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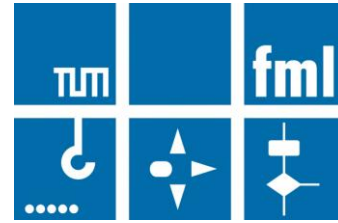## Proyecto Fin de Carrera

Evaluación de reglas de prioridad para la asignación de recursos en la gestión de proyectos

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Resumen

En el presente documento se afronta el problema de la gestión de proyectos con restricciones de recursos llamado Resource-Constraint Project Scheduling Problem (RCPSP). Hace referencia a la gestión de cualquier proyecto en el que se tengan unos recursos por unidad de tiempo limitados y que por tanto no permitan la realización simultánea de todas las actividades en paralelo sino que haya que elegir un orden para la realización de las mismas. Este problema se ha planteado en numerosas ocasiones en el Departamento de Logística de la Universidad Técnica de Múnich, origen de la realización de este trabajo.

El objetivo principal es realizar el proyecto empleando el menor tiempo posible y para ello se debe encontrar el orden más beneficioso para le ejecución de las actividades. Los factores a tener en cuenta no son solo la cantidad de recursos y materiales necesarios para la realización de cada una, sino también su duración, así como sus sucesores y predecesores. Para ello se utilizan las ´priority rules´ o reglas de prioridad que asignan a cada actividad un determinado valor y gracias a este valor, una prioridad con respecto a las otras actividades con las que compite. Para la realización de este proyecto se ha buscado en la bibliografía existente y se han implementado a través del programa Plant Simulation las 10 reglas de prioridad que según la documentación relativa a este tema mejor funcionan. Para hacer el estudio lo más riguroso posible, se han analizado y comparado 2040 proyectos con 10 ventanas de tiempo distintas para cada una de las 10 reglas de prioridad estudiadas, en total por tanto han sido simulados más de 200.000 proyectos.

Por último se ha introducido un recurso novedoso en este tema al que se ha denominado recurso tipo área. Consiste en la introducción de una nueva restricción para la ejecución de las actividades. Se ha desarrollado para la gestión de proyectos que deban realizarse en una superficie determinada, por ejemplo la planta de una empresa que posee distintas máquinas. A cada actividad se le asigna una cierta zona de la empresa para ser desarrollada (requiere ser realizada por una determinada máquina). Así pues mientras haya otra actividad empleando esa zona requerida, no podrá ser ejecutada al no estar disponible este nuevo recurso y por tanto puede variar el orden preestablecido por las reglas de prioridad. Se considera que además de para la planificación de proyectos a realizar dentro de empresas, puede ser de gran importancia en la gestión en proyectos de obra (requerimientos de grúas, restringir el paso hacia determinados lugares en el que se están desarrollando actividades etc.)

Los resultados obtenidos muestran que las reglas de prioridad que mejor funcionan son las llamadas Long Path Following (LPF) y Minimum Slack (MinSlack) y muestran una mejora sustancial con respecto a las reglas utilizadas en los proyectos realizados por el Departamento de Logística de la Universidad Técnica de Múnich. Además, se ha sentado una base en lo referente al recurso área que era la parte más novedosa de este trabajo para la futura investigación que será llevada a cabo por futuros alumnos de dicho centro.

Lista de contenidos.

1 Objetivo y contenidos del proyecto

El presente documento es una versión resumida del proyecto original realizado en la Universidad Técnica de Múnich, Alemania, entre los meses de mayo y octubre del año 2012 en el Departamento de Logística (Lehrstuhl Fördertechnik Materialfluss und Logistik) dirigido por el profesor Tim Horenburg.

El documento original escrito en inglés y adjuntado como anexo, aporta información detallada, extensa y amplia, con ejemplos, figuras y tablas que ayudarán al lector a comprender el contenido de este trabajo de una manera más eficaz.

El resto de la memoria se organiza como sigue. El capítulo 2 ofrece una breve introducción al problema de la gestión de proyectos con recursos limitados (RCPSP) en sus siglas inglesas.

En el capítulo 3 se puede encontrar una breve aproximación teórica de las reglas de prioridad que son el método usado para determinar el orden de ejecución de las actividades, así como el nuevo recurso introducido en este trabajo que ha sido llamado Recurso Área, la forma en como ha sido diseñado y sus aplicaciones. Además, se introduce el sistema multi-agente que es el sistema aplicado para la resolución del RCPSP mediante el cual se asignan los recursos a las actividades para que sean realizadