
		LFT	0.18	13.63	11.03	10.54	32.78	**16.99**	91.88	80.83	77.29	38.50	**72.13**

Topology		Method											
		MTS	0.14	13.59	11.04	10.41	32.57	**16.90**	92.71	80.00	77.71	38.67	**72.27**
		CPR	0.09	13.52	11.04	10.35	32.54	**16.86**	94.58	80.83	77.08	39.33	**72.96**
	0.2	LST	0.14	13.59	11.07	10.36	32.46	**16.87**	92.29	79.79	77.71	38.50	**72.07**
		LFT	0.21	13.69	11.07	10.43	32.66	**16.96**	90.63	78.75	77.71	39.00	**71.52**
		MTS	0.26	13.72	11.08	10.35	32.50	**16.91**	91.88	79.17	77.71	38.17	**71.73**
		CPR	0.14	13.59	11.05	10.42	32.52	**16.89**	93.13	79.79	78.13	39.00	**72.51**
neighboring (GR = 0.75)	0.6	LFT	0.03	13.41	10.95	10.94	34.36	**17.42**	98.13	83.75	77.50	39.00	**74.59**
		CPR	0.02	13.41	11.02	10.97	34.41	**17.45**	98.33	81.88	77.71	37.83	**73.94**
	0.5	LFT	0.04	13.44	10.90	10.63	33.78	**17.19**	97.29	82.92	78.33	39.83	**74.59**
		CPR	0.04	13.43	10.85	10.60	33.68	**17.14**	97.50	84.17	78.75	39.17	**74.90**
	0.4	LFT	0.06	13.47	10.89	10.40	32.97	**16.93**	96.67	82.29	78.54	39.67	**74.29**
		CPR	0.05	13.45	10.86	10.40	32.87	**16.90**	96.46	82.08	78.54	39.67	**74.19**
	0.3	LFT	0.12	13.56	10.94	10.33	32.45	**16.82**	93.75	80.42	78.54	39.50	**73.05**
		CPR	0.07	13.49	10.92	10.32	32.43	**16.79**	95.21	81.67	77.92	39.67	**73.61**
	0.2	LFT	0.10	13.53	11.03	10.29	32.40	**16.81**	94.17	79.79	78.13	39.00	**72.77**
		CPR	0.07	13.48	10.95	10.36	32.46	**16.81**	95.63	80.83	77.92	38.83	**73.30**
neighboring (GR = 0.5)	0.6	LFT	0.03	13.41	10.99	10.93	34.41	**17.43**	98.33	82.71	77.71	37.83	**74.15**
		CPR	0.02	13.40	10.98	10.94	34.39	**17.42**	98.75	83.33	77.71	37.83	**74.41**
	0.5	LFT	0.03	13.42	10.84	10.63	33.85	**17.18**	97.92	83.75	78.96	39.33	**74.99**
		CPR	0.02	13.41	10.83	10.65	33.79	**17.17**	98.54	84.17	78.75	40.17	**75.41**
	0.4	LFT	0.04	13.43	10.85	10.42	32.91	**16.90**	97.71	82.50	77.92	39.83	**74.49**
		CPR	0.05	13.45	10.85	10.32	32.98	**16.90**	96.67	83.33	78.96	40.17	**74.78**
	0.3	LFT	0.09	13.51	10.92	10.33	32.40	**16.79**	95.00	81.46	79.17	39.83	**73.86**
		CPR	0.05	13.46	10.93	10.30	32.53	**16.81**	97.08	81.04	78.54	39.83	**74.13**
	0.2	LFT	0.08	13.50	10.93	10.31	32.51	**16.81**	95.00	81.67	78.33	38.83	**73.46**
		CPR	0.07	13.48	10.94	10.33	32.42	**16.79**	96.25	81.67	77.92	39.67	**73.88**
neighboring (GR = 0.25)	0.6	LFT	0.02	13.40	10.99	10.91	34.45	**17.44**	98.54	82.71	78.13	37.83	**74.30**
		CPR	0.02	13.40	11.01	10.96	34.43	**17.45**	98.54	83.13	77.71	38.33	**74.43**
	0.5	LFT	0.02	13.40	10.84	10.63	33.76	**17.16**	98.54	84.17	78.54	39.67	**75.23**
		CPR	0.03	13.41	10.79	10.66	33.74	**17.15**	98.33	84.58	78.75	40.33	**75.50**
	0.4	LFT	0.02	13.39	10.78	10.37	32.95	**16.87**	99.17	84.58	79.38	40.50	**75.91**
		CPR	0.02	13.40	10.83	10.38	33.19	**16.95**	98.54	83.33	78.96	40.50	**75.33**
	0.3	LFT	0.06	13.47	10.84	10.30	32.51	**16.78**	95.83	83.54	78.75	39.83	**74.49**
		CPR	0.03	13.42	10.86	10.31	32.47	**16.77**	97.92	83.54	78.33	40.33	**75.03**
	0.2	LFT	0.14	13.59	10.91	10.33	32.54	**16.84**	92.29	81.67	78.13	40.00	**73.02**
		CPR	0.08	13.50	10.91	10.33	32.54	**16.82**	95.21	81.67	78.54	40.33	**73.94**
lbest (GR = 0.0)	0.6	LFT	0.02	13.40	10.97	10.98	34.42	**17.44**	98.75	84.58	77.71	37.33	**74.59**
		CPR	0.02	13.39	11.00	10.89	34.44	**17.43**	99.17	83.75	78.13	38.17	**74.80**
	0.5	LFT	0.03	13.41	10.91	10.64	33.81	**17.19**	98.13	83.13	78.54	39.83	**74.91**
		CPR	0.02	13.40	10.90	10.65	33.77	**17.18**	98.54	83.13	78.13	39.50	**74.82**
	0.4	LFT	0.03	13.41	10.86	10.47	32.99	**16.93**	98.13	83.75	78.75	40.00	**75.16**
		CPR	0.04	13.44	10.89	10.39	32.98	**16.92**	97.29	83.54	78.96	40.00	**74.95**
	0.3	LFT	0.08	13.51	10.95	10.42	32.61	**16.87**	95.63	81.46	78.33	39.50	**73.73**
		CPR	0.06	13.46	10.90	10.38	32.60	**16.83**	96.25	82.29	78.75	39.17	**74.11**
	0.2	LFT	0.12	13.56	11.05	10.39	32.65	**16.91**	93.33	81.46	77.71	39.00	**72.88**
		CPR	0.10	13.53	10.98	10.39	32.57	**16.87**	94.17	81.25	77.50	39.00	**72.98**

Table C.6: RCPSP test results for SDJ under different PSO topologies
(50,000 schedules – 20 forward/ 20 backward particles)

C.2. TCPSP justification schemes

C.2.1. TCPSP justification schemes comparison

N_Sch	Justification Scheme	Priority Rule	Average Cost Saving (ACS)				Problems Solved to Optimality			
			j-10	j-20	j-30	Aver.	j-10	j-20	j-30	Aver.
1,000 Schedules (10F/10B Particles)	NJ (No Justification)	EST	29.11	38.49	42.12	**36.58**	42.22	22.96	14.44	**26.54**
		LST	29.12	39.84	45.00	**37.99**	40.00	24.81	20.37	**28.40**
		GRWC	29.93	40.28	45.35	**38.52**	42.96	24.44	19.63	**29.01**
		CPR	36.12	44.57	49.24	**43.31**	75.56	40.37	28.52	**48.15**
	FJ (Free Float Justification)	EST	33.50	43.76	49.80	**42.35**	60.37	37.41	38.89	**45.56**
		LST	32.41	44.28	50.59	**42.43**	58.52	42.59	37.41	**46.17**
		GRWC	33.45	44.27	50.58	**42.77**	62.22	41.48	38.89	**47.53**
		CPR	36.74	46.61	52.00	**45.12**	84.81	53.33	47.04	**61.73**
	TJ (Total Float Justification)	EST	29.33	36.98	42.79	**36.37**	46.67	21.85	14.81	**27.78**
		LST	30.22	39.52	45.78	**38.50**	44.81	23.33	17.41	**28.52**
		GRWC	32.88	41.06	46.22	**40.05**	54.81	28.15	22.96	**35.31**
		CPR	36.98	46.42	51.09	**44.83**	85.56	51.48	36.30	**57.78**
	FTJ (Free & Total Float Justification)	EST	34.31	43.34	49.29	**42.32**	67.78	37.41	34.81	**46.67**
		LST	34.94	44.03	49.68	**42.88**	71.11	41.85	36.30	**49.75**
		GRWC	35.46	45.08	50.27	**43.60**	72.96	45.19	38.15	**52.10**
		CPR	37.13	47.31	52.46	**45.64**	88.89	61.48	52.22	**67.53**
	AFTJ (Alternating FJ & TJ)	EST	34.79	44.66	49.75	**43.07**	67.78	42.96	36.30	**49.01**
		LST	35.57	45.16	49.62	**43.45**	72.59	42.96	36.67	**50.74**
		GRWC	35.57	45.21	50.34	**43.71**	74.81	43.33	34.81	**50.99**
		CPR	37.19	46.87	51.76	**45.27**	89.63	56.30	44.81	**63.58**
5,000 Schedules (10F/10B Particles)	NJ (No Justification)	EST	30.02	38.41	42.47	**36.97**	45.19	22.96	14.07	**27.41**
		LST	30.92	39.83	44.86	**38.54**	45.19	22.59	18.89	**28.89**
		GRWC	32.22	41.12	45.77	**39.70**	52.59	27.78	20.74	**33.70**
		CPR	35.96	44.64	49.42	**43.34**	75.19	41.11	30.74	**49.01**
	FJ (Free Float Justification)	EST	33.66	44.58	50.45	**42.90**	61.85	44.07	40.74	**48.89**
		LST	33.79	45.16	51.31	**43.42**	64.81	43.33	46.30	**51.48**
		GRWC	34.74	45.28	51.46	**43.83**	69.63	47.04	45.19	**53.95**
		CPR	36.58	46.55	52.17	**45.10**	82.96	54.81	51.11	**62.96**
	TJ (Total Float Justification)	EST	29.06	37.87	42.59	**36.51**	45.19	22.96	14.44	**27.53**
		LST	30.57	39.78	45.80	**38.72**	47.78	25.56	16.67	**30.00**
		GRWC	32.90	41.08	46.14	**40.04**	52.96	26.67	21.11	**33.58**
		CPR	36.90	46.43	51.04	**44.79**	85.19	51.48	35.93	**57.53**
	FTJ (Free & Total Float Justification)	EST	34.35	43.93	48.88	**42.39**	67.78	38.89	32.22	**46.30**
		LST	35.53	44.88	49.90	**43.44**	73.33	42.96	34.07	**50.12**
		GRWC	35.68	45.32	50.04	**43.68**	74.81	46.67	39.26	**53.58**
		CPR	37.16	47.38	52.44	**45.66**	88.89	60.74	52.22	**67.28**
	AFTJ (Alternating FJ & TJ)	EST	35.23	44.94	49.83	**43.33**	70.74	43.70	33.33	**49.26**
		LST	35.41	45.24	50.34	**43.66**	73.70	44.81	39.63	**52.72**
		GRWC	35.96	45.84	50.47	**44.09**	77.04	48.52	40.37	**55.31**
		CPR	37.07	46.93	51.94	**45.31**	88.89	57.78	46.30	**64.32**
	NJ (No Justification)	EST	30.84	39.31	43.33	**37.83**	49.63	26.30	16.67	**30.86**
		LST	32.27	40.92	46.01	**39.73**	53.33	24.81	21.11	**33.09**
		GRWC	33.76	42.40	46.42	**40.86**	60.00	31.48	22.59	**38.02**
		CPR	36.32	44.99	49.85	**43.72**	76.30	40.37	29.63	**48.77**

N_Sch	Scheme	Sub	j-10	j-20	j-30	Aver.	j-10	j-20	j-30	Aver.
50,000 Schedules (20F/20B Particles)	FJ (Free Float Justification)	EST	34.56	45.74	51.23	**43.84**	67.41	51.11	43.70	**54.07**
		LST	35.45	46.45	51.88	**44.59**	73.33	60.00	50.74	**61.36**
		GRWC	36.10	46.57	51.89	**44.85**	77.41	56.30	49.63	**61.11**
		CPR	37.02	47.40	52.57	**45.66**	88.52	65.56	55.56	**69.88**
	TJ (Total Float Justification)	EST	29.27	37.90	43.19	**36.79**	47.41	21.85	15.56	**28.27**
		LST	30.30	39.94	45.33	**38.52**	45.19	24.07	19.63	**29.63**
		GRWC	32.52	40.93	46.51	**39.98**	52.59	28.52	22.96	**34.69**
		CPR	37.06	46.47	51.27	**44.93**	87.04	51.48	38.15	**58.89**
	FTJ (Free & Total Float Justification)	EST	34.92	44.01	49.26	**42.73**	70.37	41.11	33.33	**48.27**
		LST	34.76	44.53	49.88	**43.06**	70.74	40.00	35.19	**48.64**
		GRWC	35.80	44.90	50.54	**43.75**	77.04	43.33	38.52	**52.96**
		CPR	37.26	47.30	52.56	**45.70**	91.11	61.48	54.44	**69.01**
	AFTJ (Alternating FJ & TJ)	EST	35.30	44.87	50.28	**43.48**	70.74	42.96	36.30	**50.00**
		LST	35.29	45.94	50.76	**44.00**	72.96	50.74	37.04	**53.58**
		GRWC	35.88	45.56	50.77	**44.07**	77.04	47.04	41.48	**55.19**
		CPR	37.15	47.04	52.13	**45.44**	90.37	59.63	46.67	**65.56**
Summary 1,000 Sched. (10F/10B)	NJ	Best of EST, LST, GRWC & CPR	36.12	44.57	49.24	**43.31**	75.56	40.37	28.52	**48.15**
	FJ		36.74	46.61	52.00	**45.12**	84.81	53.33	47.04	**61.73**
	TJ		36.98	46.42	51.09	**44.83**	85.56	51.48	36.30	**57.78**
	FTJ		37.13	*47.31*	*52.46*	*45.64*	88.89	*61.48*	*52.22*	*67.53*
	AFTJ		*37.19*	46.87	51.76	**45.27**	89.63	56.30	44.81	**63.58**
Summary 5,000 Sched. (10F/10B)	NJ	Best of EST, LST, GRWC & CPR	35.96	44.64	49.42	**43.34**	75.19	41.11	30.74	**49.01**
	FJ		36.58	46.55	52.17	**45.10**	82.96	54.81	*51.11*	**62.96**
	TJ		36.90	46.43	51.04	**44.79**	85.19	51.48	35.93	**57.53**
	FTJ		*37.16*	*47.38*	*52.44*	*45.66*	*88.89*	*60.74*	*52.22*	*67.28*
	AFTJ		37.07	46.93	51.94	**45.31**	88.89	57.78	46.30	**64.32**
Summary 50,000 Sched. (20F/20B)	NJ	Best of EST, LST, GRWC & CPR	36.32	44.99	49.85	**43.72**	76.30	40.37	29.63	**48.77**
	FJ		37.02	47.40	52.57	**45.66**	88.52	65.56	55.56	**69.88**
	TJ		37.06	46.47	51.27	**44.93**	87.04	51.48	38.15	**58.89**
	FTJ		*37.26*	47.30	52.56	**45.70**	*91.11*	61.48	54.44	**69.01**
	AFTJ		37.15	47.04	52.13	**45.44**	90.37	59.63	46.67	**65.56**

Table C.7: Test results for different TCPSP justification schemes

C.2.1. FJ & FTJ testing with neighbouring topology

N_Sch	PSO Topology	Justific. Scheme	Average Cost Saving (ACS)				Problems Solved to Optimality			
			j-10	j-20	j-30	Aver.	j-10	j-20	j-30	Aver.
1,000 Schedules (10F/10B Particles)	gBest (GR=1.0)	FJ	36.74	46.61	52.00	**45.12**	84.81	53.33	47.04	**61.73**
		FTJ	37.13	47.31	52.46	**45.64**	88.89	61.48	52.22	**67.53**
	neighboring (GR=0.75)	FJ	36.71	46.37	51.93	**45.00**	82.59	54.44	44.44	**60.49**
		FTJ	37.10	47.28	52.44	**45.61**	87.78	61.11	51.48	**66.79**
	neighboring (GR=0.50)	FJ	36.64	46.54	52.00	**45.06**	83.33	54.44	47.41	**61.73**
		FTJ	37.20	47.25	52.45	**45.63**	89.63	58.89	51.48	**66.67**
	neighboring (GR=0.25)	FJ	36.70	46.59	51.85	**45.05**	84.81	54.81	47.04	**62.22**
		FTJ	37.16	47.22	52.38	**45.58**	89.26	58.89	50.00	**66.05**
	lBest (GR=0.0)	FJ	36.52	46.34	51.78	**44.88**	82.59	54.44	45.19	**60.74**
		FTJ	37.11	47.35	52.49	**45.65**	88.52	60.37	51.48	**66.79**

5,000 Schedules (10F/10B Particles)	gBest (GR=1.0)	FJ	36.58	46.55	52.17	**45.10**	82.96	54.81	51.11	**62.96**
		FTJ	37.16	47.38	52.44	**45.66**	88.89	60.74	52.22	**67.28**
	neighboring (GR=0.75)	FJ	36.83	46.75	52.28	**45.29**	85.19	57.41	48.89	**63.83**
		FTJ	37.14	47.38	52.47	**45.66**	88.89	60.00	50.37	**66.42**
	neighboring (GR=0.50)	FJ	36.73	46.73	51.92	**45.13**	83.70	56.67	48.89	**63.09**
		FTJ	37.16	47.18	52.48	**45.60**	89.26	61.11	53.70	**68.02**
	neighboring (GR=0.25)	FJ	36.71	46.70	52.36	**45.26**	84.44	58.52	50.00	**64.32**
		FTJ	37.12	47.26	52.46	**45.61**	89.63	60.37	48.89	**66.30**
	lBest (GR=0.0)	FJ	36.72	46.53	52.39	**45.22**	83.70	55.56	53.33	**64.20**
		FTJ	37.09	47.26	52.44	**45.59**	88.52	60.37	50.74	**66.54**
50,000 Schedules (20F/20B Particles)	gBest (GR=1.0)	FJ	37.02	47.40	52.57	**45.66**	88.52	65.56	55.56	**69.88**
		FTJ	37.26	47.30	52.56	**45.70**	91.11	61.48	54.44	**69.01**
	neighboring (GR=0.75)	FJ	36.81	47.30	52.59	**45.57**	85.19	64.07	54.07	**67.78**
		FTJ	37.28	47.18	52.41	**45.62**	91.48	58.89	52.22	**67.53**
	neighboring (GR=0.50)	FJ	37.06	47.36	52.70	**45.70**	88.15	64.07	57.78	**70.00**
		FTJ	37.23	47.31	52.44	**45.66**	91.11	62.96	49.63	**67.90**
	neighboring (GR=0.25)	FJ	37.07	47.22	52.72	**45.67**	88.15	61.11	58.52	**69.26**
		FTJ	37.20	47.27	52.40	**45.62**	90.37	60.00	50.00	**66.79**
	lBest (GR=0.0)	FJ	37.12	47.27	52.59	**45.66**	88.52	62.22	56.30	**69.01**
		FTJ	37.24	47.23	52.41	**45.63**	90.00	62.59	51.85	**68.15**
1,000 Sched. (10F/10B)	GR=1.0	Best of FJ & FTJ	37.13	47.31	52.46	**45.64**	88.89	61.48	52.22	**67.53**
	GR=0.75		37.10	47.28	52.44	**45.61**	87.78	61.11	51.48	**66.79**
	GR=0.50		37.20	47.25	52.45	**45.63**	89.63	58.89	51.48	**66.67**
	GR=0.25		37.16	47.22	52.38	**45.58**	89.26	58.89	50.00	**66.05**
	GR=0.0		37.11	47.35	52.49	**45.65**	88.52	60.37	51.48	**66.79**
5,000 Sched. (10F/10B)	GR=1.0	Best of FJ & FTJ	37.16	47.38	52.44	**45.66**	88.89	60.74	52.22	**67.28**
	GR=0.75		37.14	47.38	52.47	**45.66**	88.89	60.00	50.37	**66.42**
	GR=0.50		37.16	47.18	52.48	**45.60**	89.26	61.11	53.70	**68.02**
	GR=0.25		37.12	47.26	52.46	**45.61**	89.63	60.37	50.00	**66.30**
	GR=0.0		37.09	47.26	52.44	**45.59**	88.52	60.37	53.33	**66.54**
50,000 Sched. (20F/20B)	GR=1.0	Best of FJ & FTJ	37.26	47.40	52.57	**45.70**	91.11	65.56	55.56	**69.88**
	GR=0.75		37.28	47.30	52.59	**45.62**	91.48	64.07	54.07	**67.78**
	GR=0.50		37.23	47.36	52.70	**45.70**	91.11	64.07	57.78	**70.00**
	GR=0.25		37.20	47.27	52.72	**45.67**	90.37	61.11	58.52	**69.26**
	GR=0.0		37.24	47.27	52.59	**45.66**	90.00	62.59	56.30	**69.01**

Table C.8: TCPSP test results for *FJ & FTJ* under different PSO topologies

C.3. DDPSO testing

C.3.1. Differential density approaches comparison

N_{Sch}	Differential Densities Range	Priority Rule	AD_O j-30	AD_{CP} j-30	j-60	j-90	j-120	Aver.	Problems Solved to Optimality j-30	j-60	j-90	j-120	Aver.
1,000 Schedules (10F/10B Particles)	DJ only - No DD	LST	1.15	14.99	13.73	13.38	40.48	**20.64**	70.42	69.79	70.00	25.67	**58.97**
		LFT	1.20	15.06	13.62	13.32	40.46	**20.62**	71.88	70.63	70.63	26.33	**59.86**
		MTS	1.32	15.19	13.65	13.28	40.24	**20.59**	69.58	68.75	70.21	26.33	**58.72**
		CPR	0.73	14.43	13.26	13.08	39.79	**20.14**	77.29	72.71	71.04	27.33	**62.09**
	Random - high range [1.0-5.0]	LST	1.29	15.17	12.94	12.40	37.84	**19.59**	69.79	70.21	72.08	28.83	**60.23**
		LFT	1.29	15.17	12.96	12.31	37.73	**19.54**	70.83	70.63	71.67	29.17	**60.57**
		MTS	1.45	15.31	12.90	12.28	37.72	**19.55**	67.50	68.33	72.08	28.50	**59.10**
		CPR	0.58	14.21	12.54	12.13	37.31	**19.05**	79.58	72.08	73.54	29.33	**63.64**
	Random - medium range [0.5-2.0]	LST	1.12	14.96	13.44	13.21	40.08	**20.42**	71.46	69.38	69.38	26.50	**59.18**
		LFT	1.16	15.00	13.48	13.05	39.95	**20.37**	72.71	70.63	71.46	27.50	**60.57**
		MTS	1.29	15.16	13.36	13.16	39.73	**20.35**	70.42	70.83	71.46	27.50	**60.05**
		CPR	0.73	14.42	13.12	12.88	39.43	**19.96**	77.71	72.08	71.88	28.00	**62.42**
	Random - low range [0.1-1.0]	LST	1.62	15.66	14.28	13.83	41.38	**21.29**	67.71	66.46	68.96	23.67	**56.70**
		LFT	1.84	15.93	14.22	13.67	41.32	**21.28**	66.25	67.71	69.79	24.17	**56.98**
		MTS	1.67	15.67	14.28	13.91	41.43	**21.32**	66.67	67.50	68.96	24.00	**56.78**
		CPR	1.12	14.97	13.70	13.42	40.56	**20.66**	71.67	71.04	69.79	25.50	**59.50**
	Predefined values - high range [1.0-5.0]	LST	1.00	14.82	12.79	12.40	37.76	**19.44**	75.42	72.29	72.50	29.17	**62.34**
		LFT	0.96	14.73	12.84	12.30	37.61	**19.37**	74.79	70.42	72.50	30.67	**62.09**
		MTS	1.09	14.86	12.73	12.26	37.58	**19.36**	71.46	68.96	72.08	28.83	**60.33**
		CPR	0.54	14.16	12.49	12.10	37.33	**19.02**	81.67	73.13	73.75	29.83	**64.59**
	Predefined values - medium range [0.5-2.0]	LST	0.83	14.56	13.30	13.00	39.65	**20.13**	76.67	70.42	70.42	27.83	**61.33**
		LFT	0.89	14.64	13.28	12.84	39.47	**20.06**	75.42	70.00	72.29	28.00	**61.43**
		MTS	0.86	14.60	13.09	12.91	39.37	**19.99**	75.63	70.83	71.25	28.17	**61.47**
		CPR	0.62	14.27	13.05	12.75	38.98	**19.76**	80.42	72.50	72.08	28.67	**63.42**
	Predefined values - low range [0.1-1.0]	LST	1.28	15.18	13.97	13.64	41.16	**20.99**	70.21	68.54	68.54	25.33	**58.16**
		LFT	1.45	15.40	14.05	13.65	41.09	**21.05**	68.75	68.33	70.00	25.33	**58.10**
		MTS	1.30	15.21	13.99	13.67	40.95	**20.96**	70.00	68.33	68.96	24.67	**57.99**
		CPR	0.98	14.78	13.69	13.31	40.26	**20.51**	73.33	71.04	70.63	26.00	**60.25**
5,000 Schedules (10F/10B Particles)	DJ only - No DD	LST	0.35	13.88	12.43	12.55	38.55	**19.36**	86.25	73.96	73.75	30.50	**66.11**
		LFT	0.35	13.89	12.44	12.45	38.50	**19.32**	86.88	73.75	73.75	29.83	**66.05**
		MTS	0.33	13.87	12.41	12.40	38.35	**19.25**	86.88	74.17	74.17	30.83	**66.51**
		CPR	0.26	13.76	12.35	12.41	38.18	**19.17**	89.38	74.17	75.00	31.50	**67.51**
	Random - high range [1.0-5.0]	LST	1.36	15.28	12.80	11.85	35.70	**18.91**	70.00	71.04	72.08	31.50	**61.16**
		LFT	1.48	15.43	12.87	11.68	35.70	**18.92**	69.38	68.54	72.71	31.33	**60.49**
		MTS	1.38	15.22	12.38	11.64	35.47	**18.68**	69.58	69.17	73.54	30.00	**60.57**
		CPR	0.47	14.07	12.02	11.35	35.20	**18.16**	82.71	73.54	75.42	31.50	**65.79**
	Random - medium range [0.5-2.0]	LST	0.69	14.33	12.59	12.33	38.06	**19.33**	78.13	72.08	72.29	29.33	**62.96**
		LFT	0.66	14.34	12.48	12.35	37.91	**19.27**	81.25	72.29	73.13	30.17	**64.21**
		MTS	0.70	14.32	12.39	12.22	37.59	**19.13**	80.42	70.83	73.54	30.83	**63.91**
		CPR	0.37	13.92	12.25	12.19	37.32	**18.92**	86.04	73.33	73.96	31.00	**66.08**
	Random - low range [0.1-1.0]	LST	1.37	15.27	13.91	13.49	40.63	**20.82**	71.04	68.54	70.00	24.67	**58.56**
		LFT	1.39	15.32	14.09	13.54	40.73	**20.92**	72.92	68.13	70.00	26.00	**59.26**
		MTS	1.33	15.23	13.83	13.50	40.73	**20.82**	73.96	67.71	70.21	25.83	**59.43**
		CPR	0.93	14.70	13.33	13.08	39.93	**20.26**	76.88	71.04	71.67	27.83	**61.85**

	Predefined values - high range [1.0-5.0]	LST	0.78	14.48	12.17	11.65	35.60	**18.47**	77.50	72.71	73.54	30.83	**63.65**
		LFT	0.76	14.45	12.17	11.52	35.47	**18.40**	78.75	72.92	73.13	31.67	**64.11**
		MTS	0.91	14.63	12.19	11.53	35.37	**18.43**	76.04	70.42	73.96	30.67	**62.77**
		CPR	0.42	13.98	11.92	11.43	35.17	**18.13**	83.75	74.38	73.33	33.00	**66.11**
	Predefined values - medium range [0.5-2.0]	LST	0.46	14.07	12.33	11.96	36.99	**18.84**	82.50	72.50	73.75	31.33	**65.02**
		LFT	0.43	13.99	12.15	11.92	36.87	**18.73**	82.29	72.08	72.08	28.50	**63.74**
		MTS	0.40	13.97	12.13	11.89	36.73	**18.68**	84.58	72.92	74.58	31.67	**65.94**
		CPR	0.28	13.79	11.96	11.84	36.55	**18.54**	86.88	73.75	74.17	31.50	**66.57**
	Predefined values - low range [0.1-1.0]	LST	0.67	14.33	12.99	12.93	39.40	**19.91**	79.58	72.08	70.83	28.17	**62.67**
		LFT	0.64	14.30	13.04	12.87	39.51	**19.93**	80.63	72.71	71.67	27.83	**63.21**
		MTS	0.67	14.35	12.96	12.83	39.38	**19.88**	78.75	72.08	71.88	27.67	**62.59**
		CPR	0.48	14.09	12.79	12.73	38.95	**19.64**	82.71	72.71	73.54	29.00	**64.49**
5,000 Schedules (20F/20B Particles)	DJ only - No DD	LST	0.35	13.89	12.56	12.58	38.63	**19.41**	86.04	73.33	74.79	29.83	**66.00**
		LFT	0.33	13.86	12.51	12.52	38.57	**19.37**	87.08	73.54	74.17	31.17	**66.49**
		MTS	0.39	13.95	12.52	12.50	38.41	**19.34**	85.00	73.33	74.79	30.67	**65.95**
		CPR	0.23	13.73	12.40	12.42	38.33	**19.22**	89.58	74.17	73.96	30.50	**67.05**
	Random - high range [1.0-5.0]	LST	0.78	14.49	12.15	11.72	35.60	**18.49**	77.92	72.71	73.13	31.67	**63.85**
		LFT	0.82	14.51	12.09	11.70	35.49	**18.45**	76.04	72.50	73.13	31.83	**63.38**
		MTS	1.06	14.82	12.08	11.45	35.52	**18.47**	73.13	71.88	74.58	31.33	**62.73**
		CPR	0.31	13.85	11.86	11.34	35.26	**18.08**	87.08	73.96	75.21	32.67	**67.23**
	Random - medium range [0.5-2.0]	LST	0.60	14.23	12.46	12.30	37.99	**19.24**	80.42	72.71	72.92	31.00	**64.26**
		LFT	0.52	14.12	12.53	12.23	37.81	**19.17**	83.96	72.92	75.21	30.00	**65.52**
		MTS	0.63	14.25	12.37	12.25	37.68	**19.14**	80.42	72.92	73.75	30.33	**64.35**
		CPR	0.32	13.86	12.30	12.04	37.35	**18.88**	87.71	73.75	74.58	31.50	**66.89**
	Random - low range [0.1-1.0]	LST	1.14	14.98	13.56	13.39	40.44	**20.59**	72.50	69.79	69.38	25.33	**59.25**
		LFT	1.15	15.01	13.72	13.38	40.31	**20.61**	73.33	70.00	70.83	26.00	**60.04**
		MTS	1.21	15.03	13.67	13.35	40.47	**20.63**	72.71	69.58	69.79	26.00	**59.52**
		CPR	0.79	14.51	13.27	13.03	39.91	**20.18**	77.08	71.88	70.83	26.67	**61.61**
	Predefined - high range [1.0-5.0]	LST	0.58	14.23	12.11	11.53	35.51	**18.35**	80.21	73.75	74.17	31.83	**64.99**
		LFT	0.59	14.22	11.95	11.44	35.43	**18.26**	82.08	73.54	74.38	32.50	**65.63**
		MTS	0.83	14.49	12.01	11.49	35.42	**18.35**	77.08	71.88	74.17	31.50	**63.66**
		CPR	0.28	13.79	11.78	11.31	35.16	**18.01**	86.88	74.58	74.79	33.50	**67.44**
	Predefined - medium range [0.5-2.0]	LST	0.36	13.91	12.26	11.96	37.10	**18.81**	86.25	73.13	74.17	30.33	**65.97**
		LFT	0.33	13.85	12.10	11.93	36.95	**18.71**	87.08	73.75	73.96	31.17	**66.49**
		MTS	0.34	13.87	12.08	11.84	36.92	**18.68**	86.04	73.75	74.38	32.00	**66.54**
		CPR	0.21	13.70	12.05	11.83	36.66	**18.56**	90.00	74.17	74.79	31.83	**67.70**
	Predefined values - low range [0.1-1.0]	LST	0.64	14.29	13.08	12.92	39.52	**19.95**	79.17	72.29	72.08	27.67	**62.80**
		LFT	0.60	14.25	12.97	12.81	39.51	**19.89**	81.46	71.67	72.29	28.17	**63.40**
		MTS	0.59	14.24	12.94	12.87	39.39	**19.86**	81.25	71.67	72.08	28.00	**63.25**
		CPR	0.51	14.13	12.78	12.75	39.02	**19.67**	83.13	73.75	72.71	28.83	**64.60**
Summary 1000	DJ only	Best of LST, LFT, MTS & CPR	0.73	14.43	13.26	13.08	39.79	**20.14**	77.29	72.71	71.04	27.33	**62.09**
	Rand. High		0.58	14.21	12.54	12.13	37.31	**19.05**	79.58	72.08	73.54	29.33	**63.64**
	Rand. Med		0.73	14.42	13.12	12.88	39.43	**19.96**	77.71	72.08	71.88	28.00	**62.42**
	Rand. Low		1.12	14.97	13.70	13.42	40.56	**20.66**	71.67	71.04	69.79	25.50	**59.50**
	Pred. High		0.54	14.16	12.49	12.10	37.33	**19.02**	81.67	73.13	73.75	30.67	**64.59**
	Pred. Med		0.62	14.27	13.05	12.75	38.98	**19.76**	80.42	72.50	72.29	28.67	**63.42**
	Pred. Low		0.98	14.78	13.69	13.31	40.26	**20.51**	73.33	71.04	70.63	26.00	**60.25**
Summary 5000 (10/10)	DJ only	Best of LST, LFT, MTS & CPR	0.26	13.76	12.35	12.40	38.18	**19.17**	89.38	74.17	75.00	31.50	**67.51**
	Rand. High		0.47	14.07	12.02	11.35	35.20	**18.16**	82.71	73.54	75.42	31.50	**65.79**
	Rand. Med		0.37	13.92	12.25	12.19	37.32	**18.92**	86.04	73.33	73.96	31.00	**66.08**
	Rand. Low		0.93	14.70	13.33	13.08	39.93	**20.26**	76.88	71.04	71.67	27.83	**61.85**

			AD_O	AD_CP					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
	Pred. High		0.42	13.98	11.92	11.43	35.17	**18.13**	83.75	74.38	73.96	33.00	**66.11**
	Pred. Med.		0.28	13.79	11.96	11.84	36.55	**18.54**	86.88	73.75	74.58	31.67	**66.57**
	Pred. Low		0.48	14.09	12.79	12.73	38.95	**19.64**	82.71	72.71	73.54	29.00	**64.49**
Summary 5000 (20/20)	DJ only	Best of LST, LFT, MTS & CPR	0.23	13.73	12.40	12.42	38.33	**19.22**	89.58	74.17	74.79	31.17	**67.05**
	Rand. High		0.31	13.85	11.86	11.34	35.26	**18.08**	87.08	73.96	75.21	32.67	**67.23**
	Rand. Med		0.32	13.86	12.30	12.04	37.35	**18.88**	87.71	73.75	75.21	31.50	**66.89**
	Rand. Low		0.79	14.51	13.27	13.03	39.91	**20.18**	77.08	71.88	70.83	26.67	**61.61**
	Pred. High		0.28	13.79	11.78	11.31	35.16	**18.01**	86.88	74.58	74.79	33.50	**67.44**
	Pred. Med.		0.21	13.70	12.05	11.83	36.66	**18.56**	90.00	74.17	74.79	32.00	**67.70**
	Pred. Low		0.51	14.13	12.78	12.75	39.02	**19.67**	83.13	73.75	72.71	28.83	**64.60**
Overall Summary	DJ only	Best of LST, LFT, MTS & CPR	0.23	13.73	12.35	12.40	38.18	**19.17**	89.58	74.17	75.00	31.50	**67.51**
	Rand. High		0.31	13.85	11.86	11.34	35.20	**18.08**	87.08	73.96	75.42	32.67	**67.23**
	Rand. Med		0.32	13.86	12.25	12.04	37.32	**18.88**	87.71	73.75	75.21	31.50	**66.89**
	Rand. Low		0.79	14.51	13.27	13.03	39.91	**20.18**	77.08	71.88	71.67	27.83	**61.85**
	Pred. High		0.28	13.79	11.78	11.31	35.16	**18.01**	86.88	74.58	74.79	33.50	**67.44**
	Pred. Med.		0.21	13.70	11.96	11.83	36.55	**18.54**	90.00	74.17	74.79	32.00	**67.70**
	Pred. Low		0.48	14.09	12.78	12.73	38.95	**19.64**	83.13	73.75	73.54	29.00	**64.60**

Table C.9: RCPSP test results for different DD approaches

C.3.2. Density ranges comparison

N_Sch	w	DD Range	AD_O	AD_CP					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
1,000 Schedules (10F/10B Particles)	0.0	1	0.25	13.75	12.18	11.88	36.49	**18.58**	89.58	73.75	73.75	31.00	**66.27**
		2	0.22	13.71	11.94	11.63	35.81	**18.27**	89.79	75.42	74.79	33.00	**68.25**
		3	0.25	13.76	11.63	11.33	35.12	**17.96**	88.13	75.83	75.63	33.50	**68.27**
		4	0.23	13.73	11.63	11.25	34.85	**17.87**	89.79	74.17	75.63	33.67	**68.31**
		5	0.30	13.85	11.69	11.25	34.87	**17.92**	87.92	75.21	76.04	34.17	**68.33**
		6	0.31	13.84	11.71	11.33	35.05	**17.98**	87.08	75.63	76.04	33.33	**68.02**
		7	0.31	13.86	11.77	11.37	35.11	**18.03**	86.46	76.25	75.83	33.33	**67.97**
		8	0.35	13.92	11.79	11.37	35.14	**18.05**	85.63	74.58	75.83	33.17	**67.30**
		9	0.28	13.81	11.85	11.41	35.23	**18.07**	87.71	73.96	75.21	32.67	**67.39**
		10	0.34	13.89	11.88	11.47	35.29	**18.13**	86.67	75.63	75.42	33.17	**67.72**
	0.1	1	0.25	13.75	12.28	12.06	37.04	**18.78**	88.33	73.54	73.96	30.83	**66.67**
		2	0.23	13.73	12.03	11.79	36.25	**18.45**	89.58	74.79	74.58	32.83	**67.95**
		3	0.22	13.70	11.69	11.45	35.39	**18.06**	89.38	76.04	76.04	33.50	**68.74**
		4	0.24	13.72	11.65	11.27	35.07	**17.93**	88.75	75.42	75.83	33.33	**68.33**
		5	0.25	13.76	11.74	11.23	35.08	**17.95**	88.13	75.83	75.63	33.83	**68.35**
		6	0.32	13.86	11.79	11.37	35.15	**18.04**	86.46	75.00	76.46	33.83	**67.94**
		7	0.32	13.84	11.75	11.40	35.19	**18.04**	86.67	76.25	75.21	33.00	**67.78**
		8	0.29	13.83	11.84	11.38	35.15	**18.05**	87.08	74.38	75.21	33.33	**67.50**
		9	0.33	13.88	11.91	11.42	35.35	**18.14**	86.67	75.21	75.42	32.50	**67.45**
		10	0.34	13.88	11.86	11.48	35.27	**18.12**	85.83	75.42	75.83	33.00	**67.52**
	0.2	1	0.34	13.89	12.36	12.11	37.14	**18.88**	86.04	73.54	73.33	30.83	**65.94**
		2	0.21	13.70	12.10	11.86	36.51	**18.54**	89.79	74.58	74.58	31.67	**67.66**
		3	0.19	13.67	11.80	11.54	35.79	**18.20**	91.46	74.58	75.63	33.00	**68.67**
		4	0.22	13.72	11.66	11.34	35.16	**17.97**	89.58	75.83	75.63	33.67	**68.68**
		5	0.27	13.78	11.71	11.36	35.11	**17.99**	88.33	75.21	75.63	34.00	**68.29**
		6	0.28	13.79	11.72	11.38	35.21	**18.02**	87.29	75.63	75.42	33.33	**67.92**

	7	0.31	13.86	11.77	11.35	35.17	**18.04**	87.50	74.58	75.63	34.00	**67.93**
	8	0.29	13.82	11.88	11.43	35.22	**18.09**	87.92	75.83	75.42	32.67	**67.96**
	9	0.33	13.88	11.84	11.42	35.29	**18.11**	87.50	74.79	74.79	32.83	**67.48**
	10	0.32	13.85	11.85	11.46	35.33	**18.12**	85.83	75.63	75.42	33.17	**67.51**
0.3	1	0.43	14.02	12.45	12.23	37.29	**19.00**	82.92	73.33	72.71	29.83	**64.70**
	2	0.26	13.77	12.25	11.94	36.76	**18.68**	87.92	74.58	74.58	31.50	**67.15**
	3	0.21	13.71	11.78	11.63	35.89	**18.25**	90.21	76.88	75.83	32.67	**68.90**
	4	0.21	13.70	11.75	11.39	35.39	**18.06**	89.58	75.42	75.42	34.00	**68.60**
	5	0.25	13.75	11.72	11.34	35.10	**17.98**	88.75	75.42	76.25	33.00	**68.35**
	6	0.26	13.77	11.77	11.36	35.17	**18.02**	88.13	74.58	75.63	33.50	**67.96**
	7	0.31	13.83	11.80	11.39	35.19	**18.05**	87.08	75.42	75.63	33.67	**67.95**
	8	0.34	13.88	11.81	11.44	35.19	**18.08**	87.08	75.21	75.42	33.50	**67.80**
	9	0.32	13.87	11.84	11.45	35.37	**18.13**	86.25	75.21	75.00	32.50	**67.24**
	10	0.34	13.89	11.90	11.43	35.31	**18.13**	86.25	74.79	75.42	33.67	**67.53**
0.4	1	0.48	14.09	12.57	12.25	37.45	**19.09**	81.46	72.29	73.13	29.50	**64.09**
	2	0.28	13.80	12.29	12.01	36.80	**18.72**	87.29	74.17	74.38	30.83	**66.67**
	3	0.22	13.71	11.88	11.70	36.16	**18.36**	89.17	75.42	75.21	32.83	**68.16**
	4	0.21	13.70	11.80	11.47	35.47	**18.11**	90.00	75.83	75.42	32.83	**68.52**
	5	0.22	13.72	11.70	11.39	35.31	**18.03**	89.58	76.67	76.04	33.33	**68.91**
	6	0.27	13.79	11.73	11.38	35.24	**18.04**	87.71	75.42	76.04	33.67	**68.21**
	7	0.27	13.80	11.77	11.33	35.28	**18.05**	88.13	75.83	75.63	33.50	**68.27**
	8	0.34	13.87	11.86	11.39	35.23	**18.09**	85.21	75.63	75.42	32.67	**67.23**
	9	0.30	13.83	11.86	11.44	35.32	**18.11**	87.08	75.21	75.63	33.33	**67.81**
	10	0.35	13.90	11.95	11.46	35.28	**18.15**	86.04	74.79	76.04	33.17	**67.51**
0.5	1	0.58	14.16	12.70	12.31	37.58	**19.19**	80.83	72.29	72.29	29.50	**63.73**
	2	0.28	13.80	12.34	12.02	37.08	**18.81**	87.29	74.17	73.96	30.67	**66.52**
	3	0.21	13.70	12.01	11.77	36.39	**18.47**	90.00	75.00	75.42	31.50	**67.98**
	4	0.18	13.64	11.84	11.55	35.79	**18.21**	91.46	75.21	75.00	32.83	**68.63**
	5	0.23	13.72	11.75	11.48	35.47	**18.11**	89.79	75.63	75.63	33.17	**68.55**
	6	0.30	13.84	11.79	11.42	35.30	**18.09**	87.08	75.63	75.42	33.83	**67.99**
	7	0.30	13.84	11.82	11.44	35.30	**18.10**	87.50	74.79	75.42	32.17	**67.47**
	8	0.30	13.82	11.84	11.42	35.30	**18.10**	86.88	74.38	75.63	32.83	**67.43**
	9	0.29	13.80	11.90	11.51	35.34	**18.14**	86.88	74.79	75.21	32.83	**67.43**
	10	0.30	13.92	11.95	11.45	35.34	**18.16**	85.42	74.79	75.00	32.33	**66.89**
0.6	1	0.63	14.30	12.76	12.38	37.59	**19.26**	78.96	71.88	72.29	29.33	**63.11**
	2	0.41	14.00	12.36	12.16	37.17	**18.92**	84.79	73.13	72.71	29.67	**65.07**
	3	0.25	13.75	12.05	11.93	36.60	**18.58**	88.33	75.00	74.17	31.17	**67.17**
	4	0.23	13.72	11.89	11.63	35.97	**18.30**	89.58	76.04	75.21	32.50	**68.33**
	5	0.23	13.73	11.76	11.45	35.59	**18.13**	89.38	75.00	75.21	33.00	**68.15**
	6	0.27	13.78	11.80	11.48	35.38	**18.11**	88.13	75.83	74.58	32.33	**67.72**
	7	0.31	13.84	11.83	11.43	35.35	**18.11**	86.88	75.21	75.21	33.17	**67.61**
	8	0.30	13.82	11.82	11.43	35.43	**18.12**	86.25	74.38	75.83	32.83	**67.32**
	9	0.29	13.81	11.89	11.44	35.36	**18.13**	87.29	74.79	75.00	32.83	**67.48**
	10	0.30	13.83	11.89	11.50	35.39	**18.15**	86.67	75.21	75.83	33.00	**67.68**
0.73	1	0.65	14.34	12.79	12.41	37.66	**19.30**	78.33	72.08	72.29	29.17	**62.97**
	2	0.47	14.07	12.52	12.24	37.35	**19.05**	82.50	72.92	72.92	29.67	**64.50**
	3	0.25	13.75	12.21	11.99	36.86	**18.70**	88.13	74.58	73.75	31.33	**66.95**
	4	0.24	13.74	11.97	11.75	36.23	**18.42**	88.75	75.00	75.00	33.00	**67.94**
	5	0.22	13.72	11.84	11.62	35.71	**18.22**	89.17	75.63	75.00	33.00	**68.20**
	6	0.30	13.81	11.71	11.51	35.57	**18.15**	87.29	76.04	74.79	32.33	**67.61**

N_Sch	w	DD Range	AD_O j-30	AD_{CP} j-30	j-60	j-90	j-120	Aver.	Problems Solved to Optimality j-30	j-60	j-90	j-120	Aver.
1,000 Schedules (10F/10B Particles)		7	0.29	13.83	11.78	11.46	35.46	**18.13**	88.75	75.21	75.42	33.33	**68.18**
		8	0.35	13.91	11.87	11.45	35.45	**18.17**	84.79	74.79	74.79	32.67	**66.76**
		9	0.30	13.82	11.89	11.49	35.43	**18.16**	88.13	75.00	75.21	33.00	**67.83**
		10	0.27	13.77	11.93	11.47	35.37	**18.14**	87.50	74.58	75.21	33.33	**67.66**
	Best Inertia (w)	1	0.25	13.75	12.18	11.88	36.49	**18.58**	89.58	73.75	73.96	31.00	**66.67**
		2	0.21	13.70	11.94	11.63	35.81	**18.27**	89.79	75.42	74.79	33.00	**68.25**
		3	0.19	13.67	11.63	11.33	35.12	**17.96**	91.46	76.88	76.04	33.50	**68.90**
		4	0.18	13.64	11.63	11.25	34.85	**17.87**	91.46	76.04	75.83	34.00	**68.68**
		5	0.22	13.72	11.69	11.23	34.87	**17.92**	89.79	76.67	76.25	34.17	**68.91**
		6	0.26	13.77	11.71	11.33	35.05	**17.98**	88.13	76.04	76.46	33.83	**68.21**
		7	0.27	13.80	11.75	11.33	35.11	**18.03**	88.75	76.25	75.83	34.00	**68.27**
		8	0.29	13.82	11.79	11.37	35.14	**18.05**	87.92	75.83	75.83	33.50	**67.96**
		9	0.28	13.80	11.84	11.41	35.23	**18.07**	88.13	75.21	75.63	33.33	**67.83**
		10	0.27	13.77	11.85	11.43	35.27	**18.12**	87.50	75.63	76.04	33.67	**67.72**
	Aver. for all Inertia (w)	1	0.45	14.04	12.51	12.21	37.28	**19.01**	83.31	72.84	72.97	30.00	**64.69**
		2	0.30	13.82	12.23	11.95	36.71	**18.68**	87.37	74.22	74.06	31.23	**66.72**
		3	0.23	13.72	11.88	11.67	36.02	**18.32**	89.35	75.42	75.21	32.44	**68.10**
		4	0.22	13.71	11.77	11.46	35.49	**18.11**	89.69	75.36	75.39	33.23	**68.42**
		5	0.25	13.75	11.74	11.39	35.28	**18.04**	88.88	75.57	75.68	33.44	**68.39**
		6	0.29	13.81	11.75	11.40	35.26	**18.06**	87.40	75.47	75.55	33.27	**67.92**
		7	0.30	13.84	11.79	11.40	35.26	**18.07**	87.37	75.44	75.49	33.27	**67.89**
		8	0.32	13.86	11.84	11.41	35.26	**18.09**	86.35	74.90	75.44	32.96	**67.41**
		9	0.31	13.84	11.87	11.45	35.34	**18.12**	87.19	74.87	75.18	32.81	**67.51**
		10	0.32	13.87	11.90	11.47	35.32	**18.14**	86.28	75.10	75.52	33.10	**67.50**

Table C.10: RCPSP test results for different density ranges of PSO particles & different values for Inertia (w) (1,000 schedules – 10 forward/ 10 backward particles)

N_{Sch}	w	DD Range	AD_O j-30	AD_{CP} j-30	j-60	j-90	j-120	Aver.	Problems Solved to Optimality j-30	j-60	j-90	j-120	Aver.
5,000 Schedules (10F/10B Particles)	0.0	1	0.10	13.54	11.88	11.62	35.80	**18.21**	94.79	75.83	75.42	32.67	**66.27**
		2	0.09	13.52	11.60	11.38	35.17	**17.91**	94.79	77.50	76.25	34.33	**70.72**
		3	0.09	13.51	11.31	10.99	34.29	**17.53**	94.79	79.17	76.67	36.17	**71.70**
		4	0.20	13.68	11.30	10.81	33.82	**17.40**	89.58	76.67	76.67	36.17	**69.77**
		5	0.26	13.77	11.28	10.73	33.69	**17.37**	87.92	77.08	77.29	35.50	**69.45**
		6	0.33	13.76	11.27	10.75	33.57	**17.34**	88.54	77.50	76.25	36.50	**69.70**
		7	0.26	13.77	11.33	10.80	33.68	**17.39**	88.33	76.46	76.88	36.17	**69.46**
		8	0.30	13.84	11.36	10.78	33.82	**17.45**	87.08	76.88	77.08	35.33	**69.09**
		9	0.27	13.79	11.36	10.87	33.88	**17.47**	88.13	77.50	76.46	36.17	**69.56**
		10	0.25	13.76	11.36	10.85	33.86	**17.45**	87.08	77.08	76.46	35.50	**69.03**
	0.1	1	0.11	13.55	11.90	11.71	36.22	**18.34**	93.54	75.83	75.00	32.00	**69.09**
		2	0.06	13.47	11.50	11.39	35.37	**17.93**	96.46	78.13	76.46	33.83	**71.22**
		3	0.07	13.48	11.22	11.00	34.39	**17.52**	95.21	79.79	77.29	36.33	**72.16**
		4	0.18	13.66	11.30	10.84	33.85	**17.41**	90.00	77.08	76.04	36.33	**69.86**
		5	0.22	13.70	11.33	10.75	33.68	**17.37**	88.54	77.08	76.25	36.67	**69.64**
		6	0.21	13.69	11.38	10.77	33.67	**17.38**	89.58	76.04	76.04	36.17	**69.46**
		7	0.29	13.82	11.34	10.78	33.68	**17.41**	87.29	76.88	76.25	36.17	**69.15**
		8	0.25	13.75	11.37	10.81	33.80	**17.43**	88.33	76.04	75.42	34.83	**68.66**
		9	0.26	13.78	11.34	10.83	33.82	**17.44**	88.54	76.25	76.67	35.67	**69.28**
		10	0.25	13.76	11.39	10.84	33.87	**17.46**	89.58	76.88	76.67	35.83	**69.74**

	0.2	1	0.14	13.58	11.97	11.74	36.36	**18.41**	92.08	75.21	74.79	32.00	**68.52**
		2	0.07	13.48	11.55	11.45	35.56	**18.01**	96.04	77.50	76.67	34.00	**71.05**
		3	0.06	13.47	11.27	11.00	34.54	**17.57**	96.04	78.96	77.71	36.33	**72.26**
		4	0.19	13.67	11.24	10.84	33.85	**17.40**	91.25	77.08	76.67	36.83	**70.46**
		5	0.23	13.72	11.33	10.77	33.67	**17.37**	88.96	76.88	76.04	36.67	**69.64**
		6	0.29	13.82	11.34	10.78	33.68	**17.41**	87.29	76.88	76.25	36.17	**69.15**
		7	0.26	13.77	11.33	10.81	33.66	**17.39**	88.13	77.29	76.46	35.83	**69.43**
		8	0.27	13.78	11.35	10.79	33.73	**17.41**	86.88	76.25	76.46	35.83	**68.85**
		9	0.31	13.85	11.36	10.83	33.82	**17.47**	87.08	76.67	76.67	35.50	**68.98**
		10	0.25	13.77	11.40	10.86	33.84	**17.47**	88.75	76.04	76.04	35.50	**69.08**
	0.3	1	0.19	13.66	12.07	11.84	36.49	**18.52**	90.83	75.00	73.96	31.83	**67.91**
		2	0.07	13.48	11.64	11.47	35.66	**18.06**	95.63	77.71	76.67	33.50	**70.88**
		3	0.07	13.49	11.23	11.05	34.71	**17.62**	95.42	80.83	77.08	36.50	**72.46**
		4	0.13	13.57	11.29	10.80	33.96	**17.41**	93.33	76.88	77.50	36.00	**70.93**
		5	0.22	13.72	11.34	10.76	33.70	**17.38**	89.38	76.46	76.04	36.00	**69.47**
		6	0.23	13.73	11.34	10.77	33.61	**17.36**	89.17	76.46	76.04	36.33	**69.50**
		7	0.24	13.74	11.36	10.76	33.61	**17.37**	88.54	76.88	76.67	35.50	**69.40**
		8	0.29	13.82	11.34	10.76	33.72	**17.41**	87.92	77.29	76.25	35.50	**69.24**
		9	0.25	13.75	11.34	10.83	33.77	**17.42**	87.50	77.71	76.67	35.50	**69.34**
		10	0.24	13.74	11.39	10.87	33.82	**17.46**	88.13	76.88	77.08	36.67	**69.69**
	0.4	1	0.30	13.84	12.18	11.95	36.77	**18.68**	86.88	73.96	73.96	31.00	**66.45**
		2	0.09	13.51	11.68	11.54	35.81	**18.13**	94.58	77.29	76.04	33.00	**70.23**
		3	0.08	13.49	11.33	11.11	34.89	**17.71**	95.42	78.75	76.88	35.33	**71.59**
		4	0.12	13.57	11.27	10.86	34.02	**17.43**	92.50	78.54	76.88	36.67	**71.15**
		5	0.17	13.63	11.31	10.77	33.66	**17.34**	91.25	77.29	76.67	36.50	**70.43**
		6	0.25	13.75	11.29	10.76	33.69	**17.37**	88.33	76.04	76.04	35.50	**68.98**
		7	0.24	13.73	11.35	10.77	33.65	**17.37**	90.42	75.63	76.67	36.17	**69.72**
		8	0.27	13.78	11.38	10.73	33.70	**17.40**	87.29	76.25	76.88	35.50	**68.98**
		9	0.28	13.80	11.37	10.88	33.75	**17.45**	88.13	77.50	76.46	35.50	**69.40**
		10	0.26	13.78	11.32	10.84	33.85	**17.45**	87.71	77.71	75.83	35.83	**69.27**
	0.5	1	0.53	14.17	12.54	12.20	37.19	**19.03**	81.46	71.88	72.50	29.50	**63.83**
		2	0.08	13.50	11.61	11.44	35.58	**18.03**	95.00	77.92	76.88	34.00	**70.95**
		3	0.09	13.52	11.72	11.64	35.95	**18.21**	95.00	76.67	75.63	33.00	**70.07**
		4	0.12	13.56	11.27	10.89	34.23	**17.49**	93.13	77.92	77.29	36.83	**71.29**
		5	0.20	13.68	11.32	10.79	33.78	**17.39**	90.00	77.29	76.67	36.83	**70.20**
		6	0.22	13.70	11.31	10.80	33.70	**17.38**	88.75	77.08	76.04	35.83	**69.43**
		7	0.21	13.69	11.33	10.77	33.64	**17.36**	90.21	77.29	76.46	36.33	**70.07**
		8	0.29	13.81	11.31	10.78	33.72	**17.41**	88.13	77.08	76.25	36.17	**69.41**
		9	0.28	13.80	11.34	10.84	33.76	**17.44**	87.92	77.08	76.25	36.17	**69.35**
		10	0.26	13.77	11.35	10.84	33.80	**17.44**	87.92	76.88	76.46	35.67	**69.23**
	0.6	1	0.61	14.29	12.76	12.35	37.51	**19.23**	80.00	71.67	72.71	29.00	**63.34**
		2	0.10	13.54	11.84	11.63	36.13	**18.28**	94.79	76.67	75.21	32.33	**69.75**
		3	0.07	13.49	11.39	11.27	35.22	**17.84**	95.63	80.21	76.46	34.83	**71.78**
		4	0.11	13.53	11.19	10.97	34.29	**17.50**	93.96	78.96	77.08	36.50	**71.63**
		5	0.21	13.69	11.33	10.84	33.88	**17.43**	90.00	77.08	76.25	35.67	**69.75**
		6	0.19	13.66	11.30	10.76	33.63	**17.34**	89.17	76.67	76.46	36.67	**69.74**
		7	0.24	13.73	11.31	10.73	33.56	**17.33**	88.75	76.67	76.67	35.83	**69.48**
		8	0.28	13.80	11.36	10.77	33.65	**17.40**	87.29	76.25	76.46	36.17	**69.04**
		9	0.26	13.79	11.34	10.80	33.70	**17.41**	89.79	76.46	76.25	35.17	**69.42**
		10	0.29	13.82	11.38	10.83	33.85	**17.47**	86.25	76.88	76.46	36.00	**68.90**

N_Sch	w	DD Range	AD_O	AD_CP					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
	0.73	1	0.67	14.38	12.77	12.39	37.69	**19.31**	79.17	71.67	72.29	29.17	**63.07**
		2	0.19	13.66	11.97	11.83	36.33	**18.45**	91.04	75.00	74.58	31.00	**67.91**
		3	0.08	13.50	11.48	11.40	35.39	**17.94**	95.83	78.54	76.46	34.67	**71.38**
		4	0.08	13.50	11.23	11.04	34.49	**17.56**	95.00	79.79	77.71	36.17	**72.17**
		5	0.18	13.64	11.24	10.83	33.88	**17.40**	90.83	77.50	76.67	36.67	**70.42**
		6	0.25	13.75	11.28	10.74	33.74	**17.38**	88.54	76.88	76.46	36.17	**69.51**
		7	0.22	13.71	11.31	10.71	33.69	**17.36**	89.79	77.08	76.67	36.67	**70.05**
		8	0.29	13.81	11.37	10.75	33.68	**17.40**	86.67	78.13	76.04	35.83	**69.17**
		9	0.21	13.69	11.34	10.77	33.67	**17.37**	89.38	77.29	76.67	36.33	**69.92**
		10	0.26	13.77	11.45	10.85	33.87	**17.49**	88.33	76.46	76.46	36.17	**69.35**
5,000 Schedules (10F/10B Particles)	Best Inertia (w)	1	0.10	13.54	11.88	11.62	35.80	**18.21**	94.79	75.83	75.42	32.67	**69.09**
		2	0.06	13.47	11.50	11.38	35.17	**17.91**	96.46	78.13	76.88	34.33	**71.22**
		3	0.06	13.47	11.22	10.99	34.29	**17.52**	96.04	80.83	77.71	36.50	**72.46**
		4	0.08	13.50	11.19	10.80	33.82	**17.40**	95.00	79.79	77.71	36.83	**72.17**
		5	0.17	13.63	11.24	10.73	33.66	**17.34**	91.25	77.50	77.29	36.83	**70.43**
		6	0.19	13.66	11.27	10.74	33.57	**17.34**	89.58	77.50	76.46	36.67	**69.74**
		7	0.21	13.69	11.31	10.71	33.56	**17.33**	90.42	77.29	76.88	36.67	**70.07**
		8	0.25	13.75	11.31	10.73	33.65	**17.40**	88.33	78.13	77.08	36.17	**69.41**
		9	0.21	13.69	11.34	10.77	33.67	**17.37**	89.79	77.71	76.67	36.33	**69.92**
		10	0.24	13.74	11.32	10.83	33.80	**17.44**	89.58	77.71	77.08	36.67	**69.74**
	Aver. for all Inertia (w)	1	0.33	13.88	12.26	11.97	36.75	**18.72**	87.34	73.88	73.83	30.90	**66.06**
		2	0.09	13.52	11.67	11.51	35.70	**18.10**	94.79	77.21	76.09	33.25	**70.34**
		3	0.08	13.49	11.37	11.18	34.92	**17.74**	95.42	79.11	76.77	35.40	**71.67**
		4	0.14	13.59	11.26	10.88	34.06	**17.45**	92.34	77.86	76.98	36.44	**70.91**
		5	0.21	13.69	11.31	10.78	33.74	**17.38**	89.61	77.08	76.48	36.31	**69.87**
		6	0.25	13.73	11.31	10.77	33.66	**17.37**	88.67	76.69	76.20	36.17	**69.43**
		7	0.25	13.75	11.33	10.76	33.65	**17.37**	88.93	76.77	76.59	36.08	**69.59**
		8	0.28	13.80	11.36	10.77	33.73	**17.41**	87.45	76.77	76.35	35.65	**69.05**
		9	0.27	13.78	11.35	10.83	33.77	**17.43**	88.31	77.06	76.51	35.75	**69.41**
		10	0.26	13.77	11.38	10.85	33.84	**17.46**	87.97	76.85	76.43	35.90	**69.29**

Table C.11: RCPSP test results for different density ranges of PSO particles & different values for Inertia (w) (5,000 schedules – 10 forward/ 10 backward particles)

N_Sch	w	DD Range	AD_O	AD_CP					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
50,000 Schedules (20F/20B Particles)	0.0	1	0.05	13.45	11.48	11.26	35.04	**17.81**	96.88	78.96	77.08	34.83	**66.27**
		2	0.01	13.39	11.15	11.00	34.35	**17.47**	99.17	82.50	77.92	38.17	**74.44**
		3	0.03	13.43	10.92	10.58	33.49	**17.11**	98.13	82.92	78.75	39.83	**74.91**
		4	0.12	13.57	11.08	10.44	32.88	**16.99**	94.17	78.96	77.50	38.83	**72.36**
		5	0.15	13.61	11.06	10.38	32.59	**16.91**	91.67	80.00	77.71	38.33	**71.93**
		6	0.16	13.63	11.10	10.40	32.48	**16.90**	91.25	78.13	77.08	38.00	**71.11**
		7	0.15	13.60	11.10	10.40	32.53	**16.91**	92.50	78.13	77.92	36.83	**71.34**
		8	0.18	13.66	11.13	10.36	32.46	**16.91**	91.46	78.33	77.50	38.00	**71.32**
		9	0.16	13.63	11.07	10.38	32.51	**16.90**	91.46	79.17	77.71	38.83	**71.79**
		10	0.18	13.65	11.04	10.38	32.47	**16.88**	91.67	78.54	77.29	39.50	**71.75**
	0.1	1	0.04	13.45	11.49	11.35	35.31	**17.90**	97.29	79.17	77.08	34.50	**72.01**
		2	0.02	13.40	11.14	11.01	34.53	**17.52**	98.54	82.71	77.71	37.67	**74.16**
		3	0.01	13.39	10.88	10.62	33.46	**17.09**	99.17	82.92	78.33	40.50	**75.23**
		4	0.11	13.55	10.96	10.43	32.78	**16.93**	93.33	81.04	77.92	38.67	**72.74**

		5	0.13	13.58	11.08	10.38	32.57	**16.90**	92.92	78.13	77.29	38.50	**71.71**
		6	0.14	13.58	11.07	10.36	32.46	**16.87**	92.92	79.17	77.50	38.33	**71.98**
		7	0.20	13.69	11.08	10.41	32.43	**16.90**	89.79	79.79	77.92	38.50	**71.50**
		8	0.17	13.63	11.10	10.40	32.43	**16.89**	91.25	78.75	77.50	38.50	**71.50**
		9	0.16	13.62	11.12	10.34	32.45	**16.88**	91.67	78.54	77.71	38.50	**71.60**
		10	0.13	13.58	11.02	10.35	32.45	**16.85**	92.92	79.38	78.33	39.00	**72.41**
	0.2	1	0.05	13.45	11.52	11.40	35.44	**17.95**	96.88	78.13	76.67	33.33	**71.25**
		2	0.02	13.40	11.13	11.04	34.67	**17.56**	98.54	82.29	77.50	36.67	**73.75**
		3	0.02	13.40	10.85	10.61	33.59	**17.11**	98.75	84.58	78.96	39.33	**75.41**
		4	0.05	13.46	10.96	10.39	32.77	**16.90**	96.25	80.83	77.50	40.33	**73.73**
		5	0.14	13.59	11.03	10.38	32.56	**16.89**	91.88	79.38	77.71	38.00	**71.74**
		6	0.15	13.61	11.06	10.40	32.44	**16.88**	91.25	78.54	77.08	38.67	**71.39**
		7	0.17	13.64	11.07	10.39	32.39	**16.87**	91.25	79.17	77.08	38.33	**71.46**
		8	0.15	13.60	11.12	10.37	32.46	**16.89**	92.29	77.71	76.88	38.17	**71.26**
		9	0.23	13.73	11.09	10.39	32.31	**16.88**	90.00	78.54	77.29	40.33	**71.54**
		10	0.18	13.64	11.05	10.37	32.41	**16.87**	90.83	79.17	77.71	38.33	**71.51**
	0.3	1	0.07	13.48	11.62	11.40	35.54	**18.01**	95.63	77.50	76.25	32.83	**70.55**
		2	0.03	13.41	11.19	11.11	34.77	**17.62**	98.33	81.46	77.50	36.50	**73.45**
		3	0.02	13.40	10.88	10.71	33.70	**17.17**	98.75	84.38	78.96	39.33	**75.35**
		4	0.06	13.47	10.91	10.42	32.87	**16.92**	96.25	82.50	78.75	38.67	**74.04**
		5	0.13	13.57	11.06	10.42	32.54	**16.90**	93.13	78.75	77.29	38.67	**71.96**
		6	0.13	13.58	11.09	10.39	32.47	**16.88**	92.71	78.75	77.71	38.67	**71.96**
		7	0.17	13.64	11.09	10.38	32.40	**16.88**	91.25	78.33	77.50	38.17	**71.31**
		8	0.17	13.63	11.11	10.36	32.36	**16.87**	91.88	79.38	77.29	38.83	**71.84**
		9	0.13	13.57	11.13	10.38	32.42	**16.87**	92.92	78.13	76.88	37.50	**71.35**
		10	0.16	13.62	11.05	10.31	32.49	**16.87**	91.67	78.33	78.13	38.50	**71.66**
	0.4	1	0.10	13.54	11.73	11.58	35.88	**18.18**	93.96	76.46	75.83	33.00	**69.81**
		2	0.02	13.41	11.24	11.16	34.84	**17.66**	98.33	81.04	77.50	36.17	**73.26**
		3	0.01	13.39	10.86	10.73	33.82	**17.20**	98.96	85.42	78.54	38.83	**75.44**
		4	0.04	13.42	10.93	10.43	32.97	**16.94**	97.71	83.54	78.75	39.83	**74.96**
		5	0.12	13.55	11.02	10.38	32.56	**16.88**	93.54	79.17	77.71	39.50	**72.48**
		6	0.16	13.62	11.06	10.40	32.42	**16.87**	91.67	79.38	77.50	38.67	**71.80**
		7	0.15	13.61	11.06	10.37	32.40	**16.86**	91.88	79.58	77.50	37.50	**71.61**
		8	0.14	13.59	11.08	10.40	32.40	**16.87**	92.50	79.38	78.13	39.00	**72.25**
		9	0.13	13.58	11.06	10.37	32.40	**16.85**	92.50	78.96	78.13	38.50	**72.02**
		10	0.15	13.62	11.05	10.36	32.41	**16.86**	91.88	79.17	77.71	40.17	**72.23**
	0.5	1	0.39	13.95	12.26	11.99	36.68	**18.72**	82.92	72.92	73.75	30.17	**64.94**
		2	0.02	13.41	11.30	11.19	34.98	**17.72**	98.33	79.38	77.71	35.33	**72.69**
		3	0.02	13.40	10.90	10.78	34.06	**17.28**	98.96	83.33	78.54	39.67	**75.13**
		4	0.03	13.43	10.87	10.45	33.09	**16.96**	97.92	83.54	78.33	40.50	**75.07**
		5	0.07	13.47	11.01	10.34	32.61	**16.86**	95.83	79.58	78.33	39.33	**73.27**
		6	0.12	13.57	11.07	10.42	32.47	**16.88**	93.33	78.96	77.29	39.17	**72.19**
		7	0.17	13.63	11.07	10.38	32.40	**16.87**	91.46	77.92	78.13	40.00	**71.88**
		8	0.13	13.57	11.09	10.40	32.38	**16.86**	92.92	80.00	77.08	39.33	**72.33**
		9	0.13	13.58	11.12	10.37	32.38	**16.86**	93.33	78.33	77.29	38.67	**71.91**
		10	0.12	13.56	11.06	10.38	32.42	**16.86**	93.33	78.75	77.29	38.83	**72.05**
	0.6	1	0.48	14.11	12.59	12.21	37.21	**19.03**	82.29	72.92	73.13	29.83	**64.54**
		2	0.05	13.44	11.32	11.23	35.10	**17.77**	97.08	79.58	76.46	35.67	**72.20**
		3	0.02	13.40	10.91	10.87	34.26	**17.36**	98.54	85.00	78.33	37.83	**74.93**
		4	0.04	13.43	10.84	10.46	33.25	**17.00**	97.71	83.75	79.17	40.50	**75.28**

	Inertia (w)	#											
		5	0.08	13.50	11.00	10.40	32.71	**16.90**	95.83	79.79	78.33	39.17	**73.28**
		6	0.14	13.59	11.06	10.40	32.45	**16.88**	93.33	78.96	77.71	39.17	**72.29**
		7	0.15	13.59	11.08	10.42	32.42	**16.88**	92.50	79.79	77.50	38.33	**72.03**
		8	0.13	13.58	11.07	10.36	32.40	**16.85**	93.54	78.33	77.50	39.00	**72.09**
		9	0.14	13.59	11.06	10.37	32.40	**16.85**	92.71	80.63	77.08	39.50	**72.48**
		10	0.11	13.54	11.01	10.36	32.39	**16.82**	94.17	81.04	77.92	38.50	**72.91**
50,000 Schedules (20F/20B Particles)	0.73	1	0.54	14.20	12.66	12.26	37.37	**19.12**	81.88	71.46	73.13	29.17	**63.91**
		2	0.04	13.44	11.50	11.36	35.38	**17.92**	97.29	78.54	76.67	34.50	**71.75**
		3	0.02	13.41	11.03	10.94	34.46	**17.46**	98.33	81.46	77.71	37.50	**73.75**
		4	0.02	13.40	10.86	10.55	33.46	**17.07**	98.33	83.75	78.33	39.50	**74.98**
		5	0.08	13.50	10.97	10.36	32.69	**16.88**	95.21	81.04	79.17	40.00	**73.85**
		6	0.11	13.54	11.00	10.39	32.53	**16.87**	94.58	80.42	78.13	39.17	**73.07**
		7	0.09	13.51	11.04	10.35	32.45	**16.84**	95.00	79.17	77.71	38.50	**72.59**
		8	0.11	13.54	11.05	10.39	32.47	**16.87**	93.75	78.54	77.08	38.33	**71.93**
		9	0.12	13.56	10.98	10.38	32.45	**16.84**	93.13	81.25	77.08	39.17	**72.66**
		10	0.11	13.55	11.04	10.35	32.35	**16.82**	93.54	79.58	77.29	39.67	**72.52**
	Best Inertia (w)	1	0.04	13.45	11.48	11.26	35.04	**17.81**	97.29	79.17	77.08	34.83	**72.01**
		2	0.01	13.39	11.13	11.00	34.35	**17.47**	99.17	82.71	77.92	38.17	**74.44**
		3	0.01	13.39	10.85	10.58	33.46	**17.09**	99.17	85.42	78.96	40.50	**75.44**
		4	0.02	13.40	10.84	10.39	32.77	**16.90**	98.33	83.75	79.17	40.50	**75.28**
		5	0.07	13.47	10.97	10.34	32.54	**16.86**	95.83	81.04	79.17	40.00	**73.85**
		6	0.11	13.54	11.00	10.36	32.42	**16.87**	94.58	80.42	78.13	39.17	**73.07**
		7	0.09	13.51	11.04	10.35	32.39	**16.84**	95.00	79.79	78.13	40.00	**72.59**
		8	0.11	13.54	11.05	10.36	32.36	**16.85**	93.75	80.00	78.13	39.33	**72.33**
		9	0.12	13.56	10.98	10.34	32.31	**16.84**	93.33	81.25	78.13	40.33	**72.66**
		10	0.11	13.54	11.01	10.31	32.35	**16.82**	94.17	81.04	78.33	40.17	**72.91**
	Aver. for all Inertia (w)	1	0.22	13.70	11.92	11.68	36.06	**18.34**	90.96	75.94	75.36	32.21	**67.91**
		2	0.03	13.41	11.24	11.14	34.83	**17.66**	98.20	80.94	77.37	36.33	**73.21**
		3	0.02	13.40	10.90	10.73	33.85	**17.22**	98.70	83.75	78.52	39.10	**75.02**
		4	0.06	13.47	10.93	10.45	33.01	**16.96**	96.46	82.24	78.28	39.60	**74.15**
		5	0.11	13.55	11.03	10.38	32.60	**16.89**	93.75	79.48	77.94	38.94	**72.53**
		6	0.14	13.59	11.06	10.40	32.46	**16.88**	92.63	79.04	77.50	38.73	**71.97**
		7	0.16	13.61	11.08	10.39	32.43	**16.88**	91.95	78.98	77.66	38.27	**71.72**
		8	0.15	13.60	11.10	10.38	32.42	**16.87**	92.45	78.80	77.37	38.65	**71.82**
		9	0.15	13.61	11.08	10.37	32.42	**16.87**	92.21	79.19	77.40	38.88	**71.92**
		10	0.14	13.60	11.04	10.36	32.42	**16.85**	92.50	79.24	77.71	39.06	**72.13**

Table C.12: RCPSP test results for different density ranges of PSO particles & different values for Inertia (w) (50,000 schedules – 20 forward/ 20 backward particles)

N_{Sch}	Inertia (w)	Density Range	Average Cost Saving (ACS)				Problems Solved to Optimality			
			j-10	j-20	j-30	Aver.	j-10	j-20	j-30	Aver.
1,000 Schedules (10F/10B Particles)	0.73	SPSO	37.13	47.31	52.46	**45.64**	88.89	61.48	52.22	**67.53**
		R01	37.14	47.24	52.39	**45.59**	88.89	61.85	49.26	**66.67**
		R02	37.13	47.33	52.40	**45.62**	88.52	62.22	50.00	**66.91**
		R03	37.21	47.18	52.44	**45.61**	90.00	58.15	51.48	**66.54**
		R04	37.19	47.21	52.50	**45.63**	90.74	58.89	51.85	**67.16**
		R05	37.17	47.23	52.40	**45.60**	88.52	58.15	51.11	**65.93**
	0.6	SPSO	37.14	47.27	52.45	**45.62**	88.89	59.26	50.37	**66.17**
		R01	37.20	47.12	52.35	**45.55**	90.00	58.15	49.26	**65.80**

		R02	37.09	47.35	52.41	**45.61**	87.78	60.37	50.00	**66.05**
		R03	37.19	47.26	52.39	**45.61**	89.63	60.74	50.74	**67.04**
		R04	37.13	47.18	52.48	**45.60**	88.52	60.37	51.48	**66.79**
		R05	37.20	47.07	52.37	**45.54**	89.63	57.78	49.63	**65.68**
	0.5	SPSO	37.24	47.34	52.49	**45.69**	90.74	62.22	51.85	**68.27**
		R01	37.10	47.28	52.39	**45.59**	87.78	61.11	50.00	**66.30**
		R02	37.12	47.30	52.43	**45.61**	88.89	58.89	51.85	**66.54**
		R03	37.17	47.24	52.40	**45.60**	88.89	60.00	50.37	**66.42**
		R04	37.23	47.26	52.36	**45.61**	90.37	59.26	50.37	**66.67**
		R05	37.20	47.18	52.32	**45.57**	89.26	60.37	50.37	**66.67**
	0.4	SPSO	37.21	47.14	52.42	**45.59**	90.00	61.11	52.22	**67.78**
		R01	37.16	47.16	52.52	**45.62**	89.63	60.37	52.59	**67.53**
		R02	37.20	47.31	52.44	**45.65**	89.63	59.26	51.11	**66.67**
		R03	37.22	47.36	52.47	**45.68**	89.63	61.48	49.63	**66.91**
		R04	37.17	47.19	52.46	**45.61**	89.63	59.63	51.11	**66.79**
		R05	37.09	47.39	52.52	**45.67**	88.15	61.11	52.59	**67.28**
	0.3	SPSO	37.19	47.15	52.44	**45.60**	89.26	59.63	49.63	**66.17**
		R01	37.21	47.23	52.47	**45.64**	89.63	59.63	52.59	**67.28**
		R02	37.20	47.14	52.40	**45.58**	90.00	59.26	50.00	**66.42**
		R03	37.19	47.07	52.40	**45.55**	88.89	60.37	52.22	**67.16**
		R04	37.17	47.04	52.41	**45.54**	89.63	57.41	51.11	**66.05**
		R05	37.19	47.33	52.39	**45.64**	90.00	60.37	50.00	**66.79**
	0.2	SPSO	37.21	47.08	52.36	**45.55**	89.63	58.52	50.37	**66.17**
		R01	37.14	47.16	52.40	**45.57**	88.89	60.00	50.00	**66.30**
		R02	37.24	47.33	52.48	**45.68**	89.63	61.85	52.59	**68.02**
		R03	37.17	47.20	52.46	**45.61**	88.89	58.52	51.48	**66.30**
		R04	37.15	47.33	52.42	**45.63**	88.89	60.37	49.63	**66.30**
		R05	37.18	47.33	52.48	**45.66**	89.26	61.85	51.85	**67.65**
	0.1	SPSO	37.17	47.27	52.34	**45.59**	89.63	59.63	50.74	**66.67**
		R01	37.14	47.23	52.34	**45.57**	89.63	58.52	50.37	**66.17**
		R02	37.19	47.24	52.31	**45.58**	89.26	60.00	50.00	**66.42**
		R03	37.22	47.17	52.40	**45.60**	89.63	59.26	50.74	**66.54**
		R04	37.16	47.10	52.44	**45.57**	88.89	57.04	49.63	**65.19**
		R05	37.05	47.11	52.35	**45.50**	87.04	60.74	49.26	**65.68**
	0.0	SPSO	37.10	47.04	52.33	**45.49**	89.63	57.78	49.63	**65.68**
		R01	37.13	47.18	52.45	**45.58**	88.89	56.67	50.74	**65.43**
		R02	37.10	47.18	52.38	**45.55**	88.89	60.00	51.11	**66.67**
		R03	37.24	47.25	52.33	**45.60**	89.63	60.00	51.11	**66.91**
		R04	37.14	47.20	52.31	**45.55**	88.89	59.26	48.89	**65.68**
		R05	37.21	47.11	52.38	**45.57**	90.37	59.63	50.00	**66.67**
Best results (1000, 10F/10B)	0.73	Best DD Range	37.21	47.33	52.50	**45.64**	90.74	62.22	52.22	**67.53**
	0.6		37.20	47.35	52.48	**45.62**	90.00	60.74	51.48	**67.04**
	0.5		37.24	47.34	52.49	**45.69**	90.74	62.22	51.85	**68.27**
	0.4		37.22	47.39	52.52	**45.68**	90.00	61.48	52.59	**67.78**
	0.3		37.21	47.33	52.47	**45.64**	90.00	60.37	52.59	**67.28**
	0.2		37.24	47.33	52.48	**45.68**	89.63	61.85	52.59	**68.02**
	0.1		37.22	47.27	52.44	**45.60**	89.63	60.74	50.74	**66.67**
	0.0		37.24	47.25	52.45	**45.60**	90.37	60.00	51.11	**66.91**
	Best w	SPSO	37.24	47.34	52.49	**45.69**	90.74	62.22	52.22	**68.27**
		R01	37.21	47.28	52.52	**45.64**	90.00	61.85	52.59	**67.53**
		R02	37.24	47.35	52.48	**45.68**	90.00	62.22	52.59	**66.91**
		R03	37.24	47.36	52.47	**45.68**	90.00	61.48	52.22	**67.04**

N_Sch	Inertia (w)	Density Range	j-10	j-20	j-30	Aver.	j-10	j-20	j-30	Aver.
		R04	37.23	47.33	52.50	**45.63**	90.74	60.37	51.85	**67.16**
		R05	37.21	47.39	52.52	**45.67**	90.37	61.85	52.59	**67.28**
Average results (1000, 10F/10B)	0.73	Average for all DD Ranges	37.16	47.25	52.43	**45.62**	89.26	60.12	50.99	**66.79**
	0.6		37.16	47.21	52.41	**45.59**	89.07	59.44	50.25	**66.26**
	0.5		37.17	47.26	52.40	**45.61**	89.32	60.31	50.80	**66.81**
	0.4		37.17	47.26	52.47	**45.64**	89.44	60.49	51.54	**67.16**
	0.3		37.19	47.16	52.42	**45.59**	89.57	59.44	50.93	**66.65**
	0.2		37.18	47.24	52.43	**45.62**	89.20	60.19	50.99	**66.79**
	0.1		37.16	47.19	52.36	**45.57**	89.01	59.20	50.12	**66.11**
	0.0		37.15	47.16	52.36	**45.56**	89.38	58.89	50.25	**66.17**
	Average for all Inertia (w) values	SPSO	37.17	47.20	52.41	**45.60**	89.58	59.95	50.88	**66.81**
		R01	37.15	47.20	52.41	**45.59**	89.17	59.54	50.60	**66.44**
		R02	37.16	47.27	52.41	**45.61**	89.07	60.23	50.83	**66.71**
		R03	37.20	47.21	52.41	**45.61**	89.40	59.81	50.97	**66.73**
		R04	37.17	47.19	52.42	**45.59**	89.44	59.03	50.51	**66.33**
		R05	37.16	47.22	52.40	**45.59**	89.03	60.00	50.60	**66.54**

Table C.13: TCPSP test results for different density ranges of PSO particles & different values for Inertia (w) (1,000 schedules – 10 forward/ 10 backward particles)

N_Sch	Inertia (w)	Density Range	Average Cost Saving (ACS)				Problems Solved to Optimality			
			j-10	j-20	j-30	Aver.	j-10	j-20	j-30	Aver.
5,000 Schedules (10F/10B Particles)	0.73	SPSO	37.16	47.38	52.44	**45.66**	88.89	60.74	52.22	**67.28**
		R01	37.23	47.33	52.56	**45.71**	89.63	61.85	53.70	**68.40**
		R02	37.21	47.22	52.55	**45.66**	88.89	59.26	52.22	**66.79**
		R03	37.19	47.33	52.44	**45.66**	90.00	60.74	50.37	**67.04**
		R04	37.18	47.15	52.42	**45.58**	89.26	58.15	50.37	**65.93**
		R05	37.17	47.22	52.45	**45.61**	90.00	59.63	52.22	**67.28**
	0.6	SPSO	37.17	47.21	52.47	**45.62**	89.26	60.00	52.22	**67.16**
		R01	37.13	47.17	52.48	**45.59**	89.26	60.37	52.59	**67.41**
		R02	37.16	47.27	52.47	**45.63**	90.00	61.48	52.59	**68.02**
		R03	37.24	47.22	52.45	**45.64**	89.63	58.89	50.00	**66.17**
		R04	37.15	47.30	52.39	**45.61**	89.26	60.00	51.85	**67.04**
		R05	37.10	47.20	52.36	**45.56**	88.52	61.11	48.15	**65.93**
	0.5	SPSO	37.15	47.11	52.43	**45.56**	89.63	60.74	50.37	**66.91**
		R01	37.20	47.22	52.43	**45.61**	90.00	61.11	50.74	**67.28**
		R02	37.20	47.29	52.50	**45.66**	88.89	60.74	53.33	**67.65**
		R03	37.14	47.24	52.44	**45.60**	88.52	59.26	49.26	**65.68**
		R04	37.17	47.36	52.42	**45.65**	89.26	60.00	52.59	**67.28**
		R05	37.19	47.31	52.28	**45.60**	89.63	59.63	49.63	**66.30**
	0.4	SPSO	37.19	47.24	52.39	**45.61**	89.26	61.48	50.74	**67.16**
		R01	37.20	47.11	52.37	**45.56**	89.63	58.89	50.74	**66.42**
		R02	37.19	47.36	52.51	**45.69**	90.74	60.00	53.33	**68.02**
		R03	37.13	47.36	52.34	**45.61**	90.00	60.00	48.89	**66.30**
		R04	37.23	47.19	52.50	**45.64**	90.00	60.00	51.11	**67.04**
		R05	37.18	47.33	52.36	**45.62**	89.26	61.11	51.11	**67.16**
	0.3	SPSO	37.22	47.24	52.44	**45.63**	90.00	59.26	52.22	**67.16**
		R01	37.19	47.28	52.45	**45.64**	88.89	60.37	50.37	**66.54**
		R02	37.14	47.33	52.42	**45.63**	88.15	60.37	51.48	**66.67**
		R03	37.27	47.10	52.34	**45.57**	91.11	58.52	49.63	**66.42**
		R04	37.14	47.23	52.39	**45.59**	89.63	58.89	50.74	**66.42**

Section	w	Sub								
		R05	37.20	47.13	52.46	45.60	89.63	59.63	49.26	66.17
	0.2	SPSO	37.18	47.35	52.40	45.64	88.89	60.00	50.37	66.42
		R01	37.11	47.08	52.43	45.54	88.15	58.15	51.48	65.93
		R02	37.11	47.22	52.42	45.58	88.89	59.26	50.74	66.30
		R03	37.21	47.06	52.39	45.56	89.26	57.41	50.74	65.80
		R04	37.11	47.29	52.49	45.63	87.78	59.63	52.96	66.79
		R05	37.13	47.25	52.42	45.60	88.89	60.37	48.52	65.93
	0.1	SPSO	37.08	47.19	52.50	45.59	88.89	59.26	52.59	66.91
		R01	37.17	47.14	52.46	45.59	89.26	58.52	51.85	66.54
		R02	37.14	47.34	52.40	45.63	88.89	61.11	51.48	67.16
		R03	37.19	47.16	52.50	45.61	88.89	58.89	51.85	66.54
		R04	37.17	47.17	52.39	45.58	89.26	58.89	49.63	65.93
		R05	37.10	47.08	52.33	45.50	88.89	59.26	50.00	66.05
	0.0	SPSO	37.13	47.02	52.31	45.49	89.26	57.04	50.37	65.56
		R01	37.13	47.22	52.39	45.58	89.26	59.26	50.00	66.17
		R02	37.25	47.17	52.39	45.60	90.74	58.52	49.63	66.30
		R03	37.26	47.13	52.36	45.58	90.74	59.26	50.37	66.79
		R04	37.17	47.09	52.31	45.52	90.00	57.78	49.63	65.80
		R05	37.11	47.15	52.32	45.53	89.26	58.52	49.63	65.80
Best results (5000, 10F/10B)	0.73	Best DD Range	37.23	47.38	52.56	45.71	90.00	61.85	53.70	68.40
	0.6		37.24	47.30	52.48	45.64	90.00	61.48	52.59	68.02
	0.5		37.20	47.36	52.50	45.66	90.00	61.11	53.33	67.65
	0.4		37.23	47.36	52.51	45.69	90.74	61.48	53.33	68.02
	0.3		37.27	47.33	52.46	45.64	91.11	60.37	52.22	67.16
	0.2		37.21	47.35	52.49	45.64	89.26	60.37	52.96	66.79
	0.1		37.19	47.34	52.50	45.63	89.26	61.11	52.59	67.16
	0.0		37.26	47.22	52.39	45.60	90.74	59.26	50.37	66.79
	Best w	SPSO	37.22	47.38	52.50	45.66	90.00	61.48	52.59	67.28
		R01	37.23	47.33	52.56	45.71	90.00	61.85	53.70	68.40
		R02	37.25	47.36	52.55	45.69	90.74	61.48	53.33	68.02
		R03	37.27	47.36	52.50	45.66	91.11	60.74	51.85	67.04
		R04	37.23	47.36	52.50	45.65	90.00	60.00	52.96	67.28
		R05	37.20	47.33	52.46	45.62	90.00	61.11	52.22	67.28
Average results (5000, 10F/10B)	0.73	Average for all DD Ranges	37.19	47.27	52.48	45.65	89.44	60.06	51.85	67.12
	0.6		37.16	47.23	52.44	45.61	89.32	60.31	51.23	66.95
	0.5		37.17	47.26	52.42	45.62	89.32	60.25	50.99	66.85
	0.4		37.19	47.27	52.41	45.62	89.81	60.25	50.99	67.02
	0.3		37.19	47.22	52.42	45.61	89.57	59.51	50.62	66.56
	0.2		37.14	47.21	52.43	45.59	88.64	59.14	50.80	66.19
	0.1		37.14	47.18	52.43	45.58	89.01	59.32	51.23	66.52
	0.0		37.17	47.13	52.35	45.55	89.88	58.40	49.94	66.07
	Average for all Inertia (w) values	SPSO	37.16	47.22	52.42	45.60	89.26	59.81	51.39	66.82
		R01	37.17	47.19	52.45	45.60	89.26	59.81	51.44	66.84
		R02	37.17	47.28	52.46	45.64	89.40	60.09	51.85	67.11
		R03	37.20	47.20	52.41	45.60	89.77	59.12	50.14	66.34
		R04	37.16	47.22	52.41	45.60	89.31	59.17	51.11	66.53
		R05	37.15	47.21	52.37	45.58	89.26	59.91	49.81	66.33

Table C.14: TCPSP test results for different density ranges of PSO particles & different values for Inertia (w) (5,000 schedules – 10 forward/ 10 backward particles)

N_Sch	Inertia (w)	Density Range	Average Cost Saving (ACS)				Problems Solved to Optimality			
			j-10	j-20	j-30	Aver.	j-10	j-20	j-30	Aver.
50,000 Schedules (20F/20B Particles)	0.73	SPSO	37.26	47.30	52.56	**45.70**	91.11	61.48	54.44	**69.01**
		R01	37.22	47.30	52.49	**45.67**	90.00	61.11	52.96	**68.02**
		R02	37.23	47.43	52.45	**45.70**	90.00	62.22	51.48	**67.90**
		R03	37.17	47.25	52.37	**45.60**	89.63	61.85	51.85	**67.78**
		R04	37.22	47.28	52.52	**45.67**	90.00	61.48	51.85	**67.78**
		R05	37.22	47.20	52.44	**45.62**	90.74	61.11	50.74	**67.53**
	0.6	SPSO	37.28	47.30	52.38	**45.65**	91.48	62.22	51.11	**68.27**
		R01	37.31	47.21	52.38	**45.64**	92.59	61.48	51.11	**68.40**
		R02	37.26	47.32	52.52	**45.70**	91.85	62.96	54.07	**69.63**
		R03	37.21	47.24	52.52	**45.66**	90.37	60.37	52.96	**67.90**
		R04	37.19	47.20	52.39	**45.59**	90.00	59.63	50.74	**66.79**
		R05	37.22	47.33	52.48	**45.67**	90.74	60.74	50.74	**67.41**
	0.5	SPSO	37.19	47.29	52.46	**45.65**	90.00	60.74	51.11	**67.28**
		R01	37.20	47.24	52.41	**45.61**	89.63	61.85	51.11	**67.53**
		R02	37.28	47.49	52.50	**45.76**	91.85	63.70	53.70	**69.75**
		R03	37.22	47.36	52.45	**45.68**	90.00	61.85	50.00	**67.28**
		R04	37.23	47.19	52.37	**45.60**	90.37	60.00	49.63	**66.67**
		R05	37.27	47.40	52.48	**45.72**	91.48	62.22	51.48	**68.40**
	0.4	SPSO	37.24	47.23	52.44	**45.63**	90.37	60.74	50.00	**67.04**
		R01	37.28	47.29	52.42	**45.66**	91.11	63.33	51.11	**68.52**
		R02	37.26	47.15	52.43	**45.62**	91.11	59.63	51.11	**67.28**
		R03	37.22	47.16	52.40	**45.59**	91.11	61.11	50.74	**67.65**
		R04	37.30	47.33	52.40	**45.68**	91.11	61.48	51.85	**68.15**
		R05	37.14	47.17	52.40	**45.57**	90.00	60.74	50.37	**67.04**
	0.3	SPSO	37.24	47.18	52.55	**45.65**	90.37	60.74	52.59	**67.90**
		R01	37.19	47.16	52.48	**45.61**	91.48	57.78	51.48	**66.91**
		R02	37.24	47.42	52.55	**45.74**	91.11	62.96	51.85	**68.64**
		R03	37.23	47.27	52.38	**45.63**	91.11	62.59	51.48	**68.40**
		R04	37.25	47.25	52.40	**45.64**	91.11	60.74	51.48	**67.78**
		R05	37.25	47.23	52.46	**45.65**	90.74	61.48	51.48	**67.90**
	0.2	SPSO	37.23	47.37	52.47	**45.69**	91.11	62.59	50.37	**68.02**
		R01	37.28	47.41	52.40	**45.70**	91.85	62.59	50.74	**68.40**
		R02	37.28	47.24	52.45	**45.66**	91.11	61.48	51.85	**68.15**
		R03	37.26	47.24	52.52	**45.67**	90.74	61.48	51.11	**67.78**
		R04	37.22	47.36	52.38	**45.65**	90.74	63.33	49.26	**67.78**
		R05	37.25	47.27	52.42	**45.64**	91.48	59.26	50.00	**66.91**
Best results (50,000 - 20F/20B)	0.73	Best DD Range	37.26	47.43	52.56	**45.70**	91.11	62.22	54.44	**69.01**
	0.6		37.31	47.33	52.52	**45.70**	92.59	62.96	54.07	**69.63**
	0.5		37.28	47.49	52.50	**45.76**	91.85	63.70	53.70	**69.75**
	0.4		37.30	47.33	52.44	**45.68**	91.11	63.33	51.85	**68.52**
	0.3		37.25	47.42	52.55	**45.74**	91.48	62.96	52.59	**68.64**
	0.2		37.28	47.41	52.52	**45.70**	91.85	63.33	51.85	**68.40**
	Best w	SPSO	37.28	47.37	52.56	**45.70**	91.48	62.59	54.44	**69.01**
		R01	37.31	47.41	52.49	**45.70**	92.59	63.33	52.96	**68.52**
		R02	37.28	47.49	52.55	**45.76**	91.85	63.70	54.07	**69.75**
		R03	37.26	47.36	52.52	**45.68**	91.11	62.59	52.96	**68.40**
		R04	37.30	47.36	52.52	**45.68**	91.11	63.33	51.85	**68.15**
		R05	37.27	47.40	52.48	**45.72**	91.48	62.22	51.48	**68.40**

		37.22	47.29	52.47	**45.66**	90.25	61.54	52.22	**68.00**
0.73		37.22	47.29	52.47	**45.66**	90.25	61.54	52.22	**68.00**
0.6	Average for all DD Ranges	37.25	47.27	52.45	**45.65**	91.17	61.23	51.79	**68.07**
0.5		37.23	47.33	52.44	**45.67**	90.56	61.73	51.17	**67.82**
0.4		37.24	47.22	52.42	**45.62**	90.80	61.17	50.86	**67.61**
0.3		37.23	47.25	52.47	**45.65**	90.99	61.05	51.73	**67.92**
0.2		37.25	47.32	52.44	**45.67**	91.17	61.79	50.56	**67.84**
SPSO	Average for all Inertia (w) values	37.24	47.28	52.48	**45.66**	90.74	61.42	51.60	**67.92**
R01		37.25	47.27	52.43	**45.65**	91.11	61.36	51.42	**67.96**
R02		37.26	47.34	52.48	**45.69**	91.17	62.16	52.35	**68.56**
R03		37.22	47.26	52.44	**45.64**	90.49	61.54	51.36	**67.80**
R04		37.23	47.27	52.41	**45.64**	90.56	61.11	50.80	**67.49**
R05		37.22	47.27	52.45	**45.64**	90.86	60.93	50.80	**67.53**

Table C.15: TCPSP test results for different density ranges of PSO particles & different values for Inertia (w) (50,000 schedules – 20 forward/ 20 backward particles)

C.3.3. DDPSO topologies testing

N_{Sch}	w	DD Range	AD_O	AD_{CP}					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
1,000 Schedules (10F/10B Particles) (GR=0.75)	0.0	1	0.27	13.79	12.28	11.94	36.60	**18.65**	87.92	73.96	73.75	31.17	**66.70**
		2	0.20	13.69	11.95	11.73	35.91	**18.32**	89.38	75.42	75.00	32.50	**68.07**
		3	0.17	13.65	11.71	11.37	35.23	**17.99**	92.08	75.42	76.04	33.33	**69.22**
		4	0.24	13.73	11.68	11.29	34.94	**17.91**	89.17	75.83	75.83	34.33	**68.79**
		5	0.30	13.83	11.70	11.29	34.96	**17.95**	86.67	75.00	75.83	33.83	**67.83**
		6	0.28	13.80	11.67	11.29	35.10	**17.96**	87.71	75.63	76.04	33.50	**68.22**
		7	0.26	13.78	11.75	11.39	35.17	**18.02**	88.96	75.63	76.04	33.00	**68.41**
		8	0.27	13.78	11.76	11.44	35.16	**18.04**	87.71	75.63	75.63	33.33	**68.07**
		9	0.32	13.87	11.87	11.42	35.23	**18.09**	86.88	75.21	75.83	33.00	**67.73**
		10	0.32	13.86	11.88	11.41	35.22	**18.09**	87.08	74.38	76.25	33.83	**67.89**
	0.1	1	0.27	13.79	12.32	12.09	37.04	**18.81**	88.54	74.58	73.54	30.67	**66.83**
		2	0.20	13.67	12.02	11.82	36.36	**18.47**	90.63	75.63	75.00	32.17	**68.35**
		3	0.22	13.72	11.74	11.48	35.50	**18.11**	88.96	75.63	75.00	33.83	**68.35**
		4	0.25	13.74	11.68	11.33	35.11	**17.97**	88.96	75.21	76.25	34.00	**68.60**
		5	0.26	13.76	11.70	11.37	35.11	**17.98**	88.54	75.42	75.42	33.17	**68.14**
		6	0.28	13.81	11.79	11.38	35.17	**18.04**	88.54	76.04	75.00	33.83	**68.35**
		7	0.27	13.79	11.78	11.44	35.26	**18.07**	89.17	76.46	75.63	32.50	**68.44**
		8	0.24	13.74	11.79	11.36	35.27	**18.04**	88.75	74.58	75.63	32.67	**67.91**
		9	0.27	13.79	11.82	11.43	35.25	**18.07**	88.75	75.63	75.00	33.33	**68.18**
		10	0.29	13.81	11.86	11.46	35.30	**18.11**	87.50	74.38	75.42	32.50	**67.45**
	0.2	1	0.33	13.86	12.39	12.15	37.13	**18.89**	85.42	73.54	73.54	30.67	**65.79**
		2	0.21	13.69	12.14	11.88	36.60	**18.58**	90.42	75.21	74.58	31.67	**67.97**
		3	0.20	13.69	11.77	11.59	35.79	**18.21**	90.42	76.46	75.21	33.67	**68.94**
		4	0.20	13.68	11.67	11.39	35.24	**18.00**	89.58	75.63	75.00	33.50	**68.43**
		5	0.20	13.69	11.68	11.37	35.15	**17.97**	90.21	76.25	75.63	33.33	**68.85**
		6	0.26	13.76	11.73	11.38	35.22	**18.02**	88.96	76.04	75.42	33.00	**68.35**
		7	0.28	13.79	11.71	11.38	35.23	**18.03**	87.92	75.63	75.42	33.50	**68.11**
		8	0.27	13.79	11.82	11.38	35.29	**18.07**	87.92	75.42	75.83	33.17	**68.08**
		9	0.26	13.78	11.81	11.44	35.31	**18.08**	88.13	74.17	74.79	33.17	**67.56**
		10	0.25	13.76	11.90	11.49	35.39	**18.13**	89.17	74.38	75.21	32.50	**67.81**
	0.3	1	0.40	13.97	12.47	12.27	37.25	**18.99**	83.75	72.92	72.71	29.50	**64.72**
		2	0.23	13.73	12.18	11.97	36.64	**18.63**	89.79	74.58	74.38	31.33	**67.52**

		3	0.22	13.70	11.93	11.64	36.02	**18.32**	90.42	75.42	75.83	32.33	**68.50**
		4	0.20	13.68	11.71	11.46	35.46	**18.08**	90.00	75.21	75.42	33.50	**68.53**
		5	0.21	13.70	11.73	11.42	35.29	**18.03**	90.42	76.46	75.63	34.33	**69.21**
		6	0.27	13.77	11.74	11.36	35.26	**18.03**	88.54	75.42	76.04	33.50	**68.38**
		7	0.24	13.74	11.81	11.40	35.26	**18.05**	89.58	74.58	75.42	32.83	**68.10**
		8	0.29	13.82	11.78	11.43	35.26	**18.07**	87.50	74.58	75.42	33.00	**67.63**
		9	0.32	13.87	11.83	11.46	35.36	**18.13**	86.04	75.21	75.21	32.83	**67.32**
		10	0.29	13.81	11.88	11.49	35.35	**18.13**	87.71	74.79	75.42	32.33	**67.56**
	0.4	1	0.47	14.07	12.51	12.24	37.41	**19.06**	81.46	72.50	73.13	29.33	**64.10**
		2	0.30	13.84	12.18	12.03	36.76	**18.70**	86.46	74.58	73.33	30.50	**66.22**
		3	0.22	13.71	11.94	11.71	36.14	**18.37**	89.58	75.00	74.58	32.33	**67.88**
		4	0.18	13.65	11.76	11.53	35.64	**18.15**	90.21	76.46	74.79	33.00	**68.61**
		5	0.24	13.73	11.74	11.41	35.37	**18.06**	89.79	76.25	75.42	33.33	**68.70**
		6	0.21	13.69	11.75	11.41	35.40	**18.06**	90.63	76.67	75.21	33.50	**69.00**
		7	0.24	13.74	11.77	11.46	35.34	**18.08**	88.33	75.42	74.79	33.83	**68.09**
		8	0.26	13.78	11.79	11.42	35.30	**18.07**	88.33	75.42	75.83	33.17	**68.19**
		9	0.27	13.79	11.81	11.45	35.43	**18.12**	88.54	75.00	75.42	32.33	**67.82**
		10	0.34	13.89	11.85	11.44	35.35	**18.13**	85.83	75.42	74.79	33.33	**67.34**
	0.5	1	0.62	14.27	12.64	12.30	37.55	**19.19**	79.17	72.50	72.50	29.33	**63.38**
		2	0.37	13.92	12.38	12.07	36.98	**18.84**	84.79	73.96	73.54	30.17	**65.61**
		3	0.21	13.70	12.02	11.78	36.40	**18.47**	90.63	75.21	74.38	31.33	**67.89**
		4	0.21	13.69	11.81	11.58	35.81	**18.23**	90.00	75.83	75.21	32.83	**68.47**
		5	0.22	13.71	11.73	11.45	35.53	**18.11**	89.58	76.25	75.63	33.00	**68.61**
		6	0.24	13.74	11.78	11.49	35.43	**18.11**	88.33	75.83	74.79	33.33	**68.07**
		7	0.27	13.80	11.79	11.43	35.29	**18.08**	88.96	75.21	75.42	33.50	**68.27**
		8	0.29	13.82	11.81	11.42	35.41	**18.11**	87.50	75.00	75.83	33.00	**67.83**
		9	0.28	13.81	11.88	11.43	35.42	**18.13**	87.08	75.21	75.83	33.17	**67.82**
		10	0.30	13.83	11.79	11.54	35.35	**18.13**	87.92	76.04	74.58	33.17	**67.93**
	0.6	1	0.60	14.26	12.79	12.38	37.61	**19.26**	79.17	71.88	72.29	29.00	**63.08**
		2	0.39	13.97	12.43	12.15	37.13	**18.92**	84.17	73.54	73.13	30.17	**65.25**
		3	0.25	13.76	12.15	11.90	36.49	**18.58**	89.17	74.58	73.96	31.33	**67.26**
		4	0.20	13.70	11.91	11.66	35.99	**18.31**	90.42	75.00	74.38	33.17	**68.24**
		5	0.21	13.70	11.76	11.49	35.60	**18.14**	90.00	75.83	75.21	33.00	**68.51**
		6	0.26	13.76	11.82	11.46	35.42	**18.11**	88.54	75.42	75.21	33.50	**68.17**
		7	0.21	13.69	11.76	11.45	35.44	**18.09**	89.79	75.00	75.21	32.83	**68.21**
		8	0.27	13.78	11.85	11.50	35.46	**18.15**	87.50	75.00	75.21	32.33	**67.51**
		9	0.27	13.78	11.88	11.50	35.44	**18.15**	86.67	75.42	75.21	33.00	**67.57**
		10	0.27	13.79	11.93	11.48	35.39	**18.15**	87.71	74.58	75.63	32.83	**67.69**
1,000 Schedules (10F/10B Particles) (GR=0.75)	Best Inertia (w)	1	0.27	13.79	12.28	11.94	36.60	**18.65**	88.54	74.58	73.75	31.17	**66.83**
		2	0.20	13.67	11.95	11.73	35.91	**18.32**	90.63	75.63	75.00	32.50	**68.35**
		3	0.17	13.65	11.71	11.37	35.23	**17.99**	92.08	76.46	76.04	33.83	**69.22**
		4	0.18	13.65	11.67	11.29	34.94	**17.91**	90.42	76.46	76.25	34.33	**68.79**
		5	0.20	13.69	11.68	11.29	34.96	**17.95**	90.42	76.46	75.83	34.33	**69.21**
		6	0.21	13.69	11.67	11.29	35.10	**17.96**	90.63	76.67	76.04	33.83	**69.00**
		7	0.21	13.69	11.71	11.38	35.17	**18.02**	89.79	76.46	76.04	33.83	**68.44**
		8	0.24	13.74	11.76	11.36	35.16	**18.04**	88.75	75.63	75.83	33.33	**68.19**
		9	0.26	13.78	11.81	11.42	35.23	**18.07**	88.75	75.63	75.83	33.33	**68.18**
		10	0.25	13.76	11.79	11.41	35.22	**18.09**	89.17	76.04	76.25	33.83	**67.93**
	Aver. for all Inertia (w)	1	0.45	14.04	12.52	12.24	37.33	**19.03**	82.92	72.99	72.95	29.75	**64.65**
		2	0.28	13.80	12.22	11.99	36.74	**18.69**	87.71	74.58	73.99	31.00	**66.82**
		3	0.22	13.71	11.93	11.68	36.06	**18.34**	89.86	75.38	74.83	32.47	**68.14**
		4	0.21	13.69	11.76	11.49	35.54	**18.12**	89.86	75.56	75.17	33.33	**68.48**

DD Range	AD$_O$ j-30	AD$_{CP}$ j-30	j-60	j-90	j-120	Aver.	Problems Solved to Optimality j-30	j-60	j-90	j-120	Aver.
5	0.22	13.71	11.72	11.42	35.34	**18.05**	89.76	76.08	75.49	33.36	**68.67**
6	0.25	13.76	11.77	11.41	35.31	**18.06**	88.92	75.90	75.28	33.44	**68.39**
7	0.25	13.76	11.77	11.43	35.30	**18.07**	88.96	75.38	75.31	33.17	**68.20**
8	0.27	13.79	11.81	11.42	35.33	**18.09**	87.92	75.00	75.63	32.89	**67.86**
9	0.28	13.80	11.84	11.45	35.37	**18.11**	87.53	75.10	75.24	32.97	**67.71**
10	0.29	13.82	11.87	11.48	35.35	**18.13**	87.64	74.93	75.17	32.78	**67.63**

Table C.16: RCPSP test results for DDPSO under different topologies & different values for Inertia (w) (1,000 schedules – 10 forward/ 10 backward particles – GR=0.75)

N$_{Sch}$	w	DD Range	AD$_O$ j-30	AD$_{CP}$ j-30	j-60	j-90	j-120	Aver.	Problems Solved to Optimality j-30	j-60	j-90	j-120	Aver.
1,000 Schedules (10F/10B Particles) (GR=0.5)	0.0	1	0.27	13.79	12.27	11.99	36.77	**18.70**	88.54	74.58	74.17	31.00	**67.07**
		2	0.21	13.70	11.96	11.70	36.09	**18.36**	90.21	75.00	75.42	32.33	**68.24**
		3	0.19	13.68	11.74	11.42	35.38	**18.05**	92.08	75.83	76.25	34.17	**69.58**
		4	0.22	13.71	11.69	11.30	35.05	**17.94**	89.79	75.00	75.83	34.00	**68.66**
		5	0.24	13.74	11.72	11.37	35.03	**17.96**	88.33	76.67	75.21	33.67	**68.47**
		6	0.27	13.78	11.70	11.36	35.15	**18.00**	88.54	76.25	76.04	33.33	**68.54**
		7	0.27	13.88	11.75	11.41	35.18	**18.05**	86.88	75.42	75.42	33.50	**67.80**
		8	0.29	13.82	11.82	11.32	35.25	**18.05**	87.71	75.00	75.63	32.50	**67.71**
		9	0.28	13.80	11.86	11.44	35.28	**18.10**	87.50	74.38	75.42	33.33	**67.66**
		10	0.29	13.82	11.85	11.43	35.37	**18.12**	88.54	75.63	75.63	32.83	**68.16**
	0.1	1	0.29	13.81	12.36	12.08	37.04	**18.82**	87.08	73.96	73.54	30.67	**66.31**
		2	0.22	13.71	12.03	11.82	36.43	**18.50**	90.42	75.21	75.00	32.17	**68.20**
		3	0.20	13.67	11.78	11.49	35.62	**18.14**	90.63	76.04	75.42	33.33	**68.85**
		4	0.22	13.72	11.72	11.33	35.27	**18.01**	90.63	76.04	76.25	33.50	**69.10**
		5	0.24	13.74	11.75	11.37	35.24	**18.03**	88.96	75.63	75.42	33.50	**68.38**
		6	0.26	13.77	11.73	11.33	35.13	**17.99**	88.13	75.83	75.83	34.17	**68.49**
		7	0.25	13.75	11.77	11.42	35.28	**18.06**	88.13	75.42	75.00	33.67	**68.05**
		8	0.27	13.78	11.87	11.43	35.34	**18.11**	88.33	74.58	75.42	33.67	**68.00**
		9	0.26	13.77	11.85	11.47	35.36	**18.11**	88.33	75.63	74.58	33.33	**67.97**
		10	0.27	13.79	11.82	11.47	35.35	**18.11**	87.08	75.21	75.42	32.67	**67.59**
	0.2	1	0.34	13.89	12.41	12.12	37.12	**18.89**	84.79	73.13	73.54	30.50	**65.49**
		2	0.24	13.74	12.16	11.86	36.62	**18.60**	90.00	75.00	74.79	31.33	**67.78**
		3	0.18	13.65	11.83	11.60	35.80	**18.22**	91.67	76.04	75.42	33.17	**69.07**
		4	0.18	13.66	11.70	11.39	35.41	**18.04**	90.00	75.42	75.63	33.17	**68.55**
		5	0.25	13.76	11.71	11.36	35.22	**18.01**	88.96	76.04	75.42	33.33	**68.44**
		6	0.23	13.73	11.76	11.38	35.28	**18.04**	89.79	74.38	75.83	32.83	**68.21**
		7	0.25	13.75	11.84	11.43	35.41	**18.11**	88.96	75.00	75.63	32.83	**68.10**
		8	0.27	13.79	11.82	11.49	35.44	**18.13**	88.33	75.42	75.63	32.33	**67.93**
		9	0.26	13.76	11.83	11.49	35.38	**18.12**	88.54	75.00	75.21	32.33	**67.77**
		10	0.27	13.79	11.89	11.42	35.49	**18.15**	88.33	75.21	75.21	32.33	**67.77**
	0.3	1	0.41	13.99	12.52	12.20	37.32	**19.01**	83.75	72.92	72.71	29.50	**64.72**
		2	0.23	13.72	12.24	12.00	36.78	**18.69**	89.79	74.17	74.17	31.00	**67.28**
		3	0.22	13.71	11.96	11.68	36.00	**18.34**	89.58	75.21	76.04	32.33	**68.29**
		4	0.20	13.69	11.74	11.50	35.56	**18.12**	90.63	76.25	75.83	33.00	**68.93**
		5	0.19	13.67	11.72	11.47	35.40	**18.07**	90.63	75.83	75.83	34.33	**69.16**
		6	0.24	13.76	11.76	11.43	35.31	**18.06**	89.79	75.42	75.00	33.50	**68.43**
		7	0.23	13.73	11.82	11.49	35.36	**18.10**	89.38	75.00	75.42	33.33	**68.28**
		8	0.30	13.84	11.84	11.46	35.41	**18.14**	86.88	75.00	75.42	33.00	**67.57**
		9	0.27	13.79	11.88	11.49	35.39	**18.14**	87.92	75.42	76.04	32.67	**68.01**
		10	0.24	13.75	11.86	11.46	35.46	**18.13**	88.54	75.00	75.00	32.33	**67.72**

		#											
	0.4	1	0.49	14.09	12.56	12.26	37.40	**19.08**	81.67	72.71	73.13	30.17	**64.42**
		2	0.30	13.83	12.31	12.00	36.86	**18.75**	87.08	73.96	73.96	31.17	**66.54**
		3	0.18	13.64	12.04	11.78	36.23	**18.42**	90.42	75.00	74.38	32.50	**68.07**
		4	0.21	13.69	11.79	11.53	35.69	**18.18**	88.96	76.04	75.63	33.67	**68.57**
		5	0.21	13.70	11.75	11.43	35.48	**18.09**	90.63	77.29	75.21	34.00	**69.28**
		6	0.26	13.77	11.81	11.43	35.41	**18.11**	88.54	75.21	75.00	34.17	**68.23**
		7	0.29	13.81	11.79	11.47	35.44	**18.13**	87.08	74.79	75.63	33.17	**67.67**
		8	0.25	13.75	11.81	11.44	35.44	**18.11**	88.33	74.79	75.83	33.33	**68.07**
		9	0.32	13.86	11.86	11.51	35.53	**18.19**	86.46	75.21	75.83	32.50	**67.50**
		10	0.28	13.81	11.89	11.47	35.52	**18.17**	87.29	75.00	75.42	33.00	**67.68**
	0.5	1	0.55	14.19	12.66	12.29	37.50	**19.16**	81.67	72.50	72.71	29.17	**64.01**
		2	0.35	13.91	12.32	12.11	37.04	**18.84**	85.63	74.17	73.33	30.17	**65.82**
		3	0.21	13.69	12.10	11.88	36.33	**18.50**	90.00	74.79	74.38	31.67	**67.71**
		4	0.24	13.74	11.89	11.62	35.84	**18.27**	88.75	75.42	75.21	32.50	**67.97**
		5	0.24	13.72	11.79	11.46	35.62	**18.15**	89.38	75.21	75.42	32.50	**68.13**
		6	0.26	13.76	11.80	11.46	35.48	**18.13**	88.13	74.58	75.21	33.33	**67.81**
		7	0.23	13.73	11.84	11.47	35.45	**18.12**	90.63	75.42	75.21	33.50	**68.69**
		8	0.26	13.76	11.85	11.51	35.37	**18.12**	88.33	75.21	76.04	34.17	**68.44**
		9	0.25	13.76	11.89	11.49	35.47	**18.15**	88.54	73.96	76.04	33.33	**67.97**
		10	0.35	13.89	11.91	11.49	35.47	**18.19**	83.75	74.79	75.21	32.50	**66.56**
	0.6	1	0.62	14.28	12.76	12.33	37.58	**19.24**	79.38	72.08	72.92	29.17	**63.39**
		2	0.39	13.97	12.41	12.13	37.22	**18.93**	83.75	73.13	73.13	30.17	**65.04**
		3	0.25	13.76	12.18	11.93	36.62	**18.62**	88.33	74.79	73.96	31.33	**67.10**
		4	0.21	13.69	11.91	11.66	35.98	**18.31**	89.58	74.79	75.00	33.17	**68.14**
		5	0.23	13.73	11.81	11.51	35.70	**18.19**	89.17	75.21	75.42	33.00	**68.20**
		6	0.25	13.75	11.80	11.49	35.56	**18.15**	88.96	75.21	75.63	33.83	**68.41**
		7	0.24	13.73	11.83	11.47	35.49	**18.13**	88.75	75.21	75.63	33.17	**68.19**
		8	0.23	13.74	11.87	11.47	35.55	**18.16**	89.79	74.38	75.42	32.67	**68.06**
		9	0.27	13.79	11.87	11.49	35.43	**18.14**	87.92	75.63	75.21	33.00	**67.94**
		10	0.27	13.79	11.92	11.53	35.51	**18.19**	88.54	74.58	75.63	32.83	**67.90**
1,000 Schedules (10F/10B Particles) (GR=0.5)	Best Inertia (w)	1	0.27	13.79	12.27	11.99	36.77	**18.70**	88.54	74.58	74.17	31.00	**67.07**
		2	0.21	13.70	11.96	11.70	36.09	**18.36**	90.42	75.21	75.42	32.33	**68.24**
		3	0.18	13.64	11.74	11.42	35.38	**18.05**	92.08	76.04	76.25	34.17	**69.58**
		4	0.18	13.66	11.69	11.30	35.05	**17.94**	90.63	76.25	76.25	34.00	**69.10**
		5	0.19	13.67	11.71	11.36	35.03	**17.96**	90.63	77.29	75.83	34.33	**69.28**
		6	0.23	13.73	11.70	11.33	35.13	**17.99**	89.79	76.25	76.04	34.17	**68.54**
		7	0.23	13.73	11.75	11.41	35.18	**18.05**	90.63	75.42	75.63	33.67	**68.69**
		8	0.23	13.74	11.81	11.32	35.25	**18.05**	89.79	75.42	76.04	34.17	**68.44**
		9	0.25	13.76	11.83	11.44	35.28	**18.10**	88.54	75.63	76.04	33.33	**68.01**
		10	0.24	13.75	11.82	11.42	35.35	**18.11**	88.54	75.63	75.63	33.00	**68.16**
	Aver. for all Inertia (w)	1	0.42	14.01	12.51	12.18	37.25	**18.99**	83.84	73.13	73.24	30.02	**65.06**
		2	0.28	13.80	12.20	11.95	36.72	**18.67**	88.13	74.38	74.26	31.19	**66.99**
		3	0.20	13.68	11.95	11.68	36.00	**18.33**	90.39	75.39	75.12	32.64	**68.38**
		4	0.21	13.70	11.78	11.48	35.54	**18.12**	89.76	75.57	75.63	33.29	**68.56**
		5	0.23	13.72	11.75	11.42	35.38	**18.07**	89.43	75.98	75.42	33.48	**68.58**
		6	0.25	13.76	11.77	11.41	35.33	**18.07**	88.84	75.27	75.51	33.60	**68.30**
		7	0.25	13.77	11.81	11.45	35.37	**18.10**	88.54	75.18	75.42	33.31	**68.11**
		8	0.27	13.78	11.84	11.45	35.40	**18.12**	88.24	74.91	75.63	33.10	**67.97**
		9	0.27	13.79	11.86	11.48	35.41	**18.14**	87.89	75.03	75.48	32.93	**67.83**
		10	0.28	13.80	11.88	11.47	35.45	**18.15**	87.44	75.06	75.36	32.64	**67.63**

Table C.17: RCPSP test results for DDPSO under different topologies & different values for Inertia (w) (1,000 schedules – 10 forward/ 10 backward particles – GR=0.5)

N_Sch	w	DD Range	AD$_O$	AD$_{CP}$					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
1,000 Schedules (10F/10B Particles) (GR=0.25)	0.0	1	0.28	13.81	12.33	12.04	36.94	**18.78**	88.54	74.38	73.54	30.67	**66.78**
		2	0.21	13.70	12.08	11.77	36.21	**18.44**	89.58	75.21	74.17	31.50	**67.61**
		3	0.19	13.67	11.75	11.47	35.45	**18.08**	90.00	76.04	75.42	33.17	**68.66**
		4	0.19	13.67	11.70	11.34	35.17	**17.97**	91.67	75.63	75.83	34.00	**69.28**
		5	0.26	13.78	11.73	11.35	35.20	**18.01**	87.92	76.04	76.25	33.83	**68.51**
		6	0.26	13.79	11.76	11.37	35.18	**18.02**	88.54	75.83	76.04	34.00	**68.60**
		7	0.27	13.80	11.83	11.42	35.24	**18.07**	88.33	75.21	75.21	32.67	**67.85**
		8	0.27	13.80	11.82	11.42	35.32	**18.09**	88.13	75.42	75.42	33.33	**68.07**
		9	0.32	13.88	11.90	11.45	35.39	**18.15**	86.88	74.79	75.63	32.33	**67.41**
		10	0.33	13.88	11.84	11.47	35.43	**18.16**	87.29	74.79	75.42	32.83	**67.58**
	0.1	1	0.29	13.81	12.37	12.10	37.04	**18.83**	87.71	74.38	73.54	31.00	**66.66**
		2	0.18	13.66	12.14	11.86	36.43	**18.52**	90.63	75.21	73.96	31.50	**67.82**
		3	0.19	13.67	11.87	11.50	35.62	**18.17**	90.83	75.83	76.46	33.17	**69.07**
		4	0.21	13.69	11.70	11.37	35.33	**18.02**	90.00	77.08	75.42	33.83	**69.08**
		5	0.24	13.74	11.70	11.33	35.29	**18.02**	88.13	75.42	75.21	34.00	**68.19**
		6	0.23	13.78	11.76	11.45	35.32	**18.08**	87.92	75.42	75.21	33.33	**67.97**
		7	0.28	13.80	11.82	11.42	35.35	**18.10**	87.29	75.21	75.42	33.00	**67.73**
		8	0.29	13.83	11.88	11.44	35.43	**18.15**	88.13	75.00	75.83	33.00	**67.99**
		9	0.31	13.85	11.84	11.47	35.42	**18.14**	87.29	75.21	75.21	32.33	**67.51**
		10	0.32	13.87	11.93	11.47	35.50	**18.19**	87.92	74.79	75.21	32.83	**67.69**
	0.2	1	0.34	13.88	12.38	12.13	37.16	**18.89**	86.46	73.75	73.96	30.33	**66.13**
		2	0.24	13.76	12.17	11.87	36.62	**18.60**	88.96	75.21	74.38	31.33	**67.47**
		3	0.19	13.67	11.84	11.61	35.92	**18.26**	90.42	75.63	75.21	32.33	**68.40**
		4	0.22	13.69	11.70	11.43	35.45	**18.07**	89.38	76.04	75.83	33.33	**68.65**
		5	0.23	13.72	11.74	11.40	35.37	**18.05**	89.79	76.04	75.21	34.00	**68.76**
		6	0.25	13.77	11.83	11.41	35.35	**18.09**	88.75	75.00	75.83	33.50	**68.27**
		7	0.29	13.82	11.81	11.46	35.42	**18.13**	87.50	75.21	76.04	33.83	**68.15**
		8	0.29	13.83	11.84	11.46	35.41	**18.13**	87.92	75.83	75.63	33.33	**68.18**
		9	0.31	13.84	11.89	11.42	35.47	**18.16**	87.08	75.21	75.63	32.67	**67.65**
		10	0.28	13.79	11.88	11.53	35.54	**18.19**	87.50	75.00	74.38	32.67	**67.39**
	0.3	1	0.42	13.99	12.49	12.23	37.34	**19.01**	83.96	73.13	72.71	29.50	**64.82**
		2	0.25	13.76	12.20	11.98	36.73	**18.67**	88.33	74.79	74.17	31.33	**67.16**
		3	0.16	13.62	11.93	11.60	36.08	**18.31**	91.46	75.21	75.00	32.67	**68.58**
		4	0.21	13.70	11.74	11.50	35.61	**18.14**	90.00	75.83	75.21	32.67	**68.43**
		5	0.21	13.69	11.75	11.45	35.43	**18.08**	89.38	75.83	75.42	33.83	**68.61**
		6	0.22	13.72	11.78	11.44	35.43	**18.09**	90.21	75.83	75.21	32.00	**68.31**
		7	0.24	13.76	11.79	11.44	35.49	**18.12**	88.96	76.04	75.63	32.67	**68.32**
		8	0.27	13.78	11.89	11.50	35.48	**18.16**	87.08	75.00	75.42	32.67	**67.54**
		9	0.29	13.82	11.91	11.51	35.48	**18.18**	86.46	74.17	76.04	33.00	**67.42**
		10	0.27	13.78	11.89	11.50	35.52	**18.17**	87.71	75.63	75.42	32.50	**67.81**
	0.4	1	0.50	14.12	12.58	12.31	37.45	**19.11**	81.25	72.92	73.13	29.50	**64.20**
		2	0.32	13.86	12.26	12.07	36.92	**18.78**	87.08	73.96	74.17	31.67	**66.72**
		3	0.24	13.75	12.03	11.74	36.33	**18.46**	89.79	75.00	75.00	31.17	**67.74**
		4	0.19	13.66	11.80	11.59	35.77	**18.21**	90.83	75.63	75.83	32.83	**68.78**
		5	0.24	13.73	11.84	11.48	35.59	**18.16**	88.96	75.42	75.21	33.83	**68.35**
		6	0.25	13.77	11.85	11.49	35.56	**18.17**	88.96	74.79	75.00	32.67	**67.85**
		7	0.28	13.80	11.88	11.52	35.56	**18.19**	87.71	75.21	75.42	33.17	**67.88**
		8	0.29	13.83	11.87	11.55	35.59	**18.21**	88.33	74.38	74.79	32.50	**67.50**
		9	0.30	13.84	11.88	11.51	35.51	**18.19**	88.33	75.63	75.63	32.67	**68.06**
		10	0.31	13.84	11.89	11.50	35.56	**18.20**	86.88	75.21	75.63	33.17	**67.72**

	0.5	1	0.51	14.14	12.63	12.32	37.50	**19.14**	82.08	72.50	72.29	29.17	**64.01**
		2	0.31	13.86	12.32	12.14	37.03	**18.84**	86.46	73.75	73.33	30.50	**66.01**
		3	0.21	13.70	12.08	11.86	36.44	**18.52**	89.79	75.21	74.38	31.67	**67.76**
		4	0.19	13.66	11.87	11.63	35.81	**18.24**	90.00	75.63	74.79	32.33	**68.19**
		5	0.25	13.75	11.77	11.50	35.66	**18.17**	89.38	75.42	74.79	33.50	**68.27**
		6	0.18	13.66	11.85	11.49	35.57	**18.14**	90.83	75.42	75.42	32.33	**68.50**
		7	0.25	13.75	11.83	11.49	35.48	**18.14**	88.33	75.83	75.42	32.83	**68.10**
		8	0.29	13.81	11.85	11.52	35.55	**18.18**	86.67	75.42	75.21	32.50	**67.45**
		9	0.26	13.79	11.86	11.52	35.58	**18.19**	87.50	74.58	75.42	33.17	**67.67**
		10	0.30	13.84	11.96	11.53	35.65	**18.24**	87.71	74.58	75.21	32.33	**67.46**
	0.6	1	0.62	14.30	12.71	12.38	37.62	**19.25**	78.54	71.88	72.50	29.00	**62.98**
		2	0.39	13.96	12.42	12.17	37.22	**18.94**	84.17	73.54	73.33	29.50	**65.14**
		3	0.25	13.76	12.16	11.94	36.60	**18.61**	88.33	73.96	74.38	30.83	**66.88**
		4	0.22	13.71	11.97	11.63	35.98	**18.32**	90.63	75.83	75.42	32.17	**68.51**
		5	0.17	13.64	11.81	11.54	35.72	**18.18**	90.83	75.42	75.21	33.00	**68.61**
		6	0.24	13.74	11.87	11.53	35.62	**18.19**	90.21	75.42	75.63	32.67	**68.48**
		7	0.23	13.72	11.91	11.53	35.52	**18.17**	89.17	74.79	75.21	33.17	**68.08**
		8	0.27	13.79	11.86	11.51	35.59	**18.18**	88.13	74.38	75.00	32.83	**67.58**
		9	0.29	13.83	11.97	11.49	35.59	**18.22**	88.33	74.79	75.63	33.50	**68.06**
		10	0.31	13.85	11.92	11.47	35.53	**18.19**	87.71	74.79	75.42	32.67	**67.65**
1,000 Schedules (10F/10B Particles) (GR=0.25)	Best Inertia (w)	1	0.28	13.81	12.33	12.04	36.94	**18.78**	88.54	74.38	73.96	31.00	**66.78**
		2	0.18	13.66	12.08	11.77	36.21	**18.44**	90.63	75.21	74.38	31.67	**67.82**
		3	0.16	13.62	11.75	11.47	35.45	**18.08**	91.46	76.04	76.46	33.17	**69.07**
		4	0.19	13.66	11.70	11.34	35.17	**17.97**	91.67	77.08	75.83	34.00	**69.28**
		5	0.17	13.64	11.70	11.33	35.20	**18.01**	90.83	76.04	76.25	34.00	**68.76**
		6	0.18	13.66	11.76	11.37	35.18	**18.02**	90.83	75.83	76.04	34.00	**68.60**
		7	0.23	13.72	11.79	11.42	35.24	**18.07**	89.17	76.04	76.04	33.83	**68.32**
		8	0.27	13.78	11.82	11.42	35.32	**18.09**	88.33	75.83	75.83	33.33	**68.18**
		9	0.26	13.79	11.84	11.42	35.39	**18.14**	88.33	75.63	76.04	33.50	**68.06**
		10	0.27	13.78	11.84	11.47	35.43	**18.16**	87.92	75.63	75.63	33.17	**67.81**
	Aver. for all Inertia (w)	1	0.42	14.01	12.50	12.22	37.29	**19.00**	84.08	73.27	73.10	29.88	**65.08**
		2	0.27	13.79	12.23	11.98	36.74	**18.68**	87.89	74.52	73.93	31.05	**66.85**
		3	0.20	13.69	11.95	11.67	36.06	**18.34**	90.09	75.27	75.12	32.14	**68.15**
		4	0.20	13.68	11.78	11.50	35.59	**18.14**	90.36	75.95	75.48	33.02	**68.70**
		5	0.23	13.72	11.76	11.44	35.46	**18.10**	89.20	75.65	75.33	33.71	**68.47**
		6	0.23	13.75	11.81	11.45	35.43	**18.11**	89.35	75.39	75.48	32.93	**68.28**
		7	0.26	13.78	11.84	11.47	35.44	**18.13**	88.18	75.36	75.48	33.05	**68.02**
		8	0.28	13.81	11.86	11.48	35.48	**18.16**	87.77	75.06	75.33	32.88	**67.76**
		9	0.30	13.83	11.90	11.48	35.49	**18.18**	87.41	74.91	75.60	32.81	**67.68**
		10	0.30	13.84	11.90	11.50	35.53	**18.19**	87.53	74.97	75.24	32.71	**67.61**

Table C.18: RCPSP test results for DDPSO under different topologies & different values for Inertia (w) (1,000 schedules – 10 forward/ 10 backward particles – GR=0.25)

N_{Sch}	w	DD Range	AD_O	AD_{CP}					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
1,000 Schedules (10F/10B Particles) (GR=0.0)	0.0	1	0.29	13.82	12.35	12.09	37.14	**18.85**	88.96	75.00	73.33	30.67	**66.99**
		2	0.23	13.72	12.12	11.78	36.32	**18.49**	89.58	74.58	74.58	32.17	**67.73**
		3	0.21	13.70	11.75	11.52	35.53	**18.13**	89.58	76.04	75.21	32.50	**68.33**
		4	0.26	13.77	11.75	11.38	35.24	**18.03**	88.96	75.00	75.00	32.83	**67.95**
		5	0.25	13.75	11.78	11.35	35.24	**18.03**	88.75	74.58	75.42	33.33	**68.02**
		6	0.31	13.85	11.81	11.42	35.34	**18.11**	86.46	74.58	76.04	33.33	**67.60**
		7	0.33	13.87	11.84	11.47	35.40	**18.15**	86.04	74.38	75.42	33.67	**67.38**
		8	0.30	13.83	11.88	11.53	35.49	**18.18**	87.92	74.58	75.00	32.67	**67.54**
		9	0.36	13.92	11.90	11.51	35.51	**18.21**	86.67	74.79	75.63	32.83	**67.48**
		10	0.31	13.86	11.97	11.50	35.58	**18.23**	87.29	73.54	75.63	32.83	**67.32**
	0.1	1	0.30	13.83	12.35	12.12	37.16	**18.86**	87.08	74.58	74.17	30.67	**66.63**
		2	0.22	13.72	12.10	11.85	36.49	**18.54**	90.21	75.63	75.00	31.67	**68.13**
		3	0.23	13.72	11.84	11.55	35.73	**18.21**	88.96	75.63	75.00	33.00	**68.15**
		4	0.21	13.70	11.75	11.43	35.38	**18.06**	89.79	75.42	75.83	33.67	**68.68**
		5	0.22	13.72	11.76	11.38	35.39	**18.06**	89.79	76.67	75.83	33.00	**68.82**
		6	0.25	13.74	11.81	11.44	35.39	**18.10**	87.29	74.58	75.42	33.17	**67.61**
		7	0.30	13.83	11.86	11.49	35.49	**18.17**	87.71	75.42	75.00	32.83	**67.74**
		8	0.28	13.79	11.92	11.48	35.53	**18.18**	87.08	75.21	75.21	32.33	**67.46**
		9	0.32	13.87	11.95	11.51	35.62	**18.24**	87.29	75.21	75.42	33.00	**67.73**
		10	0.35	13.91	11.99	11.53	35.62	**18.26**	86.46	74.58	75.21	33.00	**67.31**
	0.2	1	0.34	13.88	12.35	12.12	37.12	**18.87**	86.25	74.17	73.54	30.17	**66.03**
		2	0.23	13.73	12.15	11.92	36.66	**18.62**	90.00	74.38	74.38	31.00	**67.44**
		3	0.22	13.71	11.89	11.63	35.91	**18.29**	90.21	74.79	74.79	32.33	**68.03**
		4	0.19	13.65	11.75	11.43	35.53	**18.09**	91.46	76.25	75.21	34.17	**69.27**
		5	0.23	13.73	11.77	11.41	35.45	**18.09**	89.58	75.42	75.42	33.33	**68.44**
		6	0.27	13.79	11.84	11.48	35.49	**18.15**	88.54	74.79	75.42	33.00	**67.94**
		7	0.29	13.81	11.83	11.46	35.57	**18.17**	87.50	74.38	75.63	32.00	**67.38**
		8	0.25	13.75	11.90	11.53	35.52	**18.17**	88.96	75.21	75.42	32.83	**68.10**
		9	0.27	13.79	11.91	11.53	35.66	**18.22**	13.79	11.91	11.53	35.66	**18.22**
		10	0.32	13.87	11.93	11.53	35.59	**18.23**	86.88	75.00	75.21	33.00	**67.52**
	0.3	1	0.41	13.98	12.48	12.20	37.28	**18.98**	83.75	72.92	73.13	29.83	**64.91**
		2	0.30	13.82	12.22	11.99	36.78	**18.70**	87.50	74.79	73.96	31.00	**66.81**
		3	0.24	13.73	11.91	11.70	36.12	**18.36**	89.38	75.00	75.00	32.17	**67.89**
		4	0.24	13.73	11.77	11.55	35.67	**18.18**	88.33	75.21	74.38	33.00	**67.73**
		5	0.24	13.74	11.73	11.45	35.43	**18.09**	89.58	76.67	75.00	33.83	**68.77**
		6	0.24	13.74	11.83	11.51	35.49	**18.15**	89.58	75.63	75.21	33.83	**68.56**
		7	0.28	13.80	11.87	11.52	35.65	**18.21**	88.54	75.42	75.42	32.17	**67.89**
		8	0.31	13.84	11.91	11.54	35.55	**18.21**	85.83	74.79	75.21	33.17	**67.25**
		9	0.33	13.88	11.91	11.57	35.62	**18.24**	86.46	74.38	75.21	32.67	**67.18**
		10	0.30	13.83	11.97	11.51	35.62	**18.23**	88.54	74.17	74.79	32.50	**67.50**
	0.4	1	0.49	14.09	12.62	12.25	37.38	**19.08**	81.88	72.29	71.88	29.33	**63.84**
		2	0.28	13.79	12.26	12.04	36.85	**18.74**	87.08	73.54	74.38	30.50	**66.38**
		3	0.25	13.75	12.03	11.79	36.29	**18.46**	88.33	74.58	74.58	32.50	**67.50**
		4	0.22	13.72	11.85	11.58	35.79	**18.24**	90.83	75.42	75.00	33.17	**68.60**
		5	0.23	13.72	11.83	11.50	35.63	**18.17**	88.75	75.00	75.42	33.00	**68.04**
		6	0.27	13.79	11.84	11.46	35.56	**18.16**	87.29	75.21	75.42	32.67	**67.65**
		7	0.28	13.80	11.83	11.48	35.55	**18.17**	87.71	75.21	75.63	33.00	**67.89**
		8	0.27	13.80	11.85	11.54	35.65	**18.21**	88.75	75.00	74.58	33.00	**67.83**
		9	0.34	13.89	11.93	11.51	35.62	**18.24**	86.25	75.83	75.63	32.83	**67.64**
		10	0.29	13.82	11.94	11.59	35.63	**18.24**	86.88	74.38	74.79	32.67	**67.18**

		#											
1,000 Schedules (10F/10B Particles) (GR=0.0)	0.5	1	0.59	14.24	12.66	12.33	37.48	19.18	79.17	72.29	72.92	29.67	63.51
		2	0.30	13.84	12.33	12.16	37.05	18.85	87.08	74.17	73.13	30.33	66.18
		3	0.25	13.75	12.06	11.82	36.51	18.54	89.38	74.58	74.58	31.33	67.47
		4	0.23	13.73	11.93	11.64	35.92	18.30	88.54	75.21	74.79	32.50	67.76
		5	0.23	13.73	11.82	11.55	35.71	18.20	89.17	76.04	75.63	33.00	68.46
		6	0.28	13.79	11.84	11.52	35.65	18.20	86.88	75.42	75.83	33.50	67.91
		7	0.28	13.79	11.85	11.49	35.65	18.20	87.92	76.04	75.00	32.67	67.91
		8	0.31	13.85	11.89	11.51	35.62	18.22	87.29	74.79	75.42	32.33	67.46
		9	0.33	13.89	11.92	11.48	35.66	18.24	86.88	75.21	75.42	33.00	67.63
		10	0.32	13.87	11.91	11.54	35.69	18.25	87.29	75.21	75.42	32.33	67.56
	0.6	1	0.62	14.30	12.77	12.38	37.68	19.28	78.96	71.88	72.50	29.00	63.08
		2	0.39	13.96	12.41	12.20	37.20	18.94	84.79	73.33	72.92	30.50	65.39
		3	0.26	13.76	12.17	11.91	36.63	18.62	88.54	74.38	74.79	31.50	67.30
		4	0.21	13.71	12.02	11.71	36.10	18.39	90.63	75.21	75.42	31.67	68.23
		5	0.19	13.68	11.90	11.54	35.90	18.25	90.83	74.79	75.42	32.33	68.34
		6	0.26	13.78	11.88	11.50	35.67	18.21	87.92	75.63	75.83	33.00	68.09
		7	0.23	13.74	11.86	11.53	35.67	18.20	89.79	76.04	75.00	32.50	68.33
		8	0.29	13.81	11.85	11.57	35.71	18.23	87.50	75.42	75.00	32.67	67.65
		9	0.29	13.83	11.90	11.57	35.68	18.25	87.92	74.79	75.42	33.00	67.78
		10	0.33	13.88	11.97	11.58	35.73	18.29	85.42	75.00	75.21	32.33	66.99
	Best Inertia (w)	1	0.29	13.82	12.35	12.09	37.12	18.85	88.96	75.00	74.17	30.67	66.99
		2	0.22	13.72	12.10	11.78	36.32	18.49	90.21	75.63	75.00	32.17	68.13
		3	0.21	13.70	11.75	11.52	35.53	18.13	90.21	76.04	75.21	33.00	68.33
		4	0.19	13.65	11.75	11.38	35.24	18.03	91.46	76.25	75.83	34.17	69.27
		5	0.19	13.68	11.73	11.35	35.24	18.03	90.83	76.67	75.83	33.83	68.82
		6	0.24	13.74	11.81	11.42	35.34	18.10	89.58	75.63	76.04	33.83	68.56
		7	0.23	13.74	11.83	11.46	35.40	18.15	89.79	76.04	75.63	33.67	68.33
		8	0.25	13.75	11.85	11.48	35.49	18.17	88.96	75.42	75.42	33.17	68.10
		9	0.27	13.79	11.90	11.48	35.51	18.21	87.92	75.83	75.63	35.66	67.78
		10	0.29	13.82	11.91	11.50	35.58	18.23	88.54	75.21	75.63	33.00	67.56
	Aver. for all Inertia (w)	1	0.43	14.02	12.51	12.21	37.32	19.02	83.72	73.30	73.07	29.90	65.00
		2	0.28	13.80	12.23	11.99	36.76	18.70	88.04	74.35	74.05	31.02	66.86
		3	0.24	13.73	11.95	11.70	36.10	18.37	89.20	75.00	74.85	32.19	67.81
		4	0.22	13.72	11.83	11.53	35.66	18.19	89.79	75.39	75.09	33.00	68.32
		5	0.23	13.72	11.80	11.45	35.53	18.13	89.49	75.60	75.45	33.12	68.41
		6	0.27	13.78	11.84	11.48	35.51	18.15	87.71	75.12	75.60	33.21	67.91
		7	0.28	13.81	11.85	11.49	35.57	18.18	87.89	75.27	75.30	32.69	67.79
		8	0.29	13.81	11.89	11.53	35.58	18.20	87.62	75.00	75.12	32.71	67.61
		9	0.32	13.87	11.92	11.53	35.63	18.23	76.46	66.02	66.32	33.29	60.52
		10	0.32	13.86	11.95	11.54	35.64	18.25	86.96	74.55	75.18	32.67	67.34

Table C.19: RCPSP test results for DDPSO under different topologies & different values for Inertia (w) (1,000 schedules – 10 forward/ 10 backward particles – GR=0.0)

N_{Sch}	w	DD Range	AD_O	AD_{CP}					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
5,000 Schedules (10F/10B Particles) (GR=0.75)	0.0	1	0.10	13.53	11.87	11.68	35.92	**18.25**	94.17	75.63	75.42	32.67	**69.47**
		2	0.06	13.47	11.56	11.34	35.23	**17.90**	96.46	78.33	76.46	34.67	**71.48**
		3	0.06	13.46	11.33	10.98	34.44	**17.55**	96.67	78.54	76.88	36.00	**72.02**
		4	0.14	13.59	11.23	10.79	33.86	**17.37**	91.88	79.17	77.71	36.17	**71.23**
		5	0.15	13.60	11.26	10.76	33.62	**17.31**	92.50	76.67	76.46	37.00	**70.66**
		6	0.21	13.69	11.30	10.75	33.60	**17.34**	90.63	77.50	77.71	36.33	**70.54**
		7	0.17	13.64	11.27	10.79	33.66	**17.34**	90.63	77.29	76.88	36.17	**70.24**
		8	0.20	13.68	11.29	10.81	33.69	**17.37**	90.42	77.50	76.67	35.83	**70.10**
		9	0.19	13.67	11.33	10.79	33.82	**17.40**	90.21	76.67	77.08	36.50	**70.11**
		10	0.25	13.75	11.35	10.84	33.78	**17.43**	88.13	77.08	76.46	37.17	**69.71**
	0.1	1	0.12	13.57	11.89	11.73	36.29	**18.37**	93.54	77.08	74.79	32.50	**69.48**
		2	0.06	13.47	11.54	11.42	35.47	**17.98**	96.46	78.13	76.46	34.67	**71.43**
		3	0.08	13.50	11.21	10.98	34.53	**17.56**	95.42	80.42	77.29	36.33	**72.36**
		4	0.13	13.57	11.20	10.82	33.93	**17.38**	93.13	80.00	76.88	35.83	**71.46**
		5	0.16	13.62	11.23	10.74	33.65	**17.31**	92.29	77.92	76.25	37.67	**71.03**
		6	0.20	13.68	11.22	10.73	33.64	**17.31**	90.00	78.54	76.88	36.33	**70.44**
		7	0.19	13.67	11.31	10.75	33.67	**17.35**	90.00	78.13	76.46	35.50	**70.02**
		8	0.23	13.72	11.26	10.76	33.72	**17.37**	88.96	77.71	76.67	36.33	**69.92**
		9	0.20	13.67	11.32	10.81	33.76	**17.39**	89.58	78.33	76.67	36.83	**70.35**
		10	0.19	13.67	11.33	10.87	33.85	**17.43**	90.00	77.29	76.25	36.00	**69.89**
	0.2	1	0.13	13.57	11.96	11.77	36.34	**18.41**	92.92	75.21	75.00	31.67	**68.70**
		2	0.07	13.49	11.62	11.46	35.63	**18.05**	95.83	77.50	76.25	34.33	**70.98**
		3	0.07	13.48	11.27	11.05	34.71	**17.63**	95.63	79.17	77.50	36.67	**72.24**
		4	0.13	13.58	11.15	10.78	33.93	**17.36**	93.13	78.54	77.71	37.00	**71.59**
		5	0.14	13.60	11.20	10.77	33.68	**17.31**	92.08	78.75	77.08	36.67	**71.15**
		6	0.16	13.63	11.27	10.68	33.58	**17.29**	91.04	76.88	77.08	37.00	**70.50**
		7	0.19	13.65	11.23	10.80	33.65	**17.33**	89.58	78.54	76.04	36.33	**70.13**
		8	0.20	13.67	11.31	10.77	33.78	**17.38**	91.04	77.71	76.88	36.33	**70.49**
		9	0.20	13.68	11.27	10.79	33.81	**17.39**	90.21	77.08	77.08	36.17	**70.14**
		10	0.21	13.70	11.39	10.85	33.82	**17.44**	89.58	77.50	76.67	36.00	**69.94**
	0.3	1	0.20	13.68	12.05	11.88	36.54	**18.54**	89.58	74.79	74.38	31.33	**67.52**
		2	0.07	13.48	11.66	11.52	35.72	**18.09**	95.63	77.71	76.04	33.17	**70.64**
		3	0.06	13.46	11.25	11.10	34.78	**17.65**	96.46	78.96	76.67	36.33	**72.10**
		4	0.12	13.56	11.21	10.80	34.02	**17.40**	93.75	79.58	76.88	37.33	**71.89**
		5	0.14	13.58	11.21	10.71	33.68	**17.30**	92.50	79.17	77.08	36.67	**71.35**
		6	0.18	13.66	11.22	10.73	33.67	**17.32**	91.25	77.71	76.88	36.17	**70.50**
		7	0.17	13.64	11.25	10.77	33.62	**17.32**	91.67	77.71	76.04	36.17	**70.40**
		8	0.19	13.67	11.28	10.78	33.77	**17.37**	91.88	76.88	76.88	36.67	**70.57**
		9	0.21	13.69	11.24	10.78	33.79	**17.38**	90.00	77.92	76.88	37.00	**70.45**
		10	0.22	13.72	11.29	10.81	33.81	**17.41**	90.00	77.71	76.46	36.33	**70.13**
	0.4	1	0.33	13.87	12.24	11.94	36.73	**18.70**	86.67	73.75	73.75	30.50	**66.17**
		2	0.08	13.50	11.68	11.54	35.81	**18.13**	94.79	77.92	76.67	33.50	**70.72**
		3	0.08	13.49	11.28	11.19	35.00	**17.74**	95.83	80.21	76.88	35.50	**72.10**
		4	0.11	13.55	11.19	10.84	34.16	**17.43**	94.38	78.33	77.29	36.83	**71.71**
		5	0.13	13.57	11.23	10.75	33.71	**17.32**	93.13	76.67	76.67	36.83	**70.82**
		6	0.15	13.61	11.22	10.74	33.62	**17.30**	91.67	79.17	76.67	37.00	**71.13**
		7	0.18	13.64	11.28	10.72	33.59	**17.31**	91.04	77.29	76.46	37.00	**70.45**
		8	0.16	13.63	11.25	10.75	33.72	**17.34**	91.67	77.29	76.67	35.67	**70.32**
		9	0.20	13.68	11.33	10.81	33.74	**17.39**	91.25	78.33	76.46	36.50	**70.64**
		10	0.19	13.67	11.31	10.82	33.79	**17.39**	90.42	77.50	76.46	36.00	**70.09**

	0.5	1	0.50	14.13	12.47	12.15	37.11	**18.97**	83.13	72.71	72.71	29.83	**64.59**
		2	0.10	13.54	11.76	11.62	36.01	**18.23**	94.38	76.67	75.63	32.67	**69.83**
		3	0.06	13.45	11.35	11.31	35.06	**17.79**	96.67	78.96	76.46	35.50	**71.90**
		4	0.08	13.49	11.11	10.88	34.33	**17.45**	95.21	79.38	77.08	36.17	**71.96**
		5	0.15	13.60	11.18	10.78	33.76	**17.33**	91.88	77.71	77.29	37.17	**71.01**
		6	0.14	13.59	11.22	10.72	33.68	**17.30**	92.08	78.13	77.08	36.67	**70.99**
		7	0.17	13.63	11.24	10.76	33.71	**17.34**	92.08	78.33	77.08	36.33	**70.96**
		8	0.20	13.67	11.29	10.76	33.67	**17.35**	90.00	76.67	77.29	35.83	**69.95**
		9	0.20	13.67	11.30	10.82	33.74	**17.38**	90.21	77.29	76.88	36.17	**70.14**
		10	0.18	13.65	11.29	10.81	33.73	**17.37**	90.00	78.33	77.29	36.33	**70.49**
	0.6	1	0.62	14.30	12.70	12.35	37.52	**19.22**	79.58	72.50	72.08	28.83	**63.25**
		2	0.10	13.53	11.84	11.70	36.13	**18.30**	94.38	76.04	75.21	32.17	**69.45**
		3	0.06	13.47	11.42	11.32	35.21	**17.86**	96.25	78.96	76.25	34.67	**71.53**
		4	0.09	13.52	11.19	10.98	34.45	**17.53**	94.79	79.58	77.29	36.33	**72.00**
		5	0.13	13.58	11.17	10.75	33.88	**17.34**	93.13	78.96	76.88	37.00	**71.49**
		6	0.15	13.61	11.20	10.68	33.70	**17.30**	91.25	77.92	77.08	37.33	**70.90**
		7	0.18	13.65	11.31	10.83	33.81	**17.40**	90.83	77.29	77.08	36.50	**70.43**
		8	0.19	13.67	11.32	10.77	33.68	**17.36**	90.63	75.83	77.08	36.83	**70.09**
		9	0.18	13.65	11.34	10.87	34.01	**17.47**	90.83	77.92	76.67	36.00	**70.35**
		10	0.24	13.74	11.36	10.87	34.06	**17.51**	88.96	77.71	76.67	36.17	**69.88**
5,000 Schedules (10F/10B Particles) (GR=0.75)	Best Inertia (w)	1	0.10	13.53	11.87	11.68	35.92	**18.25**	94.17	77.08	75.42	32.67	**69.48**
		2	0.06	13.47	11.54	11.34	35.23	**17.90**	96.46	78.33	76.67	34.67	**71.48**
		3	0.06	13.45	11.21	10.98	34.44	**17.55**	96.67	80.42	77.50	36.67	**72.36**
		4	0.08	13.49	11.11	10.78	33.86	**17.36**	95.21	80.00	77.71	37.33	**72.00**
		5	0.13	13.57	11.17	10.71	33.62	**17.30**	93.13	79.17	77.29	37.67	**71.49**
		6	0.14	13.59	11.20	10.68	33.58	**17.29**	92.08	79.17	77.71	37.33	**71.13**
		7	0.17	13.63	11.23	10.72	33.59	**17.31**	92.08	78.54	77.08	37.00	**70.96**
		8	0.16	13.63	11.25	10.75	33.67	**17.34**	91.88	77.71	77.29	36.83	**70.57**
		9	0.18	13.65	11.24	10.78	33.74	**17.38**	91.25	78.33	77.08	37.00	**70.64**
		10	0.18	13.65	11.29	10.81	33.73	**17.37**	90.42	78.33	77.29	37.17	**70.49**
	Aver. for all Inertia (w)	1	0.29	13.81	12.17	11.93	36.64	**18.64**	88.51	74.52	74.02	31.05	**67.03**
		2	0.08	13.50	11.67	11.52	35.71	**18.10**	95.42	77.47	76.10	33.60	**70.65**
		3	0.07	13.47	11.30	11.13	34.82	**17.68**	96.13	79.32	76.85	35.86	**72.04**
		4	0.11	13.55	11.18	10.84	34.10	**17.42**	93.75	79.23	77.26	36.52	**71.69**
		5	0.14	13.59	11.21	10.75	33.71	**17.32**	92.50	77.98	76.82	37.00	**71.07**
		6	0.17	13.64	11.24	10.72	33.64	**17.31**	91.13	77.98	77.05	36.69	**70.71**
		7	0.18	13.65	11.27	10.77	33.67	**17.34**	90.83	77.80	76.58	36.29	**70.37**
		8	0.20	13.67	11.29	10.77	33.72	**17.36**	90.65	77.08	76.88	36.21	**70.21**
		9	0.20	13.67	11.30	10.81	33.81	**17.40**	90.33	77.65	76.82	36.45	**70.31**
		10	0.21	13.70	11.33	10.84	33.83	**17.42**	89.58	77.59	76.61	36.29	**70.02**

Table C.20: RCPSP test results for DDPSO under different topologies & different values for Inertia (w) (5,000 schedules – 10 forward/ 10 backward particles – GR=0.75)

N_{Sch}	w	DD Range	AD_O j-30	AD_{CP} j-30	j-60	j-90	j-120	Aver.	Problems Solved to Optimality j-30	j-60	j-90	j-120	Aver.
5,000 Schedules (10F/10B Particles) (GR=0.5)	0.0	1	0.14	13.60	11.92	11.66	36.00	**18.30**	93.13	76.04	75.42	32.83	**69.35**
		2	0.08	13.50	11.59	11.39	35.33	**17.95**	95.63	77.50	76.46	34.33	**70.98**
		3	0.08	13.51	11.28	11.05	34.50	**17.58**	95.00	80.42	77.29	36.17	**72.22**
		4	0.15	13.60	11.24	10.82	33.91	**17.39**	93.13	78.13	76.88	37.00	**71.28**
		5	0.14	13.59	11.18	10.76	33.69	**17.30**	92.71	78.33	77.08	36.50	**71.16**
		6	0.17	13.64	11.24	10.71	33.69	**17.32**	91.04	78.96	77.50	36.00	**70.88**
		7	0.20	13.68	11.24	10.79	33.59	**17.33**	91.04	77.29	77.08	36.33	**70.44**
		8	0.17	13.64	11.28	10.82	33.72	**17.37**	90.42	76.88	76.88	37.00	**70.29**
		9	0.21	13.70	11.31	10.85	33.90	**17.44**	89.79	77.92	76.46	36.17	**70.08**
		10	0.19	13.67	11.37	10.87	33.94	**17.46**	91.25	76.46	76.88	35.50	**70.02**
	0.1	1	0.11	13.54	11.89	11.71	36.29	**18.36**	94.38	75.42	75.00	31.83	**69.16**
		2	0.06	13.47	11.57	11.41	35.56	**18.00**	95.83	77.92	75.83	34.83	**71.10**
		3	0.08	13.50	11.29	11.05	34.56	**17.60**	95.21	78.54	76.46	35.83	**71.51**
		4	0.12	13.56	11.21	10.83	33.98	**17.39**	93.96	80.00	77.29	36.00	**71.81**
		5	0.15	13.60	11.21	10.76	33.68	**17.31**	92.08	79.38	76.67	37.00	**71.28**
		6	0.17	13.64	11.27	10.71	33.66	**17.32**	91.88	77.50	76.88	37.00	**70.81**
		7	0.17	13.63	11.24	10.78	33.73	**17.35**	90.83	77.50	76.67	36.83	**70.46**
		8	0.18	13.65	11.29	10.74	33.75	**17.36**	91.04	78.33	77.29	36.17	**70.71**
		9	0.18	13.65	11.31	10.84	33.85	**17.41**	90.83	77.50	76.88	36.83	**70.51**
		10	0.21	13.70	11.34	10.86	33.96	**17.47**	90.21	77.92	76.88	35.83	**70.21**
	0.2	1	0.14	13.59	11.96	11.81	36.37	**18.43**	92.08	76.04	74.38	32.00	**68.63**
		2	0.06	13.47	11.55	11.48	35.63	**18.03**	96.46	79.17	76.46	34.67	**71.69**
		3	0.05	13.46	11.28	11.09	34.71	**17.64**	96.46	79.17	77.08	36.00	**72.18**
		4	0.09	13.51	11.15	10.83	34.00	**17.37**	94.79	78.75	76.88	36.67	**71.77**
		5	0.15	13.60	11.16	10.74	33.73	**17.31**	92.29	78.13	77.08	37.33	**71.21**
		6	0.15	13.61	11.27	10.71	33.63	**17.30**	91.88	77.50	76.88	36.67	**70.73**
		7	0.19	13.66	11.25	10.74	33.69	**17.33**	89.58	78.54	77.08	37.17	**70.59**
		8	0.16	13.63	11.27	10.78	33.80	**17.37**	92.71	78.54	77.29	36.50	**71.26**
		9	0.16	13.61	11.29	10.84	33.83	**17.39**	91.88	77.50	76.88	36.67	**70.73**
		10	0.18	13.64	11.31	10.86	33.96	**17.44**	91.46	77.92	76.67	36.00	**70.51**
	0.3	1	0.17	13.64	12.07	11.86	36.49	**18.51**	91.04	75.42	74.38	31.50	**68.08**
		2	0.10	13.52	11.66	11.52	35.79	**18.12**	94.58	77.08	75.83	33.83	**70.33**
		3	0.06	13.46	11.28	11.19	34.85	**17.69**	96.25	79.58	76.04	35.50	**71.84**
		4	0.08	13.49	11.16	10.83	34.15	**17.41**	95.42	78.96	77.71	36.83	**72.23**
		5	0.14	13.59	11.19	10.77	33.79	**17.34**	93.13	78.13	77.29	35.67	**71.05**
		6	0.15	13.62	11.24	10.73	33.68	**17.31**	91.88	78.96	76.67	36.50	**71.00**
		7	0.16	13.62	11.29	10.77	33.75	**17.36**	92.71	77.71	76.88	36.33	**70.91**
		8	0.17	13.63	11.27	10.77	33.78	**17.36**	91.25	78.75	76.46	36.50	**70.74**
		9	0.22	13.72	11.31	10.80	33.83	**17.42**	89.79	77.50	76.67	36.00	**69.99**
		10	0.16	13.62	11.27	10.85	33.84	**17.40**	92.50	78.75	76.67	36.50	**71.10**
	0.4	1	0.29	13.81	12.13	11.96	36.73	**18.66**	87.29	74.58	74.17	31.00	**66.76**
		2	0.08	13.51	11.73	11.56	35.76	**18.14**	95.00	76.88	76.25	33.17	**70.32**
		3	0.05	13.45	11.33	11.22	34.99	**17.75**	96.67	79.38	76.88	36.33	**72.31**
		4	0.10	13.53	11.15	10.87	34.19	**17.44**	93.96	80.00	77.08	36.83	**71.97**
		5	0.11	13.54	11.21	10.76	33.82	**17.33**	93.96	78.54	76.67	36.00	**71.29**
		6	0.14	13.58	11.19	10.74	33.69	**17.30**	93.13	78.96	77.08	36.83	**71.50**
		7	0.17	13.62	11.24	10.76	33.68	**17.33**	91.88	77.29	76.67	36.33	**70.54**
		8	0.15	13.61	11.35	10.77	33.78	**17.38**	92.08	77.71	75.63	36.33	**70.44**
		9	0.22	13.70	11.27	10.80	33.76	**17.39**	90.21	77.92	76.88	37.17	**70.54**
		10	0.20	13.69	11.30	10.84	34.00	**17.46**	90.63	78.13	76.67	35.33	**70.19**

	0.5	1	0.52	14.13	12.46	12.14	37.17	**18.97**	80.21	73.54	73.13	30.17	**64.26**
		2	0.10	13.53	11.76	11.60	35.92	**18.20**	94.79	76.88	76.04	32.67	**70.09**
		3	0.08	13.49	11.38	11.27	35.12	**17.82**	94.79	79.17	76.88	36.00	**71.71**
		4	0.09	13.50	11.17	10.96	34.42	**17.51**	95.00	78.54	76.67	36.83	**71.76**
		5	0.10	13.53	11.13	10.80	33.91	**17.34**	94.38	79.17	76.67	36.83	**71.76**
		6	0.16	13.62	11.19	10.76	33.71	**17.32**	91.46	77.50	77.08	37.17	**70.80**
		7	0.17	13.63	11.24	10.77	33.80	**17.36**	91.67	78.33	76.67	36.00	**70.67**
		8	0.15	13.61	11.26	10.75	33.76	**17.34**	91.04	78.13	76.67	36.17	**70.50**
		9	0.18	13.65	11.32	10.83	33.82	**17.40**	90.42	76.88	77.08	36.33	**70.18**
		10	0.19	13.66	11.35	10.86	33.88	**17.44**	90.83	77.50	76.67	36.83	**70.46**
	0.6	1	0.60	14.25	12.72	12.35	37.53	**19.21**	79.17	72.08	72.50	29.33	**63.27**
		2	0.12	13.56	11.87	11.71	36.07	**18.30**	93.96	76.04	75.63	32.50	**69.53**
		3	0.06	13.47	11.43	11.33	35.22	**17.86**	96.25	79.17	76.25	35.00	**71.67**
		4	0.09	13.51	11.19	11.03	34.50	**17.56**	95.21	79.58	77.08	37.00	**72.22**
		5	0.12	13.56	11.17	10.80	33.98	**17.38**	93.54	78.13	76.46	37.33	**71.36**
		6	0.11	13.54	11.25	10.79	33.76	**17.34**	93.54	78.33	76.88	36.67	**71.35**
		7	0.18	13.65	11.25	10.75	33.67	**17.33**	90.83	77.92	76.67	36.33	**70.44**
		8	0.17	13.63	11.24	10.76	33.76	**17.35**	90.42	77.71	76.88	36.83	**70.46**
		9	0.16	13.62	11.32	10.80	33.83	**17.39**	91.04	77.92	76.88	35.83	**70.42**
		10	0.21	13.69	11.30	10.84	33.86	**17.42**	89.38	78.13	76.46	37.17	**70.28**
5,000 Schedules (10F/10B Particles) (GR=0.5)	Best Inertia (w)	1	0.11	13.54	11.89	11.66	36.00	**18.30**	94.38	76.04	75.42	32.83	**69.35**
		2	0.06	13.47	11.55	11.39	35.33	**17.95**	96.46	79.17	76.46	34.83	**71.69**
		3	0.05	13.45	11.28	11.05	34.50	**17.58**	96.67	80.42	77.29	36.33	**72.31**
		4	0.08	13.49	11.15	10.82	33.91	**17.37**	95.42	80.00	77.71	37.00	**72.23**
		5	0.10	13.53	11.13	10.74	33.68	**17.30**	94.38	79.38	77.29	37.33	**71.76**
		6	0.11	13.54	11.19	10.71	33.63	**17.30**	93.54	78.96	77.50	37.17	**71.50**
		7	0.16	13.62	11.24	10.74	33.59	**17.33**	92.71	78.54	77.08	37.17	**70.91**
		8	0.15	13.61	11.24	10.74	33.72	**17.34**	92.71	78.75	77.29	37.00	**71.26**
		9	0.16	13.61	11.27	10.80	33.76	**17.39**	91.88	77.92	77.08	37.17	**70.73**
		10	0.16	13.62	11.27	10.84	33.84	**17.40**	92.50	78.75	76.88	37.17	**71.10**
	Aver. for all Inertia (w)	1	0.28	13.80	12.16	11.93	36.65	**18.63**	88.18	74.73	74.14	31.24	**67.07**
		2	0.09	13.51	11.68	11.53	35.72	**18.11**	95.18	77.35	76.07	33.71	**70.58**
		3	0.07	13.48	11.32	11.17	34.85	**17.70**	95.80	79.35	76.70	35.83	**71.92**
		4	0.10	13.53	11.18	10.88	34.16	**17.44**	94.49	79.14	77.08	36.74	**71.86**
		5	0.13	13.57	11.18	10.77	33.80	**17.33**	93.15	78.54	76.85	36.67	**71.30**
		6	0.15	13.60	11.23	10.73	33.69	**17.32**	92.11	78.24	76.99	36.69	**71.01**
		7	0.18	13.64	11.25	10.77	33.70	**17.34**	91.22	77.80	76.82	36.48	**70.58**
		8	0.16	13.63	11.28	10.77	33.76	**17.36**	91.28	78.01	76.73	36.50	**70.63**
		9	0.19	13.67	11.31	10.82	33.83	**17.41**	90.57	77.59	76.82	36.43	**70.35**
		10	0.19	13.67	11.32	10.86	33.92	**17.44**	90.89	77.83	76.70	36.17	**70.40**

Table C.21: RCPSP test results for DDPSO under different topologies & different values for Inertia (w) (5,000 schedules – 10 forward/ 10 backward particles – GR=0.5)

N_{Sch}	w	DD Range	AD_O	AD_{CP}					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
5,000 Schedules (10F/10B Particles) (GR=0.25)	0.0	1	0.12	13.57	11.92	11.69	36.11	**18.32**	93.13	75.63	75.00	32.00	**68.94**
		2	0.06	13.47	11.60	11.38	35.49	**17.99**	96.25	77.29	76.46	33.17	**70.79**
		3	0.07	13.48	11.31	11.04	34.55	**17.60**	95.21	78.75	77.50	36.17	**71.91**
		4	0.11	13.54	11.22	10.85	33.96	**17.39**	93.75	79.17	76.88	36.83	**71.66**
		5	0.15	13.60	11.19	10.81	33.77	**17.34**	92.29	78.54	76.67	36.33	**70.96**
		6	0.13	13.57	11.24	10.81	33.74	**17.34**	92.92	78.13	77.08	36.33	**71.11**
		7	0.19	13.68	11.27	10.77	33.76	**17.37**	91.04	78.13	77.08	36.67	**70.73**
		8	0.20	13.68	11.31	10.86	33.84	**17.42**	91.25	77.50	76.46	36.67	**70.47**
		9	0.23	13.72	11.32	10.84	33.94	**17.46**	88.75	77.50	77.08	35.50	**69.71**
		10	0.19	13.67	11.37	10.90	34.04	**17.49**	90.63	77.50	76.88	35.83	**70.21**
	0.1	1	0.13	13.57	11.87	11.76	36.25	**18.36**	93.54	76.46	75.21	32.17	**69.34**
		2	0.07	13.49	11.60	11.45	35.58	**18.03**	95.42	77.92	76.46	33.83	**70.91**
		3	0.06	13.48	11.32	11.10	34.64	**17.63**	96.04	78.75	77.08	37.00	**72.22**
		4	0.10	13.53	11.19	10.83	34.05	**17.40**	94.17	77.92	77.71	36.83	**71.66**
		5	0.14	13.60	11.19	10.78	33.79	**17.34**	93.13	79.17	76.46	36.33	**71.27**
		6	0.14	13.59	11.27	10.78	33.77	**17.35**	92.50	77.29	76.88	36.50	**70.79**
		7	0.17	13.64	11.32	10.82	33.81	**17.40**	91.04	77.50	77.08	36.50	**70.53**
		8	0.17	13.65	11.29	10.86	33.90	**17.42**	91.46	77.71	76.88	37.50	**70.89**
		9	0.19	13.66	11.31	10.88	33.94	**17.45**	91.04	78.13	76.88	36.50	**70.64**
		10	0.20	13.68	11.38	10.87	34.04	**17.49**	90.42	77.08	76.88	35.67	**70.01**
	0.2	1	0.13	13.58	11.93	11.75	36.41	**18.42**	92.92	75.00	74.58	32.17	**68.67**
		2	0.08	13.50	11.63	11.50	35.63	**18.07**	94.79	77.71	76.04	34.33	**70.72**
		3	0.06	13.47	11.28	11.12	34.72	**17.64**	96.25	78.54	76.67	35.83	**71.82**
		4	0.08	13.49	11.16	10.87	34.10	**17.41**	95.00	79.58	76.88	37.00	**72.11**
		5	0.13	13.58	11.17	10.79	33.80	**17.33**	92.92	78.54	76.25	36.67	**71.09**
		6	0.17	13.64	11.21	10.78	33.77	**17.35**	90.83	78.13	76.46	36.33	**70.44**
		7	0.18	13.65	11.24	10.80	33.78	**17.36**	91.04	77.92	77.29	36.00	**70.56**
		8	0.18	13.65	11.30	10.84	33.85	**17.41**	91.04	78.13	76.67	36.17	**70.50**
		9	0.18	13.65	11.30	10.84	33.88	**17.42**	90.21	78.54	76.67	36.17	**70.40**
		10	0.20	13.68	11.35	10.90	33.96	**17.47**	90.63	78.96	76.88	36.00	**70.61**
	0.3	1	0.18	13.65	11.99	11.83	36.56	**18.51**	90.00	75.21	74.79	31.83	**67.96**
		2	0.07	13.49	11.67	11.51	35.78	**18.11**	95.83	77.92	76.46	33.33	**70.89**
		3	0.05	13.45	11.31	11.16	34.81	**17.68**	96.67	80.42	76.67	36.33	**72.52**
		4	0.06	13.48	11.17	10.88	34.15	**17.42**	96.25	79.58	77.08	35.83	**72.19**
		5	0.12	13.56	11.17	10.77	33.79	**17.32**	94.58	78.33	76.67	38.00	**71.90**
		6	0.15	13.59	11.23	10.77	33.80	**17.35**	92.50	78.54	77.08	36.17	**71.07**
		7	0.12	13.57	11.31	10.77	33.69	**17.33**	93.54	77.50	77.29	37.00	**71.33**
		8	0.17	13.63	11.29	10.79	33.88	**17.40**	91.67	77.50	76.67	35.83	**70.42**
		9	0.15	13.61	11.32	10.87	33.90	**17.42**	92.08	77.71	76.46	36.83	**70.77**
		10	0.17	13.64	11.35	10.88	34.01	**17.47**	91.46	77.92	76.67	36.17	**70.55**
	0.4	1	0.27	13.78	12.16	11.97	36.77	**18.67**	87.08	74.38	73.75	31.00	**66.55**
		2	0.09	13.51	11.69	11.57	35.88	**18.16**	95.63	75.83	75.63	33.33	**70.10**
		3	0.05	13.46	11.35	11.22	35.03	**17.76**	96.46	78.75	76.46	34.67	**71.58**
		4	0.09	13.51	11.22	10.93	34.28	**17.48**	94.79	78.33	77.50	36.67	**71.82**
		5	0.11	13.55	11.18	10.81	33.91	**17.36**	93.75	79.17	76.67	36.17	**71.44**
		6	0.13	13.58	11.21	10.80	33.75	**17.34**	93.13	78.96	76.88	36.50	**71.36**
		7	0.18	13.65	11.28	10.79	33.78	**17.37**	91.25	79.38	76.67	36.33	**70.91**
		8	0.16	13.62	11.29	10.81	33.87	**17.40**	92.08	77.29	77.29	36.17	**70.71**
		9	0.17	13.64	11.31	10.84	33.90	**17.43**	92.08	77.92	77.50	36.17	**70.92**
		10	0.16	13.62	11.28	10.83	33.95	**17.42**	92.50	78.13	77.08	36.50	**71.05**

	#											
0.5	1	0.48	14.10	12.44	12.17	37.24	**18.99**	82.71	72.92	72.29	29.83	**64.44**
	2	0.08	13.50	11.75	11.62	35.90	**18.19**	95.21	76.67	75.83	32.83	**70.14**
	3	0.06	13.46	11.40	11.28	35.08	**17.80**	96.67	78.75	77.08	35.67	**72.04**
	4	0.07	13.48	11.14	10.96	34.37	**17.49**	96.25	80.21	76.88	37.50	**72.71**
	5	0.10	13.53	11.21	10.80	33.99	**17.38**	94.38	78.54	77.08	37.33	**71.83**
	6	0.15	13.60	11.21	10.77	33.81	**17.35**	91.88	79.17	77.50	36.83	**71.34**
	7	0.16	13.61	11.26	10.77	33.85	**17.37**	91.67	78.33	77.29	36.17	**70.86**
	8	0.19	13.65	11.28	10.80	33.82	**17.39**	91.67	77.50	77.08	37.33	**70.90**
	9	0.17	13.64	11.36	10.86	33.90	**17.44**	91.25	77.29	76.67	36.83	**70.51**
	10	0.15	13.60	11.30	10.84	33.96	**17.43**	92.08	77.92	76.88	35.83	**70.68**
0.6	1	0.59	14.26	12.77	12.34	37.56	**19.23**	80.63	72.29	72.50	29.00	**63.60**
	2	0.12	13.57	11.84	11.67	36.12	**18.30**	93.96	76.04	75.42	32.17	**69.40**
	3	0.07	13.48	11.42	11.34	35.23	**17.86**	96.25	77.71	76.04	34.83	**71.21**
	4	0.09	13.50	11.21	11.01	34.50	**17.55**	95.00	79.38	76.88	36.67	**71.98**
	5	0.08	13.50	11.20	10.79	33.98	**17.37**	95.00	78.54	77.08	37.00	**71.91**
	6	0.13	13.59	11.23	10.82	33.80	**17.36**	92.50	79.38	76.88	36.83	**71.40**
	7	0.17	13.63	11.22	10.76	33.81	**17.36**	92.50	78.13	77.29	36.67	**71.15**
	8	0.20	13.68	11.30	10.83	33.90	**17.42**	90.42	78.54	76.88	36.17	**70.50**
	9	0.20	13.68	11.27	10.81	33.94	**17.43**	90.00	78.54	76.88	35.83	**70.31**
	10	0.17	13.63	11.31	10.88	33.94	**17.44**	90.83	77.08	76.67	35.83	**70.10**

5,000 Schedules (10F/10B Particles) (GR=0.25)		#											
	Best Inertia (w)	1	0.12	13.57	11.87	11.69	36.11	**18.32**	93.54	76.46	75.21	32.17	**69.34**
		2	0.06	13.47	11.60	11.38	35.49	**17.99**	96.25	77.92	76.46	34.33	**70.91**
		3	0.05	13.45	11.28	11.04	34.55	**17.60**	96.67	80.42	77.50	37.00	**72.52**
		4	0.06	13.48	11.14	10.83	33.96	**17.39**	96.25	80.21	77.71	37.50	**72.71**
		5	0.08	13.50	11.17	10.77	33.77	**17.32**	95.00	79.17	77.08	38.00	**71.91**
		6	0.13	13.57	11.21	10.77	33.74	**17.34**	93.13	79.38	77.50	36.83	**71.40**
		7	0.12	13.57	11.22	10.76	33.69	**17.33**	93.54	79.38	77.29	37.00	**71.33**
		8	0.16	13.62	11.28	10.79	33.82	**17.39**	92.08	78.54	77.29	37.50	**70.90**
		9	0.15	13.61	11.27	10.81	33.88	**17.42**	92.08	78.54	77.50	36.83	**70.92**
		10	0.15	13.60	11.28	10.83	33.94	**17.42**	92.50	78.96	77.08	36.50	**71.05**
	Aver. for all Inertia (w)	1	0.27	13.79	12.15	11.93	36.70	**18.64**	88.57	74.55	74.02	31.14	**67.07**
		2	0.08	13.50	11.68	11.53	35.77	**18.12**	95.30	77.05	76.04	33.29	**70.42**
		3	0.06	13.47	11.34	11.18	34.87	**17.71**	96.22	78.81	76.79	35.79	**71.90**
		4	0.09	13.50	11.19	10.90	34.20	**17.45**	95.03	79.17	77.11	36.76	**72.02**
		5	0.12	13.56	11.19	10.79	33.86	**17.35**	93.72	78.69	76.70	36.83	**71.49**
		6	0.14	13.59	11.23	10.79	33.78	**17.35**	92.32	78.51	76.96	36.50	**71.07**
		7	0.17	13.63	11.27	10.78	33.78	**17.37**	91.73	78.13	77.14	36.48	**70.87**
		8	0.18	13.65	11.29	10.83	33.86	**17.41**	91.37	77.74	76.85	36.55	**70.63**
		9	0.18	13.66	11.31	10.85	33.92	**17.43**	90.77	77.95	76.88	36.26	**70.46**
		10	0.18	13.65	11.33	10.87	33.99	**17.46**	91.22	77.80	76.85	35.98	**70.46**

Table C.22: RCPSP test results for DDPSO under different topologies & different values for Inertia (w) (5,000 schedules – 10 forward/ 10 backward particles – GR=0.25)

N_Sch	w	DD Range	AD$_O$	AD$_{CP}$					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
5,000 Schedules (10F/10B Particles) (GR=0.0)	0.0	1	0.12	13.56	11.92	11.79	36.46	**18.43**	93.54	75.21	74.79	31.50	**68.76**
		2	0.07	13.49	11.65	11.46	35.57	**18.04**	95.83	77.29	76.46	33.50	**70.77**
		3	0.07	13.48	11.31	11.02	34.63	**17.61**	95.83	78.96	76.67	36.00	**71.86**
		4	0.11	13.53	11.28	10.92	34.02	**17.44**	94.38	78.13	76.88	36.33	**71.43**
		5	0.17	13.64	11.32	10.82	33.93	**17.43**	91.25	76.67	76.67	35.17	**69.94**
		6	0.23	13.74	11.31	10.84	33.94	**17.46**	89.58	77.71	77.08	35.67	**70.01**
		7	0.17	13.64	11.30	10.87	33.92	**17.43**	91.67	78.13	77.29	35.83	**70.73**
		8	0.22	13.72	11.43	10.90	33.94	**17.50**	89.58	77.08	76.46	35.83	**69.74**
		9	0.23	13.74	11.32	10.92	34.06	**17.51**	88.96	77.29	76.67	35.83	**69.69**
		10	0.26	13.79	11.39	10.94	34.09	**17.55**	88.33	76.67	76.67	35.50	**69.29**
	0.1	1	0.12	13.57	11.91	11.74	36.23	**18.36**	93.54	75.83	75.00	32.17	**69.14**
		2	0.07	13.48	11.62	11.47	35.64	**18.05**	96.25	77.71	76.25	33.33	**70.89**
		3	0.07	13.49	11.32	11.09	34.61	**17.63**	95.63	78.54	76.46	36.33	**71.74**
		4	0.09	13.51	11.28	10.87	34.02	**17.42**	95.21	78.13	77.29	36.17	**71.70**
		5	0.17	13.63	11.27	10.80	33.88	**17.40**	92.08	77.92	76.67	36.67	**70.83**
		6	0.16	13.62	11.29	10.84	33.86	**17.40**	92.50	77.29	76.88	35.83	**70.63**
		7	0.21	13.70	11.32	10.81	33.88	**17.43**	89.38	77.71	76.88	36.17	**70.03**
		8	0.23	13.73	11.38	10.85	34.01	**17.49**	89.38	77.50	76.88	35.50	**69.81**
		9	0.21	13.70	11.37	10.89	34.05	**17.50**	90.42	77.92	77.29	36.50	**70.53**
		10	0.23	13.72	11.39	10.91	34.11	**17.53**	89.58	77.71	76.46	35.17	**69.73**
	0.2	1	0.15	13.60	11.97	11.82	36.40	**18.45**	92.29	75.00	74.79	31.67	**68.44**
		2	0.09	13.51	11.64	11.50	35.66	**18.08**	94.79	78.13	76.25	33.67	**70.71**
		3	0.09	13.51	11.29	11.15	34.75	**17.68**	95.00	79.58	76.67	35.00	**71.56**
		4	0.09	13.52	11.29	10.88	34.10	**17.45**	94.17	78.75	77.50	36.50	**71.73**
		5	0.13	13.57	11.26	10.85	33.92	**17.40**	93.54	77.50	76.67	36.33	**71.01**
		6	0.18	13.66	11.34	10.82	33.85	**17.42**	90.00	78.54	77.08	36.50	**70.53**
		7	0.18	13.65	11.27	10.82	33.92	**17.42**	91.25	79.17	76.67	36.17	**70.81**
		8	0.19	13.66	11.31	10.86	33.91	**17.43**	91.25	77.92	76.67	36.17	**70.50**
		9	0.20	13.67	11.37	10.92	34.00	**17.49**	89.17	77.29	76.67	35.33	**69.61**
		10	0.22	13.72	11.39	10.91	34.09	**17.53**	89.79	77.50	75.63	35.50	**69.60**
	0.3	1	0.17	13.63	12.05	11.86	36.52	**18.52**	92.08	75.21	74.38	31.33	**68.25**
		2	0.05	13.45	11.68	11.56	35.77	**18.11**	96.88	77.08	76.04	33.33	**70.83**
		3	0.07	13.48	11.31	11.18	34.86	**17.71**	96.04	78.54	77.29	36.00	**71.97**
		4	0.09	13.51	11.24	10.91	34.19	**17.46**	94.58	77.71	77.08	36.33	**71.43**
		5	0.09	13.52	11.20	10.81	33.87	**17.35**	95.00	79.58	76.88	36.83	**72.07**
		6	0.14	13.59	11.27	10.78	33.80	**17.36**	92.71	78.54	76.88	37.00	**71.28**
		7	0.18	13.65	11.29	10.85	33.90	**17.42**	90.63	78.75	77.08	36.83	**70.82**
		8	0.18	13.65	11.33	10.89	33.92	**17.45**	90.63	77.50	76.88	36.00	**70.25**
		9	0.24	13.75	11.36	10.89	34.05	**17.51**	88.54	77.50	76.88	36.33	**69.81**
		10	0.19	13.67	11.40	10.91	34.09	**17.52**	91.25	78.13	76.46	35.83	**70.42**
	0.4	1	0.29	13.82	12.20	11.96	36.80	**18.69**	87.92	73.96	73.75	30.50	**66.53**
		2	0.09	13.52	11.70	11.57	35.82	**18.15**	94.17	75.63	75.63	33.33	**69.69**
		3	0.07	13.48	11.35	11.20	34.98	**17.75**	96.04	79.17	76.88	35.50	**71.90**
		4	0.08	13.50	11.20	10.95	34.28	**17.48**	94.58	78.96	76.67	37.50	**71.93**
		5	0.13	13.58	11.26	10.80	33.92	**17.39**	93.33	78.13	77.08	37.33	**71.47**
		6	0.17	13.64	11.26	10.80	33.86	**17.39**	91.25	77.71	77.29	36.83	**70.77**
		7	0.17	13.65	11.27	10.78	33.80	**17.37**	91.46	77.71	77.08	36.50	**70.69**
		8	0.20	13.67	11.31	10.88	33.88	**17.44**	90.42	78.54	76.46	36.33	**70.44**
		9	0.18	13.65	11.41	10.85	33.98	**17.47**	91.25	76.88	77.08	35.83	**70.26**
		10	0.22	13.70	11.39	10.89	34.11	**17.52**	89.79	78.54	76.04	35.83	**70.05**

		#											
	0.5	1	0.52	14.16	12.48	12.23	37.17	**19.01**	81.67	72.29	72.92	29.33	**64.05**
		2	0.09	13.51	11.74	11.61	35.93	**18.20**	95.21	76.67	75.21	33.17	**70.06**
		3	0.08	13.50	11.39	11.25	35.14	**17.82**	95.63	79.17	77.08	35.67	**71.89**
		4	0.07	13.48	11.26	10.99	34.37	**17.52**	95.42	78.13	77.29	35.67	**71.63**
		5	0.11	13.54	11.24	10.80	34.01	**17.40**	93.96	78.75	77.08	36.33	**71.53**
		6	0.15	13.60	11.25	10.80	33.83	**17.37**	91.88	78.54	76.67	36.83	**70.98**
		7	0.18	13.64	11.36	10.79	33.88	**17.42**	91.25	77.71	76.46	36.00	**70.35**
		8	0.19	13.66	11.39	10.84	33.95	**17.46**	90.63	77.92	77.08	36.33	**70.49**
		9	0.22	13.70	11.41	10.88	34.05	**17.51**	90.21	77.08	76.88	35.17	**69.83**
		10	0.20	13.67	11.37	10.87	34.05	**17.49**	91.04	77.71	76.04	36.00	**70.20**
	0.6	1	0.58	14.23	12.75	12.38	37.56	**19.23**	80.63	72.08	72.29	29.17	**63.54**
		2	0.13	13.58	11.88	11.65	36.10	**18.30**	92.71	75.42	75.42	32.33	**68.97**
		3	0.07	13.47	11.47	11.33	35.30	**17.89**	96.04	78.33	76.88	34.50	**71.44**
		4	0.09	13.52	11.29	10.98	34.54	**17.58**	95.42	78.75	76.67	36.50	**71.83**
		5	0.11	13.54	11.24	10.86	34.06	**17.42**	94.17	78.54	76.25	36.33	**71.32**
		6	0.14	13.58	11.23	10.84	33.86	**17.38**	91.67	78.75	77.08	36.50	**71.00**
		7	0.17	13.64	11.32	10.80	33.83	**17.40**	91.88	77.08	77.08	36.33	**70.59**
		8	0.18	13.66	11.32	10.85	33.91	**17.43**	91.46	77.29	76.67	36.50	**70.48**
		9	0.19	13.66	11.33	10.84	33.93	**17.44**	90.63	78.54	76.67	36.00	**70.46**
		10	0.18	13.66	11.34	10.89	34.04	**17.48**	90.83	77.92	76.88	36.33	**70.49**

5,000 Schedules (10F/10B Particles) (GR=0.0)													
	Best Inertia (w)	1	0.12	13.56	11.91	11.74	36.23	**18.36**	93.54	75.83	75.00	32.17	**69.14**
		2	0.05	13.45	11.62	11.46	35.57	**18.04**	96.88	78.13	76.46	33.67	**70.89**
		3	0.07	13.47	11.29	11.02	34.61	**17.61**	96.04	79.58	77.29	36.33	**71.97**
		4	0.07	13.48	11.20	10.87	34.02	**17.42**	95.42	78.96	77.50	37.50	**71.93**
		5	0.09	13.52	11.20	10.80	33.87	**17.35**	95.00	79.58	77.08	37.33	**72.07**
		6	0.14	13.58	11.23	10.78	33.80	**17.36**	92.71	78.75	77.29	37.00	**71.28**
		7	0.17	13.64	11.27	10.78	33.80	**17.37**	91.88	79.17	77.29	36.83	**70.82**
		8	0.18	13.65	11.31	10.84	33.88	**17.43**	91.46	78.54	77.08	36.50	**70.50**
		9	0.18	13.65	11.32	10.84	33.93	**17.44**	91.25	78.54	77.29	36.50	**70.53**
		10	0.18	13.66	11.34	10.87	34.04	**17.48**	91.25	78.54	76.88	36.33	**70.49**
	Aver. for all Inertia (w)	1	0.28	13.80	12.18	11.97	36.73	**18.67**	88.81	74.23	73.99	30.81	**66.96**
		2	0.08	13.50	11.70	11.55	35.78	**18.13**	95.12	76.85	75.89	33.24	**70.27**
		3	0.07	13.49	11.35	11.17	34.90	**17.73**	95.74	78.90	76.85	35.57	**71.76**
		4	0.09	13.51	11.26	10.93	34.22	**17.48**	94.82	78.36	77.05	36.43	**71.67**
		5	0.13	13.57	11.26	10.82	33.94	**17.40**	93.33	78.15	76.76	36.43	**71.17**
		6	0.17	13.63	11.28	10.82	33.86	**17.40**	91.37	78.15	76.99	36.45	**70.74**
		7	0.18	13.65	11.31	10.82	33.87	**17.41**	91.07	78.04	76.93	36.26	**70.58**
		8	0.20	13.68	11.35	10.87	33.93	**17.46**	90.48	77.68	76.73	36.10	**70.24**
		9	0.21	13.70	11.36	10.88	34.02	**17.49**	89.88	77.50	76.88	35.86	**70.03**
		10	0.21	13.70	11.38	10.90	34.08	**17.52**	90.09	77.74	76.31	35.74	**69.97**

Table C.23: RCPSP test results for DDPSO under different topologies & different values for Inertia (w) (5,000 schedules – 10 forward/ 10 backward particles – GR=0.0)

N_{Sch}	w	DD Range	AD_O	AD_{CP}					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
50,000 Schedules (20F/20B Particles) (GR=0.75)	0.0	1	0.05	13.45	11.50	11.28	35.07	**17.83**	96.67	78.13	76.67	35.17	**71.66**
		2	0.02	13.41	11.17	10.99	34.40	**17.49**	98.33	82.29	77.92	37.50	**74.01**
		3	0.02	13.41	10.92	10.66	33.55	**17.13**	98.33	83.33	78.13	39.33	**74.78**
		4	0.05	13.45	10.97	10.40	32.81	**16.91**	96.46	80.83	78.75	40.00	**74.01**
		5	0.08	13.53	11.00	10.33	32.49	**16.84**	94.38	80.83	78.33	39.00	**73.14**
		6	0.09	13.51	11.03	10.32	32.39	**16.81**	94.38	79.38	77.92	38.67	**72.58**
		7	0.10	13.53	11.01	10.31	32.34	**16.80**	93.96	80.42	78.54	39.33	**73.06**
		8	0.11	13.54	11.00	10.35	32.38	**16.82**	94.17	79.79	78.13	39.50	**72.90**
		9	0.11	13.54	11.00	10.33	32.50	**16.84**	93.75	80.00	78.33	38.83	**72.73**
		10	0.12	13.57	11.02	10.35	32.48	**16.85**	93.13	79.38	78.33	39.00	**72.46**
	0.1	1	0.04	13.44	11.50	11.36	35.34	**17.91**	97.50	77.50	76.46	35.00	**71.61**
		2	0.02	13.40	11.16	11.09	34.62	**17.57**	98.75	82.08	77.50	37.17	**73.88**
		3	0.01	13.39	10.86	10.65	33.56	**17.12**	99.17	83.96	78.13	40.17	**75.35**
		4	0.06	13.47	10.91	10.35	32.80	**16.88**	96.46	82.08	78.33	40.50	**74.34**
		5	0.08	13.49	10.95	10.33	32.44	**16.80**	95.83	81.46	77.92	40.50	**73.93**
		6	0.09	13.52	10.95	10.31	32.40	**16.79**	94.79	80.83	78.13	39.83	**73.40**
		7	0.08	13.49	10.99	10.33	32.31	**16.78**	95.21	80.63	78.13	38.83	**73.20**
		8	0.10	13.52	11.02	10.34	32.37	**16.81**	93.75	80.83	77.71	39.17	**72.86**
		9	0.12	13.55	11.02	10.36	32.45	**16.85**	92.71	80.21	77.71	39.33	**72.49**
		10	0.11	13.55	11.01	10.34	32.49	**16.85**	93.33	80.42	77.50	38.83	**72.52**
	0.2	1	0.04	13.44	11.54	11.36	35.45	**17.95**	97.08	78.33	76.88	34.33	**71.66**
		2	0.02	13.41	11.19	11.09	34.65	**17.58**	98.33	81.67	77.50	36.83	**73.58**
		3	0.03	13.41	10.85	10.66	33.68	**17.15**	98.13	84.79	78.13	40.17	**75.30**
		4	0.05	13.46	10.93	10.42	32.78	**16.89**	96.67	82.50	77.71	40.50	**74.34**
		5	0.11	13.54	11.21	10.76	33.82	**17.33**	93.96	78.54	76.67	36.00	**71.29**
		6	0.09	13.51	10.98	10.31	32.37	**16.79**	94.58	80.00	78.54	38.67	**72.95**
		7	0.08	13.49	11.03	10.35	32.37	**16.81**	95.42	80.63	77.92	39.00	**73.24**
		8	0.10	13.53	11.02	10.35	32.35	**16.81**	94.58	80.00	78.13	38.83	**72.89**
		9	0.11	13.55	10.97	10.32	32.36	**16.80**	94.58	81.46	78.33	39.83	**73.55**
		10	0.10	13.53	11.00	10.35	32.45	**16.83**	93.96	80.42	77.92	39.17	**72.86**
	0.3	1	0.06	13.47	11.58	11.39	35.54	**18.00**	96.04	77.50	76.67	34.17	**71.09**
		2	0.01	13.39	11.25	11.12	34.77	**17.63**	98.96	80.42	77.29	36.33	**73.25**
		3	0.03	13.41	10.91	10.72	33.84	**17.22**	97.92	84.38	77.92	39.33	**74.89**
		4	0.04	13.43	10.91	10.39	32.90	**16.91**	97.08	82.71	78.33	40.50	**74.66**
		5	0.06	13.46	10.95	10.31	32.47	**16.80**	96.25	81.46	78.75	39.83	**74.07**
		6	0.05	13.46	11.00	10.34	32.37	**16.79**	96.88	80.00	78.33	39.33	**73.64**
		7	0.08	13.49	11.03	10.33	32.32	**16.79**	95.21	79.58	77.92	38.67	**72.84**
		8	0.09	13.51	11.02	10.31	32.34	**16.79**	95.00	79.58	78.13	39.33	**73.01**
		9	0.08	13.50	11.02	10.38	32.40	**16.82**	95.21	80.42	77.29	39.50	**73.10**
		10	0.10	13.53	10.92	10.35	32.40	**16.80**	94.17	81.25	77.71	38.67	**72.95**
	0.4	1	0.10	13.53	11.73	11.59	35.76	**18.15**	94.17	76.46	75.83	33.00	**69.86**
		2	0.02	13.41	11.23	11.18	34.87	**17.67**	98.33	80.83	77.29	35.83	**73.07**
		3	0.02	13.40	10.93	10.76	33.99	**17.27**	98.75	82.71	78.75	38.67	**74.72**
		4	0.04	13.43	10.84	10.40	33.04	**16.93**	97.92	83.54	78.33	41.33	**75.28**
		5	0.05	13.45	10.99	10.39	32.56	**16.85**	96.67	80.63	77.92	40.33	**73.89**
		6	0.08	13.49	10.98	10.35	32.43	**16.81**	95.63	80.63	77.92	39.17	**73.33**
		7	0.10	13.54	10.99	10.33	32.30	**16.79**	93.96	80.21	77.92	39.83	**72.98**
		8	0.10	13.53	11.02	10.32	32.38	**16.81**	94.17	80.00	77.50	39.00	**72.67**
		9	0.12	13.56	11.02	10.32	32.31	**16.80**	93.96	79.38	78.13	39.50	**72.74**
		10	0.10	13.53	10.97	10.35	32.50	**16.84**	95.00	81.04	77.92	38.67	**73.16**

50,000 Schedules (20F/20B Particles) (GR=0.75)	0.5	1	0.32	13.85	12.16	11.90	36.57	**18.62**	86.67	73.75	73.54	30.17	**66.03**
		2	0.03	13.41	11.32	11.20	34.94	**17.72**	97.92	80.83	77.08	35.67	**72.88**
		3	0.02	13.40	10.93	10.82	34.13	**17.32**	98.75	84.17	78.13	38.67	**74.93**
		4	0.03	13.41	10.85	10.43	33.20	**16.97**	98.33	82.71	78.75	39.67	**74.86**
		5	0.06	13.46	10.94	10.35	32.59	**16.84**	96.25	81.88	77.71	39.00	**73.71**
		6	0.06	13.47	11.02	10.31	32.42	**16.80**	96.04	80.21	78.13	39.67	**73.51**
		7	0.10	13.54	10.98	10.31	32.35	**16.79**	94.58	79.79	78.13	39.50	**73.00**
		8	0.09	13.51	11.00	10.31	32.30	**16.78**	95.42	80.42	77.71	38.67	**73.05**
		9	0.09	13.51	10.98	10.34	32.37	**16.80**	94.58	80.63	77.92	39.00	**73.03**
		10	0.08	13.50	10.96	10.32	32.45	**16.81**	94.79	80.63	77.71	38.83	**72.99**
	0.6	1	0.43	14.02	12.53	12.16	37.19	**18.98**	83.96	72.50	72.71	29.67	**64.71**
		2	0.04	13.44	11.37	11.29	35.07	**17.79**	97.29	79.58	76.67	35.00	**72.14**
		3	0.02	13.40	10.95	10.90	34.22	**17.37**	98.75	82.71	78.13	38.50	**74.52**
		4	0.02	13.40	10.87	10.49	33.38	**17.03**	98.54	82.92	78.75	39.33	**74.89**
		5	0.06	13.45	10.90	10.32	32.66	**16.83**	96.46	81.46	78.54	40.17	**74.16**
		6	0.06	13.47	10.92	10.33	32.50	**16.80**	95.83	81.67	77.92	39.00	**73.60**
		7	0.07	13.48	11.02	10.28	32.34	**16.78**	95.83	80.00	78.33	39.17	**73.33**
		8	0.08	13.49	10.98	10.34	32.32	**16.78**	96.04	80.63	78.13	39.67	**73.61**
		9	0.09	13.50	10.96	10.34	32.35	**16.79**	95.00	80.83	77.71	38.83	**73.09**
		10	0.07	13.48	10.97	10.35	32.39	**16.80**	95.63	81.46	77.29	39.50	**73.47**
	Best Inertia (w)	1	0.04	13.44	11.50	11.28	35.07	**17.83**	97.50	78.33	76.88	35.17	**71.66**
		2	0.01	13.39	11.16	10.99	34.40	**17.49**	98.96	82.29	77.92	37.50	**74.01**
		3	0.01	13.39	10.85	10.65	33.55	**17.12**	99.17	84.79	78.75	40.17	**75.35**
		4	0.02	13.40	10.84	10.35	32.78	**16.88**	98.54	83.54	78.75	41.33	**75.28**
		5	0.05	13.45	10.90	10.31	32.44	**16.80**	96.67	81.88	78.75	40.50	**74.16**
		6	0.05	13.46	10.92	10.31	32.37	**16.79**	96.88	81.67	78.54	39.83	**73.64**
		7	0.07	13.48	10.98	10.28	32.30	**16.78**	95.83	80.63	78.54	39.83	**73.33**
		8	0.08	13.49	10.98	10.31	32.30	**16.78**	96.04	80.83	78.13	39.67	**73.61**
		9	0.08	13.50	10.96	10.32	32.31	**16.79**	95.21	81.46	78.33	39.83	**73.55**
		10	0.07	13.48	10.92	10.32	32.39	**16.80**	95.63	81.46	78.33	39.50	**73.47**
	Aver. for all Inertia (w)	1	0.15	13.60	11.79	11.58	35.85	**18.20**	93.15	76.31	75.54	33.07	**69.52**
		2	0.02	13.41	11.24	11.14	34.76	**17.64**	98.27	81.10	77.32	36.33	**73.26**
		3	0.02	13.40	10.91	10.74	33.85	**17.23**	98.54	83.72	78.18	39.26	**74.93**
		4	0.04	13.43	10.90	10.41	32.99	**16.93**	97.35	82.47	78.42	40.26	**74.63**
		5	0.07	13.49	10.99	10.40	32.72	**16.90**	95.68	80.89	77.98	39.26	**73.45**
		6	0.07	13.49	10.98	10.33	32.41	**16.80**	95.45	80.39	78.13	39.19	**73.29**
		7	0.09	13.51	11.01	10.32	32.33	**16.79**	94.88	80.18	78.13	39.19	**73.09**
		8	0.10	13.52	11.01	10.33	32.35	**16.80**	94.73	80.18	77.92	39.17	**73.00**
		9	0.10	13.53	11.00	10.34	32.39	**16.81**	94.26	80.42	77.92	39.26	**72.96**
		10	0.10	13.53	10.98	10.34	32.45	**16.83**	94.29	80.65	77.77	38.95	**72.92**

Table C.24: RCPSP test results for DDPSO under different topologies & different values for Inertia (w) (50,000 schedules – 20 forward/ 20 backward particles – GR=0.75)

N_{Sch}	w	DD Range	AD_O	AD_{CP}					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
50,000 Schedules (20F/20B Particles) (GR=0.5)	0.0	1	0.04	13.44	11.52	11.31	35.20	**17.87**	97.71	78.33	76.88	35.17	**72.02**
		2	0.02	13.40	11.18	11.01	34.46	**17.51**	98.75	81.88	77.50	37.33	**73.86**
		3	0.02	13.40	10.93	10.63	33.58	**17.14**	98.75	82.92	78.54	39.33	**74.89**
		4	0.02	13.40	10.92	10.40	32.84	**16.89**	98.75	82.08	78.33	40.17	**74.83**
		5	0.07	13.49	10.95	10.33	32.45	**16.81**	96.04	80.42	78.13	40.67	**73.81**
		6	0.11	13.54	10.94	10.33	32.34	**16.79**	93.96	80.63	78.75	39.17	**73.13**
		7	0.11	13.55	10.98	10.33	32.37	**16.81**	94.38	80.21	77.92	39.67	**73.04**
		8	0.09	13.50	10.97	10.33	32.45	**16.81**	95.42	80.42	78.75	39.67	**73.56**
		9	0.11	13.54	10.99	10.34	32.47	**16.83**	93.75	79.79	77.29	39.33	**72.54**
		10	0.10	13.52	10.96	10.34	32.49	**16.83**	94.38	81.46	77.92	39.17	**73.23**
	0.1	1	0.04	13.43	11.45	11.36	35.39	**17.91**	97.50	78.75	76.88	34.67	**71.95**
		2	0.02	13.40	11.17	11.07	34.63	**17.57**	98.75	81.46	77.50	37.00	**73.68**
		3	0.02	13.40	10.85	10.62	33.63	**17.13**	98.75	83.54	78.96	39.67	**75.23**
		4	0.03	13.41	10.88	10.35	32.78	**16.86**	98.13	82.08	78.75	39.33	**74.57**
		5	0.06	13.46	10.91	10.33	32.45	**16.79**	96.25	82.08	77.92	39.17	**73.85**
		6	0.08	13.51	10.94	10.28	32.41	**16.78**	95.42	80.83	78.13	39.67	**73.51**
		7	0.06	13.47	10.96	10.31	32.36	**16.77**	96.67	80.63	77.71	39.50	**73.63**
		8	0.08	13.51	11.00	10.30	32.41	**16.80**	95.21	80.83	78.33	39.17	**73.39**
		9	0.10	13.52	10.95	10.36	32.51	**16.83**	94.38	80.83	77.92	38.67	**72.95**
		10	0.10	13.53	10.98	10.30	32.52	**16.83**	93.96	81.04	77.92	40.00	**73.23**
	0.2	1	0.05	13.44	11.50	11.34	35.39	**17.92**	96.67	78.13	76.88	34.17	**71.46**
		2	0.01	13.39	11.17	11.10	34.73	**17.60**	99.17	81.88	77.71	36.33	**73.77**
		3	0.02	13.40	10.90	10.63	33.74	**17.17**	98.75	83.75	78.33	40.17	**75.25**
		4	0.03	13.42	10.86	10.37	32.92	**16.90**	97.71	83.54	78.75	40.17	**75.04**
		5	0.07	13.49	10.90	10.29	32.35	**16.76**	95.83	82.08	78.33	40.83	**74.27**
		6	0.07	13.49	10.95	10.31	32.38	**16.78**	95.21	81.46	78.13	39.83	**73.66**
		7	0.09	13.52	10.93	10.28	32.34	**16.77**	94.79	82.29	78.54	38.67	**73.57**
		8	0.11	13.54	10.97	10.33	32.42	**16.82**	93.75	80.00	78.13	40.00	**72.97**
		9	0.11	13.55	10.99	10.33	32.42	**16.82**	93.96	80.00	78.13	39.83	**72.98**
		10	0.11	13.55	10.96	10.35	32.50	**16.84**	93.96	80.42	78.13	40.33	**73.21**
	0.3	1	0.06	13.47	11.56	11.46	35.54	**18.01**	96.04	77.71	76.25	33.33	**70.83**
		2	0.02	13.40	11.25	11.14	34.83	**17.65**	98.54	80.21	77.29	36.00	**73.01**
		3	0.03	13.41	10.84	10.71	33.90	**17.21**	98.13	84.38	78.96	39.50	**75.24**
		4	0.04	13.44	10.81	10.44	32.97	**16.92**	97.29	83.54	78.13	40.50	**74.86**
		5	0.07	13.47	10.89	10.31	32.52	**16.80**	95.63	83.33	78.96	39.50	**74.35**
		6	0.08	13.49	10.97	10.31	32.31	**16.77**	95.63	80.42	78.96	39.33	**73.58**
		7	0.09	13.51	10.94	10.32	32.35	**16.78**	95.42	80.21	77.71	39.83	**73.29**
		8	0.11	13.54	10.96	10.33	32.43	**16.82**	94.17	80.63	78.13	39.17	**73.02**
		9	0.11	13.54	11.02	10.34	32.40	**16.83**	94.58	79.79	77.92	40.00	**73.07**
		10	0.09	13.51	10.95	10.34	32.45	**16.81**	95.00	80.83	77.92	38.83	**73.15**
	0.4	1	0.11	13.54	11.70	11.55	35.76	**18.14**	93.96	76.04	76.25	33.33	**69.90**
		2	0.02	13.41	11.27	11.17	34.89	**17.68**	98.33	81.25	77.08	35.67	**73.08**
		3	0.01	13.39	10.92	10.75	34.06	**17.28**	98.96	83.54	78.33	39.33	**75.04**
		4	0.01	13.39	10.80	10.40	33.09	**16.92**	98.96	84.58	78.13	40.33	**75.50**
		5	0.07	13.48	10.85	10.31	32.53	**16.79**	96.04	82.29	78.54	40.17	**74.26**
		6	0.08	13.49	10.92	10.30	32.41	**16.78**	95.63	81.67	78.54	39.50	**73.83**
		7	0.07	13.49	10.95	10.28	32.33	**16.76**	95.42	80.42	78.13	39.67	**73.41**
		8	0.08	13.50	10.95	10.32	32.40	**16.79**	95.00	80.83	77.29	38.67	**72.95**
		9	0.11	13.53	10.96	10.33	32.44	**16.82**	94.17	80.63	77.50	39.83	**73.03**
		10	0.10	13.53	10.93	10.34	32.51	**16.83**	94.58	80.83	77.71	39.33	**73.11**

		#											
	0.5	1	0.38	13.93	12.16	11.91	36.65	**18.66**	84.17	73.96	73.33	30.33	**65.45**
		2	0.01	13.39	11.30	11.21	34.94	**17.71**	98.96	80.21	77.08	35.83	**73.02**
		3	0.02	13.40	10.97	10.85	34.19	**17.35**	98.75	83.13	78.13	39.50	**74.88**
		4	0.02	13.41	10.82	10.45	33.22	**16.97**	98.33	82.50	78.33	39.83	**74.75**
		5	0.04	13.43	10.88	10.31	32.56	**16.79**	97.50	82.29	78.75	40.17	**74.68**
		6	0.05	13.46	10.95	10.33	32.43	**16.79**	96.67	81.88	78.75	39.83	**74.28**
		7	0.08	13.49	10.96	10.30	32.41	**16.79**	95.63	81.04	77.71	40.67	**73.76**
		8	0.07	13.47	10.95	10.32	32.33	**16.77**	96.25	80.63	77.92	39.50	**73.57**
		9	0.10	13.53	10.97	10.30	32.46	**16.81**	93.96	80.63	78.54	39.33	**73.11**
		10	0.11	13.55	10.98	10.32	32.51	**16.84**	93.75	80.42	77.50	39.00	**72.67**
	0.6	1	0.52	14.15	12.60	12.25	37.17	**19.04**	79.58	72.50	72.50	29.17	**63.44**
		2	0.02	13.41	11.36	11.25	35.09	**17.78**	98.54	79.58	76.67	34.83	**72.41**
		3	0.02	13.41	10.99	10.88	34.21	**17.37**	98.33	82.29	77.92	38.00	**74.14**
		4	0.02	13.41	10.80	10.53	33.37	**17.03**	98.54	85.00	78.33	40.33	**75.55**
		5	0.04	13.44	10.88	10.33	32.63	**16.82**	97.50	83.13	79.17	40.67	**75.11**
		6	0.06	13.47	10.89	10.29	32.46	**16.78**	96.04	82.92	78.96	40.00	**74.48**
		7	0.09	13.50	10.93	10.30	32.40	**16.78**	95.21	82.08	77.92	39.50	**73.68**
		8	0.09	13.51	10.93	10.31	32.39	**16.79**	94.79	81.25	77.71	39.83	**73.40**
		9	0.10	13.52	10.98	10.33	32.43	**16.82**	94.58	80.83	77.50	39.67	**73.15**
		10	0.10	13.52	10.96	10.33	32.50	**16.83**	93.96	80.42	78.75	39.50	**73.16**

		#											
50,000 Schedules (20F/20B Particles) (GR=0.5)	Best Inertia (w)	1	0.04	13.43	11.45	11.31	35.20	**17.87**	97.71	78.75	76.88	35.17	**72.02**
		2	0.01	13.39	11.17	11.01	34.46	**17.51**	99.17	81.88	77.71	37.33	**73.86**
		3	0.01	13.39	10.84	10.62	33.58	**17.13**	98.96	84.38	78.96	40.17	**75.25**
		4	0.01	13.39	10.80	10.35	32.78	**16.86**	98.96	85.00	78.75	40.50	**75.55**
		5	0.04	13.43	10.85	10.29	32.35	**16.76**	97.50	83.33	79.17	40.83	**75.11**
		6	0.05	13.46	10.89	10.28	32.31	**16.77**	96.67	82.92	78.96	40.00	**74.48**
		7	0.06	13.47	10.93	10.28	32.33	**16.76**	96.67	82.29	78.54	40.67	**73.76**
		8	0.07	13.47	10.93	10.30	32.33	**16.77**	96.25	81.25	78.75	40.00	**73.57**
		9	0.10	13.52	10.95	10.30	32.40	**16.81**	94.58	80.83	78.54	40.00	**73.15**
		10	0.09	13.51	10.93	10.30	32.45	**16.81**	95.00	81.46	78.75	40.33	**73.23**
	Aver. for all Inertia (w)	1	0.17	13.63	11.78	11.60	35.87	**18.22**	92.23	76.49	75.57	32.88	**69.29**
		2	0.02	13.40	11.24	11.13	34.80	**17.64**	98.72	80.92	77.26	36.14	**73.26**
		3	0.02	13.40	10.92	10.73	33.90	**17.24**	98.63	83.36	78.45	39.36	**74.95**
		4	0.03	13.41	10.84	10.42	33.03	**16.93**	98.24	83.33	78.39	40.10	**75.02**
		5	0.06	13.47	10.90	10.31	32.50	**16.79**	96.40	82.23	78.54	40.17	**74.33**
		6	0.08	13.49	10.94	10.31	32.39	**16.78**	95.51	81.40	78.60	39.62	**73.78**
		7	0.08	13.50	10.95	10.30	32.37	**16.78**	95.36	80.98	77.95	39.64	**73.48**
		8	0.09	13.51	10.96	10.32	32.40	**16.80**	94.94	80.65	78.04	39.43	**73.26**
		9	0.11	13.53	10.98	10.33	32.45	**16.82**	94.20	80.36	77.83	39.52	**72.98**
		10	0.10	13.53	10.96	10.33	32.50	**16.83**	94.23	80.77	77.98	39.45	**73.11**

Table C.25: RCPSP test results for DDPSO under different topologies & different values for Inertia (w) (50,000 schedules – 20 forward/ 20 backward particles – GR=0.5)

N$_{Sch}$	w	DD Range	AD$_O$	AD$_{CP}$					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
50,000 Schedules (20F/20B Particles) (GR=0.25)	0.0	1	0.05	13.45	11.54	11.36	35.32	**17.92**	97.08	78.54	76.25	33.67	**71.39**
		2	0.01	13.39	11.21	11.07	34.61	**17.57**	99.17	81.25	77.71	37.00	**73.78**
		3	0.02	13.41	10.90	10.66	33.63	**17.15**	98.33	84.58	78.33	39.17	**75.10**
		4	0.04	13.44	10.87	10.37	32.79	**16.87**	97.29	82.29	78.54	41.17	**74.82**
		5	0.05	13.45	10.83	10.32	32.47	**16.77**	97.50	82.92	78.54	39.83	**74.70**
		6	0.07	13.49	10.88	10.31	32.41	**16.77**	95.83	81.88	78.54	39.67	**73.98**
		7	0.07	13.48	10.96	10.32	32.45	**16.81**	95.83	80.83	77.92	40.50	**73.77**
		8	0.06	13.48	10.93	10.34	32.48	**16.81**	96.04	81.88	77.50	39.67	**73.77**
		9	0.09	13.51	10.94	10.33	32.55	**16.83**	94.38	80.83	78.54	39.50	**73.31**
		10	0.10	13.53	10.98	10.36	32.56	**16.86**	93.96	80.63	78.54	39.17	**73.07**
	0.1	1	0.04	13.43	11.49	11.38	35.34	**17.91**	97.29	77.92	76.67	34.00	**71.47**
		2	0.02	13.40	11.18	11.11	34.67	**17.59**	98.54	81.46	77.29	37.50	**73.70**
		3	0.02	13.40	10.89	10.63	33.67	**17.15**	98.54	83.75	78.13	39.50	**74.98**
		4	0.03	13.42	10.88	10.38	32.82	**16.88**	97.92	82.92	79.58	40.67	**75.27**
		5	0.05	13.45	10.85	10.26	32.48	**16.76**	96.88	82.50	78.13	40.50	**74.50**
		6	0.06	13.47	10.87	10.30	32.36	**16.75**	96.25	81.25	78.96	40.50	**74.24**
		7	0.07	13.48	10.92	10.32	32.48	**16.80**	96.04	80.83	78.13	39.67	**73.67**
		8	0.08	13.50	10.93	10.35	32.40	**16.79**	95.21	82.08	77.92	39.50	**73.68**
		9	0.08	13.50	10.92	10.36	32.49	**16.82**	94.79	81.67	77.71	39.33	**73.38**
		10	0.07	13.49	10.96	10.34	32.55	**16.83**	96.04	80.42	77.71	39.00	**73.29**
	0.2	1	0.05	13.45	11.50	11.38	35.39	**17.93**	96.67	77.92	76.46	33.67	**71.18**
		2	0.01	13.39	11.19	11.10	34.76	**17.61**	98.96	81.67	77.29	36.17	**73.52**
		3	0.01	13.39	10.88	10.67	33.75	**17.17**	98.96	84.79	78.33	40.17	**75.56**
		4	0.03	13.42	10.84	10.39	32.92	**16.89**	97.92	83.13	78.75	40.50	**75.07**
		5	0.05	13.45	10.80	10.32	32.53	**16.77**	97.08	83.75	78.13	40.00	**74.74**
		6	0.06	13.46	10.90	10.31	32.39	**16.77**	96.25	81.88	78.33	40.00	**74.11**
		7	0.06	13.47	10.90	10.31	32.43	**16.78**	96.46	81.67	77.71	40.67	**74.13**
		8	0.08	13.49	10.94	10.37	32.43	**16.81**	95.21	80.83	77.92	40.33	**73.57**
		9	0.08	13.49	10.91	10.37	32.53	**16.83**	95.63	82.08	77.92	39.83	**73.86**
		10	0.07	13.49	10.93	10.33	32.58	**16.83**	95.63	81.04	78.75	39.83	**73.81**
	0.3	1	0.06	13.47	11.55	11.43	35.53	**17.99**	96.25	77.71	76.88	33.83	**71.17**
		2	0.02	13.40	11.19	11.14	34.79	**17.63**	98.75	81.46	77.50	35.83	**73.39**
		3	0.02	13.40	10.89	10.74	33.90	**17.23**	98.75	83.96	78.33	39.33	**75.09**
		4	0.04	13.43	10.82	10.40	32.99	**16.91**	97.50	83.13	79.38	41.00	**75.25**
		5	0.06	13.46	10.86	10.34	32.51	**16.79**	96.25	82.71	77.92	40.83	**74.43**
		6	0.04	13.44	10.89	10.29	32.44	**16.77**	97.08	81.67	78.75	39.50	**74.25**
		7	0.06	13.46	10.86	10.30	32.45	**16.77**	96.46	81.88	77.92	40.50	**74.19**
		8	0.07	13.48	10.91	10.32	32.45	**16.79**	95.63	82.50	78.13	40.17	**74.10**
		9	0.09	13.51	10.93	10.35	32.45	**16.81**	94.79	81.88	78.13	40.17	**73.74**
		10	0.07	13.47	10.94	10.35	32.52	**16.82**	95.63	81.46	78.33	40.83	**74.06**
	0.4	1	0.09	13.51	11.68	11.55	35.84	**18.15**	95.21	76.88	76.25	33.00	**70.33**
		2	0.04	13.43	11.22	11.19	34.90	**17.68**	97.71	80.63	76.88	36.00	**72.80**
		3	0.01	13.39	10.90	10.78	33.97	**17.26**	98.96	84.79	78.13	39.67	**75.39**
		4	0.02	13.40	10.79	10.42	33.06	**16.92**	98.33	83.75	78.54	40.67	**75.32**
		5	0.04	13.43	10.85	10.31	32.58	**16.80**	97.08	82.50	78.96	40.33	**74.72**
		6	0.05	13.44	10.86	10.28	32.48	**16.77**	96.88	82.50	78.54	40.00	**74.48**
		7	0.07	13.48	10.90	10.30	32.41	**16.77**	96.04	82.08	78.75	39.83	**74.18**
		8	0.06	13.46	10.90	10.30	32.44	**16.77**	96.25	80.21	77.92	40.00	**73.59**
		9	0.08	13.49	10.91	10.31	32.47	**16.80**	95.42	81.04	78.33	40.50	**73.82**
		10	0.07	13.48	10.95	10.35	32.55	**16.83**	95.42	81.04	77.92	38.83	**73.30**

	0.5	1	0.33	13.87	12.15	11.92	36.60	**18.63**	86.25	73.75	73.13	30.50	**65.91**
		2	0.03	13.42	11.32	11.22	34.99	**17.74**	97.92	80.00	76.88	35.33	**72.53**
		3	0.02	13.40	10.94	10.84	34.15	**17.33**	98.75	83.33	78.33	39.00	**74.85**
		4	0.01	13.39	10.81	10.42	33.24	**16.97**	98.96	84.38	78.96	40.67	**75.74**
		5	0.03	13.41	10.83	10.34	32.62	**16.80**	98.13	83.33	78.54	40.83	**75.21**
		6	0.05	13.46	10.85	10.27	32.41	**16.75**	96.88	82.71	78.96	40.00	**74.64**
		7	0.06	13.46	10.87	10.31	32.41	**16.76**	96.04	82.71	78.75	39.67	**74.29**
		8	0.05	13.45	10.90	10.30	32.39	**16.76**	96.67	81.67	78.13	39.83	**74.07**
		9	0.06	13.47	10.94	10.33	32.47	**16.80**	96.46	81.88	78.33	39.67	**74.08**
		10	0.08	13.50	10.94	10.32	32.48	**16.81**	95.21	81.88	78.13	39.33	**73.64**
	0.6	1	0.42	14.00	12.47	12.16	37.19	**18.95**	82.71	73.13	73.13	29.50	**64.61**
		2	0.03	13.42	11.41	11.28	35.12	**17.81**	97.50	78.96	77.08	35.00	**72.14**
		3	0.01	13.39	10.96	10.86	34.27	**17.37**	98.96	84.58	78.13	38.67	**75.08**
		4	0.03	13.41	10.77	10.46	33.32	**16.99**	98.13	85.83	78.75	40.50	**75.80**
		5	0.05	13.45	10.83	10.31	32.45	**16.76**	96.67	82.71	78.54	40.50	**74.60**
		6	0.04	13.43	10.82	10.34	32.73	**16.83**	97.71	84.79	78.54	39.33	**75.09**
		7	0.06	13.46	10.87	10.26	32.37	**16.74**	96.25	82.29	79.17	40.50	**74.55**
		8	0.04	13.44	10.91	10.30	32.41	**16.76**	97.29	82.92	78.13	39.33	**74.42**
		9	0.06	13.46	10.93	10.32	32.45	**16.79**	96.04	81.25	78.13	40.00	**73.85**
		10	0.06	13.47	10.91	10.31	32.53	**16.81**	96.04	82.29	78.33	40.67	**74.33**

50,000 Schedules (20F/20B Particles) (GR=0.25)	Best Inertia (w)	1	0.04	13.43	11.49	11.36	35.32	**17.91**	97.29	78.54	76.88	34.00	**71.47**
		2	0.01	13.39	11.18	11.07	34.61	**17.57**	99.17	81.67	77.71	37.50	**73.78**
		3	0.01	13.39	10.88	10.63	33.63	**17.15**	98.96	84.79	78.33	40.17	**75.56**
		4	0.01	13.39	10.77	10.37	32.79	**16.87**	98.96	85.83	79.58	41.17	**75.80**
		5	0.03	13.41	10.80	10.26	32.45	**16.76**	98.13	83.75	78.96	40.83	**75.21**
		6	0.04	13.43	10.82	10.27	32.36	**16.75**	97.71	84.79	78.96	40.50	**75.09**
		7	0.06	13.46	10.86	10.26	32.37	**16.74**	96.46	82.71	79.17	40.67	**74.55**
		8	0.04	13.44	10.90	10.30	32.39	**16.76**	97.29	82.92	78.13	40.33	**74.42**
		9	0.06	13.46	10.91	10.31	32.45	**16.79**	96.46	82.08	78.54	40.50	**74.08**
		10	0.06	13.47	10.91	10.31	32.48	**16.81**	96.04	82.29	78.75	40.83	**74.33**
	Aver. for all Inertia (w)	1	0.15	13.60	11.77	11.60	35.89	**18.21**	93.07	76.55	75.54	32.60	**69.44**
		2	0.02	13.41	11.25	11.16	34.83	**17.66**	98.36	80.77	77.23	36.12	**73.12**
		3	0.02	13.40	10.91	10.74	33.91	**17.24**	98.75	84.26	78.24	39.36	**75.15**
		4	0.03	13.42	10.83	10.40	33.02	**16.92**	98.01	83.63	78.93	40.74	**75.33**
		5	0.05	13.44	10.84	10.31	32.52	**16.78**	97.08	82.92	78.39	40.40	**74.70**
		6	0.05	13.46	10.87	10.30	32.46	**16.77**	96.70	82.38	78.66	39.86	**74.40**
		7	0.06	13.47	10.90	10.30	32.43	**16.77**	96.16	81.76	78.33	40.19	**74.11**
		8	0.06	13.47	10.92	10.33	32.43	**16.79**	96.04	81.73	77.95	39.83	**73.89**
		9	0.08	13.49	10.93	10.34	32.49	**16.81**	95.36	81.52	78.15	39.86	**73.72**
		10	0.07	13.49	10.94	10.34	32.54	**16.83**	95.42	81.25	78.24	39.67	**73.64**

Table C.26: RCPSP test results for DDPSO under different topologies & different values for Inertia (w) (50,000 schedules – 20 forward/ 20 backward particles – GR=0.25)

N_{Sch}	w	DD Range	AD_O	AD_{CP}					Problems Solved to Optimality				
			j-30	j-30	j-60	j-90	j-120	Aver.	j-30	j-60	j-90	j-120	Aver.
50,000 Schedules (20F/20B Particles) (GR=0.0)	0.0	1	0.05	13.45	11.59	11.42	35.52	**17.99**	97.08	78.33	76.88	33.83	**71.53**
		2	0.02	13.41	11.24	11.12	34.73	**17.63**	98.13	81.04	77.08	36.83	**73.27**
		3	0.02	13.40	10.96	10.66	33.70	**17.18**	98.54	83.33	77.92	39.50	**74.82**
		4	0.04	13.43	10.96	10.46	33.00	**16.96**	97.50	82.92	78.54	39.83	**74.70**
		5	0.08	13.50	10.99	10.41	32.66	**16.89**	95.00	81.04	77.92	39.17	**73.28**
		6	0.09	13.52	11.04	10.41	32.59	**16.89**	94.58	81.46	77.71	38.50	**73.06**
		7	0.12	13.56	10.99	10.39	32.61	**16.89**	93.54	80.42	77.71	38.00	**72.42**
		8	0.11	13.55	11.03	10.40	32.64	**16.90**	93.54	80.00	77.50	38.17	**72.30**
		9	0.15	13.61	11.04	10.40	32.65	**16.92**	92.92	79.58	78.13	39.00	**72.41**
		10	0.15	13.61	11.03	10.45	32.65	**16.93**	91.67	80.00	77.71	39.33	**72.18**
	0.1	1	0.03	13.42	11.51	11.40	35.39	**17.93**	97.92	78.75	76.46	33.83	**71.74**
		2	0.02	13.40	11.18	11.10	34.70	**17.59**	98.75	81.46	77.29	37.67	**73.79**
		3	0.02	13.39	10.93	10.71	33.69	**17.18**	98.96	82.50	78.13	39.67	**74.81**
		4	0.03	13.42	10.95	10.47	32.94	**16.95**	97.71	80.63	78.33	38.83	**73.88**
		5	0.07	13.48	10.96	10.38	32.60	**16.85**	95.63	81.67	78.54	39.67	**73.88**
		6	0.10	13.53	11.00	10.42	32.60	**16.89**	93.33	81.04	77.29	38.83	**72.63**
		7	0.10	13.54	11.00	10.37	32.54	**16.86**	93.54	82.08	77.71	38.83	**73.04**
		8	0.13	13.58	11.02	10.39	32.64	**16.91**	92.29	81.04	77.71	38.67	**72.43**
		9	0.11	13.55	11.05	10.43	32.63	**16.91**	94.38	80.21	77.71	38.33	**72.66**
		10	0.14	13.61	11.04	10.39	32.66	**16.93**	92.29	80.42	78.33	38.17	**72.30**
	0.2	1	0.04	13.44	11.57	11.43	35.47	**17.98**	96.88	77.29	76.67	34.00	**71.21**
		2	0.02	13.40	11.21	11.09	34.74	**17.61**	98.54	81.67	77.29	36.50	**73.50**
		3	0.02	13.40	10.94	10.70	33.78	**17.20**	98.75	82.71	78.33	39.50	**74.82**
		4	0.04	13.43	10.92	10.45	32.95	**16.94**	97.71	82.92	77.92	39.33	**74.47**
		5	0.05	13.45	10.93	10.43	32.68	**16.87**	96.88	82.08	77.92	38.17	**73.76**
		6	0.09	13.51	10.98	10.39	32.52	**16.85**	94.58	80.42	78.13	39.50	**73.16**
		7	0.10	13.52	11.01	10.43	32.56	**16.88**	94.17	80.63	77.50	38.50	**72.70**
		8	0.13	13.57	11.01	10.40	32.55	**16.89**	92.92	80.63	77.71	38.33	**72.40**
		9	0.10	13.53	11.04	10.39	32.61	**16.89**	93.96	80.00	77.92	38.67	**72.64**
		10	0.12	13.56	11.04	10.41	32.65	**16.91**	93.75	80.63	77.50	38.50	**72.59**
	0.3	1	0.07	13.48	11.57	11.46	35.56	**18.02**	95.83	77.08	76.04	33.33	**70.57**
		2	0.02	13.40	11.20	11.13	34.79	**17.63**	98.54	81.67	77.50	36.17	**73.47**
		3	0.01	13.39	10.95	10.74	33.88	**17.24**	98.96	83.75	78.54	38.83	**75.02**
		4	0.04	13.43	10.93	10.45	33.05	**16.96**	97.71	82.50	78.13	40.00	**74.58**
		5	0.06	13.46	10.92	10.39	32.67	**16.86**	96.46	83.96	78.54	40.00	**74.74**
		6	0.08	13.50	10.96	10.41	32.54	**16.85**	95.21	81.04	77.92	39.17	**73.33**
		7	0.10	13.52	11.00	10.39	32.57	**16.87**	94.79	80.63	78.33	39.17	**73.23**
		8	0.12	13.56	11.00	10.38	32.60	**16.89**	93.54	80.42	77.71	38.67	**72.58**
		9	0.11	13.55	11.00	10.40	32.61	**16.89**	93.75	80.63	77.71	38.67	**72.69**
		10	0.14	13.60	11.04	10.37	32.65	**16.92**	92.50	80.21	78.13	38.67	**72.38**
	0.4	1	0.11	13.55	11.72	11.57	35.86	**18.17**	94.38	75.83	75.83	32.67	**69.68**
		2	0.02	13.40	11.28	11.18	34.95	**17.70**	98.54	80.42	76.88	35.83	**72.92**
		3	0.01	13.39	10.92	10.77	34.03	**17.28**	99.17	83.54	78.33	38.50	**74.89**
		4	0.02	13.41	10.91	10.45	33.14	**16.98**	98.33	82.29	78.33	40.17	**74.78**
		5	0.05	13.45	10.95	10.36	32.70	**16.86**	97.08	82.71	77.92	39.83	**74.39**
		6	0.07	13.48	10.93	10.39	32.61	**16.85**	95.83	81.67	78.33	39.17	**73.75**
		7	0.11	13.54	10.97	10.42	32.55	**16.87**	93.96	82.08	77.71	39.00	**73.19**
		8	0.12	13.55	11.01	10.41	32.54	**16.88**	93.75	80.42	77.92	39.17	**72.81**
		9	0.12	13.56	11.05	10.37	32.60	**16.90**	93.13	80.42	77.71	38.67	**72.48**
		10	0.13	13.59	11.03	10.41	32.58	**16.90**	92.92	81.04	77.29	38.50	**72.44**

		#											
50,000 Schedules (20F/20B Particles) (GR=0.0)	0.5	1	0.34	13.89	12.17	12.00	36.57	18.66	85.21	74.17	73.33	30.50	65.80
		2	0.03	13.42	11.28	11.23	34.95	17.72	97.71	79.38	76.88	36.33	72.57
		3	0.01	13.39	10.96	10.85	34.17	17.34	99.17	83.75	78.33	38.50	74.94
		4	0.02	13.41	10.84	10.53	33.26	17.01	98.33	83.75	78.54	40.00	75.16
		5	0.03	13.42	10.90	10.37	32.77	16.87	97.92	82.50	78.13	40.00	74.64
		6	0.07	13.49	10.96	10.38	32.64	16.87	95.83	80.83	78.33	39.83	73.71
		7	0.07	13.49	10.99	10.39	32.58	16.86	95.21	82.29	77.71	38.83	73.51
		8	0.12	13.56	11.03	10.41	32.52	16.88	93.75	80.21	77.92	38.83	72.68
		9	0.10	13.54	11.01	10.40	32.57	16.88	93.96	80.63	77.71	39.50	72.95
		10	0.12	13.56	11.03	10.45	32.67	16.93	93.54	79.38	77.29	38.67	72.22
	0.6	1	0.51	14.13	12.61	12.24	37.26	19.06	80.21	72.92	72.71	29.00	63.71
		2	0.04	13.43	11.39	11.29	35.13	17.81	97.50	79.79	76.88	35.50	72.42
		3	0.02	13.40	11.00	10.89	34.29	17.40	98.75	83.75	77.92	38.83	74.81
		4	0.01	13.39	10.88	10.57	33.38	17.05	99.17	83.33	78.54	39.33	75.09
		5	0.03	13.41	10.92	10.42	32.87	16.90	98.33	82.92	77.92	40.17	74.83
		6	0.05	13.46	10.94	10.38	32.63	16.85	97.08	82.71	77.71	39.00	74.13
		7	0.09	13.53	10.98	10.41	32.54	16.86	94.38	80.83	78.13	39.50	73.21
		8	0.10	13.53	10.99	10.37	32.53	16.86	94.58	81.25	77.50	39.67	73.25
		9	0.12	13.56	10.97	10.41	32.62	16.89	93.13	81.04	77.50	38.67	72.58
		10	0.13	13.58	11.05	10.42	32.61	16.91	92.71	79.38	77.29	39.00	72.09
	Best Inertia (w)	1	0.03	13.42	11.51	11.40	35.39	17.93	97.92	78.75	76.88	34.00	71.74
		2	0.02	13.40	11.18	11.09	34.70	17.59	98.75	81.67	77.50	37.67	73.79
		3	0.01	13.39	10.92	10.66	33.69	17.18	99.17	83.75	78.54	39.67	75.02
		4	0.01	13.39	10.84	10.45	32.94	16.94	99.17	83.75	78.54	40.17	75.16
		5	0.03	13.41	10.90	10.36	32.60	16.85	98.33	83.96	78.54	40.17	74.83
		6	0.05	13.46	10.93	10.38	32.52	16.85	97.08	82.71	78.33	39.83	74.13
		7	0.07	13.49	10.97	10.37	32.54	16.86	95.21	82.29	78.33	39.50	73.51
		8	0.10	13.53	10.99	10.37	32.52	16.86	94.58	81.25	77.92	39.67	73.25
		9	0.10	13.53	10.97	10.37	32.57	16.88	94.38	81.04	78.13	39.50	72.95
		10	0.12	13.56	11.03	10.37	32.58	16.90	93.75	81.04	78.33	39.33	72.59
	Aver. for all Inertia (w)	1	0.16	13.62	11.82	11.64	35.95	18.26	92.50	76.34	75.42	32.45	69.18
		2	0.02	13.41	11.25	11.16	34.86	17.67	98.24	80.77	77.11	36.40	73.13
		3	0.02	13.39	10.95	10.76	33.94	17.26	98.90	83.33	78.21	39.05	74.87
		4	0.03	13.42	10.91	10.48	33.10	16.98	98.07	82.62	78.33	39.64	74.67
		5	0.05	13.45	10.94	10.39	32.71	16.87	96.76	82.41	78.13	39.57	74.22
		6	0.08	13.50	10.97	10.40	32.59	16.86	95.21	81.31	77.92	39.14	73.39
		7	0.10	13.53	10.99	10.40	32.56	16.87	94.23	81.28	77.83	38.83	73.04
		8	0.12	13.56	11.01	10.40	32.58	16.89	93.48	80.57	77.71	38.79	72.64
		9	0.12	13.56	11.02	10.40	32.61	16.90	93.60	80.36	77.77	38.79	72.63
		10	0.13	13.58	11.04	10.41	32.64	16.92	92.77	80.15	77.65	38.69	72.31

Table C.27: RCPSP test results for DDPSO under different topologies & different values for Inertia (w) (50,000 schedules – 20 forward/ 20 backward particles – GR=0.0)

N_{Sch}	Topology	Density Range	Average Cost Saving (ACS)				Problems Solved to Optimality			
			j-10	j-20	j-30	Aver.	j-10	j-20	j-30	Aver.
1,000 Schedules (10F/10B Particles)	gBest (GR=1.0)	SPSO	37.13	47.31	52.46	**45.64**	88.89	61.48	52.22	**67.53**
		R01	37.14	47.24	52.39	**45.59**	88.89	61.85	49.26	**66.67**
		R02	37.13	47.33	52.40	**45.62**	88.52	62.22	50.00	**66.91**
		R03	37.21	47.18	52.44	**45.61**	90.00	58.15	51.48	**66.54**
		R04	37.19	47.21	52.50	**45.63**	90.74	58.89	51.85	**67.16**
		R05	37.17	47.23	52.40	**45.60**	88.52	58.15	51.11	**65.93**
	GR=0.75	SPSO	37.11	47.22	52.42	**45.59**	88.15	58.15	50.00	**65.43**
		R01	37.22	47.07	52.44	**45.58**	89.63	58.89	52.22	**66.91**
		R02	37.19	47.12	52.39	**45.57**	89.63	60.00	50.37	**66.67**
		R03	37.19	47.19	52.51	**45.63**	89.26	56.67	51.85	**65.93**
		R04	37.15	47.19	52.38	**45.57**	88.15	59.63	50.74	**66.17**
		R05	37.11	47.13	52.50	**45.58**	89.63	58.89	51.11	**66.54**
	GR=0.5	SPSO	37.19	47.21	52.43	**45.61**	90.00	59.26	50.74	**66.67**
		R01	37.15	47.23	52.46	**45.61**	89.26	59.26	50.37	**66.30**
		R02	37.22	47.28	52.48	**45.66**	90.00	62.22	51.85	**68.02**
		R03	37.16	47.36	52.45	**45.66**	89.26	62.22	51.48	**67.65**
		R04	37.16	47.25	52.39	**45.60**	90.00	60.00	49.26	**66.42**
		R05	37.11	47.30	52.36	**45.59**	89.26	60.00	50.37	**66.54**
	GR=0.25	SPSO	37.18	47.18	52.36	**45.58**	88.89	58.52	50.37	**65.93**
		R01	37.16	47.13	52.39	**45.56**	89.26	58.15	49.63	**65.68**
		R02	37.23	47.27	52.45	**45.65**	90.00	60.37	50.74	**67.04**
		R03	37.17	47.11	52.39	**45.56**	90.00	58.15	50.37	**66.17**
		R04	37.08	47.26	52.41	**45.59**	88.15	60.74	50.37	**66.42**
		R05	37.20	47.18	52.46	**45.61**	90.00	57.04	51.85	**66.30**
	lBest (GR=0.0)	SPSO	37.14	47.24	52.46	**45.61**	89.63	60.74	51.11	**67.16**
		R01	37.16	47.06	52.39	**45.54**	89.26	58.15	50.74	**66.05**
		R02	37.15	47.20	52.37	**45.57**	90.00	58.89	50.74	**66.54**
		R03	37.13	47.29	52.44	**45.62**	88.52	60.74	51.48	**66.91**
		R04	37.14	47.15	52.46	**45.58**	89.26	57.41	51.48	**66.05**
		R05	37.11	47.15	52.47	**45.58**	88.52	59.26	50.37	**66.05**
5,000 Schedules (10F/10B Particles)	gBest (GR=1.0)	SPSO	37.16	47.38	52.44	**45.66**	88.89	60.74	52.22	**67.28**
		R01	37.23	47.33	52.56	**45.71**	89.63	61.85	53.70	**68.40**
		R02	37.21	47.22	52.55	**45.66**	88.89	59.26	52.22	**66.79**
		R03	37.19	47.33	52.44	**45.66**	90.00	60.74	50.37	**67.04**
		R04	37.18	47.15	52.42	**45.58**	89.26	58.15	50.37	**65.93**
		R05	37.17	47.22	52.45	**45.61**	90.00	59.63	52.22	**67.28**
	GR=0.75	SPSO	37.18	47.30	52.38	**45.62**	88.89	59.63	51.11	**66.54**
		R01	37.18	47.29	52.37	**45.61**	89.26	58.15	50.74	**66.05**
		R02	37.13	47.27	52.44	**45.61**	88.89	61.11	50.74	**66.91**
		R03	37.17	47.28	52.43	**45.63**	90.37	60.00	52.96	**67.78**
		R04	37.26	47.24	52.46	**45.66**	90.00	60.00	51.11	**67.04**
		R05	37.14	47.37	52.38	**45.63**	88.52	58.52	51.11	**66.05**
	GR=0.5	SPSO	37.25	47.34	52.54	**45.71**	91.48	61.48	53.33	**68.77**
		R01	37.17	47.40	52.50	**45.69**	90.00	61.85	50.37	**67.41**
		R02	37.16	47.17	52.49	**45.61**	89.63	59.26	51.48	**66.79**
		R03	37.16	47.29	52.43	**45.63**	90.37	60.37	48.52	**66.42**
		R04	37.16	47.16	52.45	**45.59**	88.52	58.15	51.85	**66.17**
		R05	37.15	47.31	52.44	**45.63**	88.89	61.11	51.48	**67.16**
	GR=0.25	SPSO	37.26	47.32	52.55	**45.71**	90.00	61.85	51.48	**67.78**
		R01	37.26	47.22	52.49	**45.66**	90.37	58.89	52.59	**67.28**
		R02	37.13	47.29	52.37	**45.60**	88.15	60.37	50.37	**66.30**
		R03	37.15	47.19	52.32	**45.55**	88.89	60.00	51.11	**66.67**
		R04	37.21	47.31	52.44	**45.65**	88.89	60.74	51.48	**67.04**
		R05	37.17	47.23	52.40	**45.60**	88.52	60.00	49.26	**65.93**

	lBest (GR=0.0)	SPSO	37.17	47.33	52.45	45.65	88.89	59.63	52.22	66.91
		R01	37.18	47.21	52.47	45.62	89.63	59.63	51.48	66.91
		R02	37.14	47.13	52.49	45.59	88.52	56.30	51.11	65.31
		R03	37.18	47.24	52.40	45.61	89.26	60.74	50.74	66.91
		R04	37.15	47.36	52.38	45.63	88.89	59.63	50.74	66.42
		R05	37.16	47.33	52.42	45.64	88.89	60.00	51.85	66.91
50,000 Schedules (20F/20B Particles)	gBest (GR=1.0)	SPSO	37.26	47.30	52.56	45.70	91.11	61.48	54.44	69.01
		R01	37.22	47.30	52.49	45.67	90.00	61.11	52.96	68.02
		R02	37.23	47.43	52.45	45.70	90.00	62.22	51.48	67.90
		R03	37.17	47.25	52.37	45.60	89.63	61.85	51.85	67.78
		R04	37.22	47.28	52.52	45.67	90.00	61.48	51.85	67.78
		R05	37.22	47.20	52.44	45.62	90.74	61.11	50.74	67.53
	GR=0.75	SPSO	37.22	47.27	52.38	45.62	91.11	62.22	50.37	67.90
		R01	37.25	47.28	52.42	45.65	91.85	62.59	51.11	68.52
		R02	37.20	47.26	52.47	45.64	90.74	61.48	50.74	67.65
		R03	37.24	47.24	52.42	45.63	90.37	61.85	50.37	67.53
		R04	37.22	47.24	52.39	45.62	90.00	60.37	51.48	67.28
		R05	37.19	47.17	52.49	45.61	91.11	60.37	51.48	67.65
	GR=0.5	SPSO	37.22	47.29	52.45	45.65	90.74	63.33	51.48	68.52
		R01	37.19	47.31	52.48	45.66	90.37	61.11	52.22	67.90
		R02	37.20	47.25	52.47	45.64	90.37	63.33	51.48	68.40
		R03	37.26	47.19	52.47	45.64	91.11	61.11	50.74	67.65
		R04	37.30	47.23	52.38	45.64	91.85	61.48	51.48	68.27
		R05	37.27	47.21	52.48	45.65	91.48	62.59	51.11	68.40
	GR=0.25	SPSO	37.21	47.35	52.47	45.68	90.74	61.85	52.59	68.40
		R01	37.12	47.31	52.45	45.63	89.63	62.59	52.59	68.27
		R02	37.21	47.43	52.45	45.70	91.11	65.19	50.00	68.77
		R03	37.26	47.33	52.50	45.70	90.74	61.85	51.85	68.15
		R04	37.20	47.29	52.37	45.62	90.37	61.11	51.11	67.53
		R05	37.28	47.22	52.34	45.61	91.48	62.59	51.11	68.40
	lBest (GR=0.0)	SPSO	37.27	47.35	52.45	45.69	91.85	62.96	50.00	68.27
		R01	37.24	47.22	52.46	45.64	90.74	60.00	52.96	67.90
		R02	37.24	47.22	52.42	45.63	90.74	60.74	51.48	67.65
		R03	37.21	47.29	52.33	45.61	90.00	62.96	50.00	67.65
		R04	37.24	47.34	52.48	45.69	91.48	62.22	52.22	68.64
		R05	37.27	47.34	52.43	45.68	91.11	63.33	50.74	68.40
1,000 Schedules (10F/10B Particles)	GR=1.0 GR=0.75 GR=0.50 GR=0.25 GR=0.0	Best DD Range	37.21	47.33	52.50	45.64	90.74	62.22	52.22	67.53
			37.22	47.22	52.51	45.63	89.63	60.00	52.22	66.91
			37.22	47.36	52.48	45.66	90.00	62.22	51.85	68.02
			37.23	47.27	52.46	45.65	90.00	60.74	51.85	67.04
			37.16	47.29	52.47	45.62	90.00	60.74	51.48	67.16
	Best Topology	SPSO	37.19	47.31	52.46	45.64	90.00	61.48	52.22	67.53
		R01	37.22	47.24	52.46	45.61	89.63	61.85	52.22	66.91
		R02	37.23	47.33	52.48	45.66	90.00	62.22	51.85	68.02
		R03	37.21	47.36	52.51	45.66	90.00	62.22	51.85	67.65
		R04	37.19	47.26	52.50	45.63	90.74	60.74	51.85	67.16
		R05	37.20	47.30	52.50	45.61	90.00	60.00	51.85	66.54
5,000 Schedules (10F/10B Particles)	GR=1.0 GR=0.75 GR=0.50 GR=0.25 GR=0.0	Best DD Range	37.23	47.38	52.56	45.71	90.00	61.85	53.70	68.40
			37.26	47.37	52.46	45.66	90.37	61.11	52.96	67.78
			37.25	47.40	52.54	45.71	91.48	61.85	53.33	68.77
			37.26	47.32	52.55	45.71	90.37	61.85	52.59	67.78
			37.18	47.36	52.49	45.65	89.63	60.74	52.22	66.91
	Best Topology	SPSO	37.26	47.38	52.55	45.71	91.48	61.85	53.33	68.77
		R01	37.26	47.40	52.56	45.71	90.37	61.85	53.70	68.40
		R02	37.21	47.29	52.55	45.66	89.63	61.11	52.22	66.91
		R03	37.19	47.33	52.44	45.66	90.37	60.74	52.96	67.78

		R04	37.26	47.36	52.46	**45.66**	90.00	60.74	51.85	**67.04**
		R05	37.17	47.37	52.45	**45.64**	90.00	61.11	52.22	**67.28**
50,000 Schedules (20F/20B Particles)	Best DD Range	GR=1.0	37.26	47.43	52.56	**45.70**	91.11	62.22	54.44	**69.01**
		GR=0.75	37.25	47.28	52.49	**45.65**	91.85	62.59	51.48	**68.52**
		GR=0.50	37.30	47.31	52.48	**45.66**	91.85	63.33	52.22	**68.52**
		GR=0.25	37.28	47.43	52.50	**45.70**	91.48	65.19	52.59	**68.77**
		GR=0.0	37.27	47.35	52.48	**45.69**	91.85	63.33	52.96	**68.64**
	Best Topology	SPSO	37.27	47.35	52.56	**45.70**	91.85	63.33	54.44	**69.01**
		R01	37.25	47.31	52.49	**45.67**	91.85	62.59	52.96	**68.52**
		R02	37.24	47.43	52.47	**45.70**	91.11	65.19	51.48	**68.77**
		R03	37.26	47.33	52.50	**45.70**	91.11	62.96	51.85	**68.15**
		R04	37.30	47.34	52.52	**45.69**	91.85	62.22	52.22	**68.64**
		R05	37.28	47.34	52.49	**45.68**	91.48	63.33	51.48	**68.40**

Table C.28: RCPSP test results for DDPSO under different topologies (w=0.73)

Appendix D: Case Study Details

For the purpose of verifying the developed dynamic scheduling model, the *CCC/TAV JV (or CTJ)* was selected as a sample entity containing all the necessary characteristics to resemble an enterprise. This enables verifying the dynamic scheduling capabilities of the proposed model, as well as the inter-project resource allocation features.

This entity, *CTJ*, is a joint venture between *Consolidated Contractors Company (CCC)* and *TAV construction,* established to execute the awarded construction packages within *Development of Muscat International Airport (DMIA)* project in *Sultanate of Oman.*

D.1. DMIA General Information

DMIA is a mega project which involves the construction of a new airport (new airfield, new terminal building, new air traffic control tower, and new airport management buildings), and the refurbishment of the existing airfield. The project was initiated to meet the growth in passengers' numbers from and to the *Sultanate of Oman's*, which reached the existing airport's maximum capacity.

Figure D.1: DMIA 3D model

The client is the *Ministry of Transport & Communications,* the project manager is *ADPi,* and the main consultant is *COWI-Larsen Joint Venture (or CL-JV).* The works of this mega project was divided into several contract packages, from which the followings were explained due to their relevance to the case study:

- Main Contract 1 (MC1): Involves the construction of the new airfield (4-km runway and about 15 km of taxiways), all the infrastructure of the new airport (10 utility networks, a storm water drainage system, 34 power substations, 23 lifting/pumping stations, a generators plant, and 2 large chiller plants), all airside roads (total length of about 35 km), all landside roads & bridges (about 45 km of roads, 2 interchanges and 8 bridges), and the refurbishment of the existing airfield (4-km runway and about 10 km of taxiways). The contract was awarded to *CTJ*, or the case study entity.

- Main Contract 2 (MC2): Involves the construction of the *Air Traffic Control (ATC)* tower (97m high), and the construction of airport management buildings/complexes (7 nos.). The contract was awarded to *Carillion-Allawi Joint Venture.*

- Main Contract 3 (MC3): Involves the construction of the *Passenger Terminal Building (PTB),* a two story car park (7000+ parking spaces), and maintenance workshops. The contract was awarded to the *Consortium of Bechtel, ENKA, and BEC (BEB consortium).*

- Main Contract 4a (MC4a): Involves the construction of the new *Civil Aviation Head Quarter.* The contract was awarded to *Towell Construction LLC.*

- Main Contract 6 (MC6): Involves the installation and testing of the airport's IT infrastructure. The contract was awarded to *Ultra Electronics Airport Systems.*

- Fuel Farm package: Involves the construction of 4 fuel tanks, fuel farm administration building, fuel farm utilities, and few other fuel farm structures. The packages was awarded to *CTJ*, and added to the scope of MC1.

D.2. DMIA master schedule

The construction of the DMIA project was planned in two main phases:

- Phase 1: the construction of the new airfield, all utilities, the ATC tower, and the new airport management buildings. This will enable the new airfield to be operational and the air traffic to be shifted from the existing airfield to the new airfield, and to be operated from the new ATC tower.

- Phase 2: the refurbishment of the existing airfield and the completion of all remaining airport works (PTB, maintenance workshops, fuel farm, and landside roads & bridges).

D.3. Main Contract 1 (MC1) project details

The MC1 is the applied case study in this research. The contract value, including variations, exceeded 500 million OMR (1.3 billion USD). The MC1 works was huge with more than 35 million m3 of earthworks, nearly 3 million m3 of pavement, nearly 1 million m3 of concrete, more than 300,000 m of HV/MV power cables, nearly 1.5 million m of LV and other conductors, 156 pumps, 116 power transformers, 13 power switchgears, 17 generators, 14 chillers, and many other civil and MEP works.

Due to the complexity and mass of works to be accomplished, the *CTJ* top management decided to split the MC1 into four projects, with four

separate construction teams; while few support functions are to be shared between the three projects.

D.3.1. Project organization

The MC1 scope of works was split geographically, as shown in figure D.2, into 3 projects: *Northern Development Area (NDA), Airfield Area (AFA)* and *Roads & Bridges (R&B).* In addition to a fourth project for the MEP works.
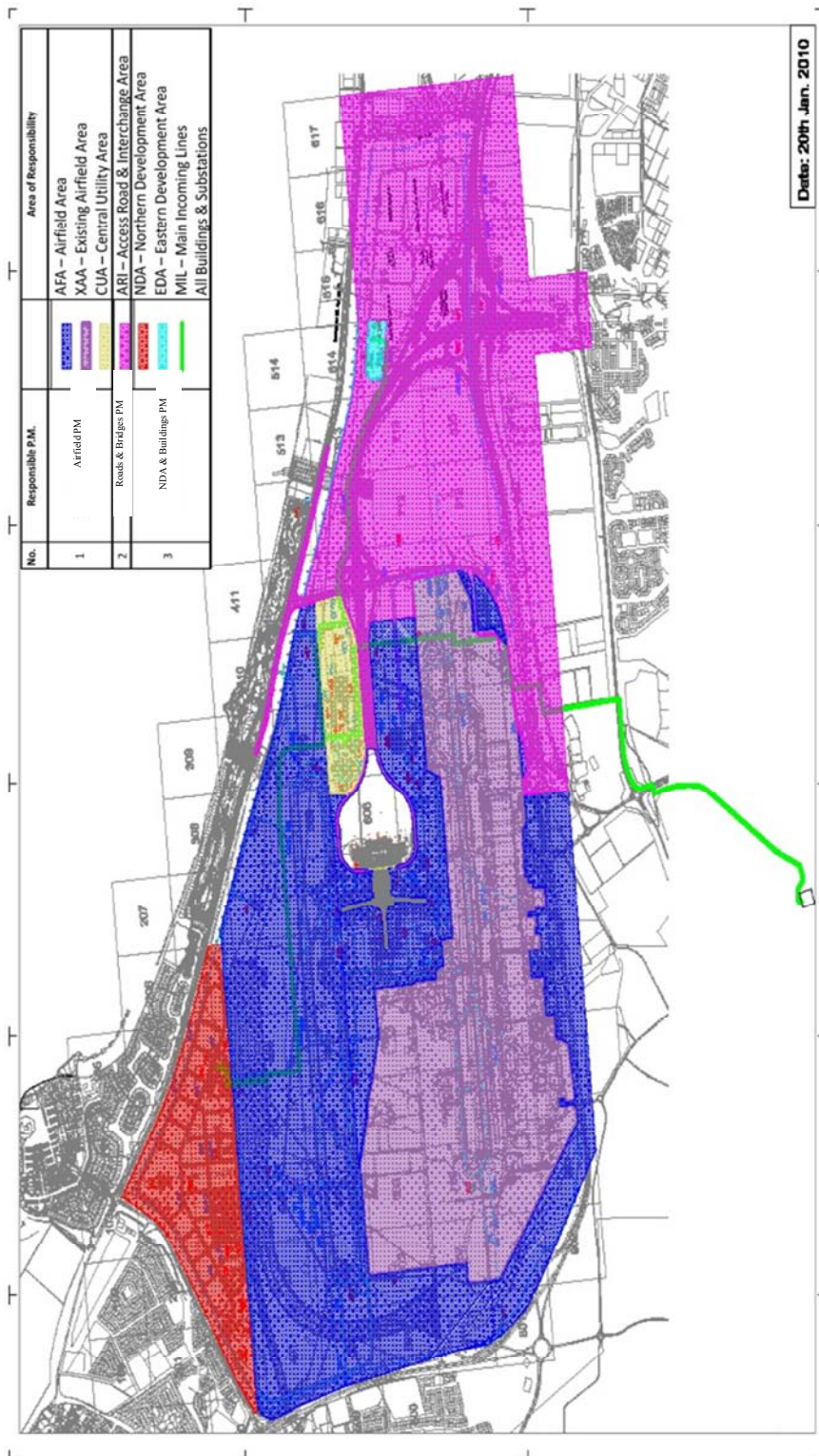

Figure D.2: DMIA geographical scope distribution between project management teams

The *Airfield* project involved the construction of the new airfield (including all new runway, taxiways, airside roads, and airfield utilities), roads & utilities of the Central Utility Area (CUA), the construction of aircraft stands and aprons, the construction of the fuel farm area (civil works), and the refurbishment works for the existing airport (existing runway & taxiways).

The *NDA & Buildings* project involved the construction of the Northern Development Area (NDA), the Eastern Development Area (EDA), all buildings (in NDA, CUA & EDA), and the main incoming power lines civil works.

The *Roads & Bridges* project involved the construction of all landside roads, bridges & interchanges, landscaping works, water features, and overall DMIA traffic management during the project construction.

The *MEP* project involved the installation & testing of all electrical and mechanical system within utility networks, pumping/lifting stations, buildings services, generator plant, chiller plants, and the mechanical works for the fuel farm and the fuel system.

And finally, the project organization included few other support functions shared with all project management teams, such as: project controls, HSE, QA/QC, and engineering.

D.3.2. Work Breakdown Structure (WBS)

The project WBS was arranged (as shown in figure D.3) to match the overall master schedule (phase 1 & phase 2), the geographical distribution, and further details to support proper planning and monitoring functions.

The 5th WBS level, or the *Major Disciplines*, represented the main level for work packaging for construction supervision. This level was detailed, along with higher WBS level, in figure D.4; where major disciplines (or L5 elements) were arranged by type and assigned to different project management teams.
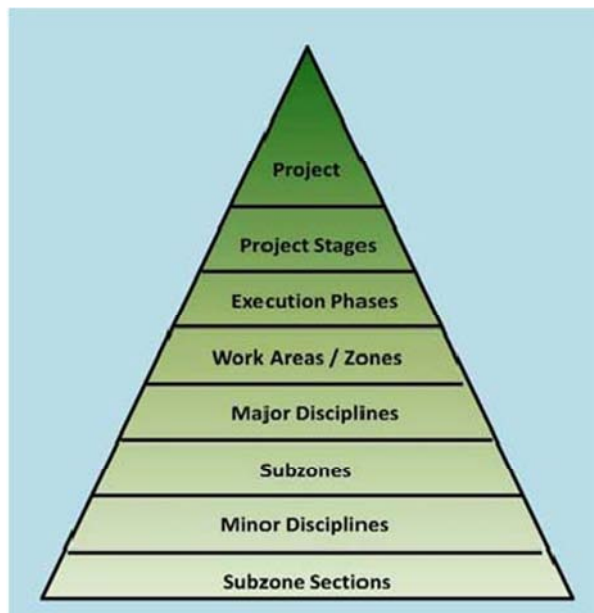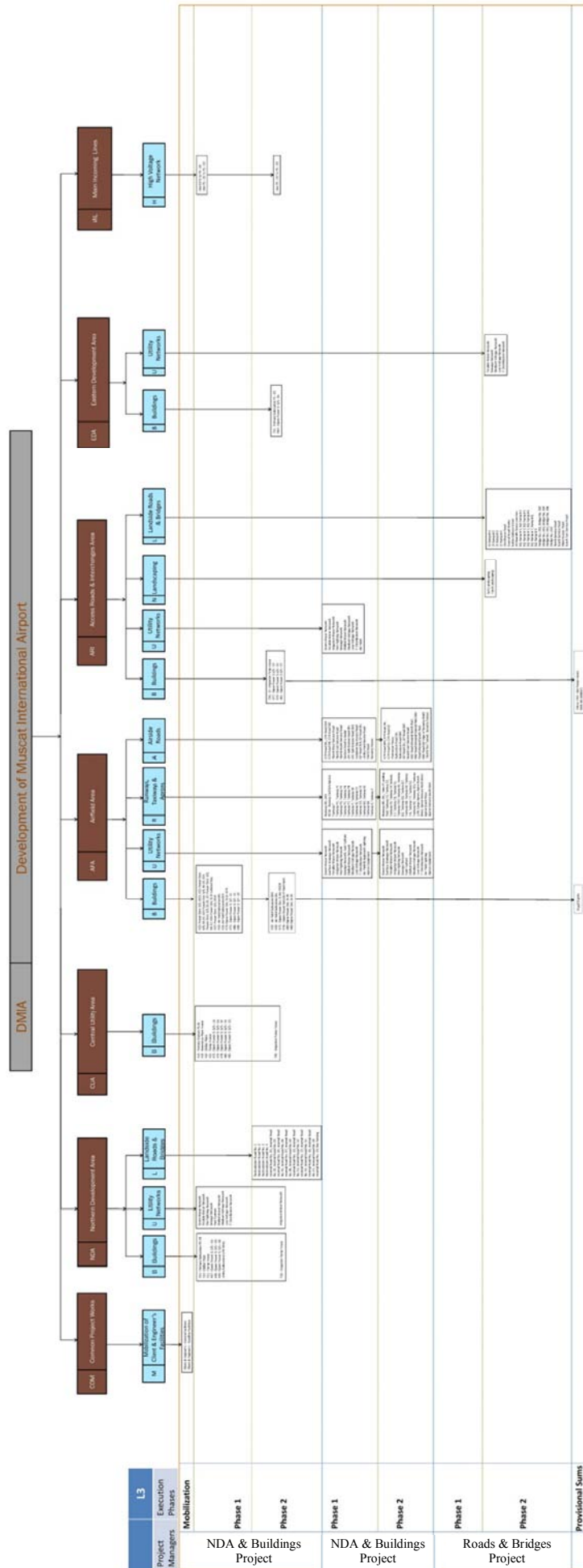

Figure D.3: DMIA Summary WBS

Figure D.4: DMIA detailed work breakdown structure

D.3.3. Project resources

For the ease of resources management, the project resources were arranged in two main groups: *commodities* and *crews*. The project *commodities* represent the project construction products, which resemble non-renewable resources in the scheduling context, and can be easily converted to corresponding material requirements. While the *crew* resources are renewable resources grouped in teams structures corresponding to the output commodities (for ex: the *utilities networks excavation commodity* is having a corresponding *trench excavation crew*). These *crew* resources can also be converted easily to its breakdown to enable assessing the requirement from each equipment type or manpower trade.

The project schedule contained hundreds of resources, between labour crews, equipment crews, material supplies, and commodities (or output products). Not all resources were necessarily required to be optimized; however, the following resources were marked for optimization throughout the case study testing:

- Constrained resources due to resources availability: Concrete paving crews, piling crews, stone columns installation crews, power cabling crews, in addition to several mechanical & electrical equipment installation crews.

- Constrained resources due to plant productivity constraints: Concrete (for planned concrete plants' productivity), asphalt (for asphalt plant's productivity), and rock fill (for available crushers' productivity). Any requirements above the productivity of available plants were considered with extra cost for outsourcing.

- Resources to be levelled to minimize resources costs: Aggregate paving crews, asphalt paving crews, excavation crews, backfilling crews, and piping crews.

Appendix E: Validation Feedback Forms for the new Dynamic Scheduling Solution for Construction Enterprises

Planning is the core of project management; so, its success contributes much to the success of projects. For the planning function to be successful, a complete and flexible resourced schedule must be generated before the commencement of the project, and must be properly maintained during the execution.

Real-time events extremely disrupt the integrity of project schedules. The presence and implementation of a predefined Dynamic Scheduling strategy to mitigate these disruptions is a must for the successful implementation of project planning.

During the past few years, we have been working on the development of a Dynamic Scheduling solution for Construction enterprises; from the basic framework to the detailed model, optimization algorithms and a prototype software tool. The solution development is completed, and a verification case study was performed on a mega project in Oman.

As part of the new solution's validation process, this survey (and the associated DS solution presentation) was prepared to present the solution's outputs to Construction Project Management experts, and collect their experienced opinions about the validity and practicality of using this solution in construction projects.

Participant's General Information:
This section is intended to collect some information about your experience which will help us during the analysis of the survey results.

Name: …………………………………………………..…..

E-Mail address: ………………………………………..…..

Current Organization: …………………………………….

1. *What is the category of your current organization?*
   - ☐ Project Management Consultants
   - ☐ General Engineering Consultants
   - ☐ General Contractors
   - ☐ Specialized Contractor (please state specialty field) …………...

2. *What is the level of your current occupation?*
   - ☐ Top management
   - ☐ Department management
   - ☐ Senior level
   - ☐ Junior level

3. *What are your total years of experience within Project Management different fields?*
   - ☐ More than 15 years
   - ☐ From 10 to 15 years
   - ☐ From 5 to 10 years
   - ☐ Less than 5 years

4. What are your total years of experience within Planning/Scheduling field?

☐ More than 15 years   ☐ From 10 to 15 years

☐ From 5 to 10 years   ☐ Less than 5 years

5. Please list the countries you worked in (starting from recent)? (The question is required only to check that the survey was attended by various PM backgrounds)

…………………………..

6. Have you participated in the questionnaire survey performed earlier under the same research before the DS model's design?

☐ Yes   ☐ No

The proposed Dynamic Scheduling solution's design:

After reviewing the DS validation presentation, this section includes few questions on the proposed DS solution's design and the overall solution's practicality and efficiency.

7. From your general project controls experience, if you believe that there is a necessity for a new system to support current practices in schedules optimization, then please specify in which schedule quality gates do you think this is required? (select all applicable answers)

☐ Baseline schedules preparation

☐ Revised schedules preparation

☐ Progress updates & look-ahead schedules preparation

☐ What-If schedules preparation

8. From the presented test results of the proposed DS system, within which schedule quality gates do you think this proposed system can be <u>practically</u> used in construction projects? (select all applicable answers)

☐ Baseline schedules preparation

☐ Revised schedules preparation

☐ Progress updates & look-ahead schedules preparation

☐ What-If schedules preparation

9. For the proposed DS system, how effective do you believe the system can support the <u>baseline/revised</u> schedules preparation process?

☐ Strongly effective. The optimized solution alternatives presented in the example and the case study showed significant improvement to schedule's quality.

☐ Seems effective. The example and case study showed improvement, and probably this can be applicable to other construction projects.

☐ Not sure. I was not able to judge from the given presentation.

☐ Not effective. I don't believe the case study results can be generalized to other construction projects.

10. *Similarly, how effective do you believe the system can support the <u>progress updates & look-ahead</u> schedules preparation process?*

      ☐ Strongly effective.

      ☐ Seems effective.

      ☐ Not sure.

      ☐ Not effective.

11. *Finally, how effective do you believe the system can support the <u>what-if</u> schedules preparation process?*

      ☐ Strongly effective.

      ☐ Seems effective.

      ☐ Not sure.

      ☐ Not effective.

12. *In general, do you think the overall DS solution can be <u>easily</u> used by construction projects' planning teams?*

      ☐ From the presentation, the system seems easy to use by any planner.

      ☐ With few practicing, the system can be easily used.

      ☐ The system seems complicated and requires a lot of practice.

      ☐ Only very experienced planners can use it.

13. *Please specify any other comments/suggestions on the proposed DS system's design*

      ………………………………………………………………………………………………………

The Dynamic Scheduler user interface:

The Dynamic Scheduler was developed as a prototype tool to test the functionality of the proposed DS system. In the DS validation presentation, several screen shots from the tool were provided to show the main software's features and functionalities. This section investigates the PM experts' opinions about this tool.

14. *From the given presentation, how effective do you think the software tool achieved the required integration with current PM practices as per the DS model's requirements?*

      ☐ Strongly effective. The data transfer to and from the software requires minimal effort.

      ☐ Seems effective. The data transfer is simple, but can be further improved.

      ☐ Not sure. I was not able to judge from the given presentation.

      ☐ Not effective. There are many complications in the process which require planners to digest before using the tool. [Please specify details]

15. *Similarly, how effective do you think the software tool provided the ability to define and/or modify additional project/optimization data?*

☐ Strongly effective. The tool provides the necessary user interface to define/modify the data required for the optimization process to proceed.

☐ Seems effective. The tool provides the required interface, but needs to be more user-friendly.

☐ Not sure. I was not able to judge from the given presentation.

☐ Not effective. The software does not allow manipulating some essential data required for optimization. [Please specify details]

16. *Finally, how effective do you think the software tool provided the ability to view optimized alternatives?*

☐ Strongly effective. The functionality for viewing alternatives provides all necessary information for the planner to initially select a solution; any further differentiation between alternatives can be made within the planning tool after exporting.

☐ Seems effective. Viewing alternative solutions is informative, but the related user interface can be further improved to allow planners to make determinate selection.

☐ Not sure. I was not able to judge from the given presentation.

☐ Not effective. I don't believe the developed interface for viewing alternatives is sufficient for planners to select an optimized solution. [Please specify details]

17. *Please specify any other comments/suggestions for improving the Dynamic Scheduler software tool*

……………………………………………………………………………………………

Future communications:

18. *Would you like to receive a complimentary copy of the Dynamic Scheduler after the completion of its validation?*

☐ Yes   ☐ No

19. *After the analysis completion of this survey's responses, would you like to receive a summary of the survey's results?*

☐ Yes, I need it for other research topic in the same/similar field

☐ Yes, it's good to know the common opinions about the new system

☐ No, not interested

20. *Would you like to receive any updates in future for researches with similar topics? (More than one choice can be selected)*

☐ Yes, for any innovative works in the planning/scheduling field

☐ Yes, for research topics related to Schedules Optimization

☐ Yes, for research topics related to Dynamic Scheduling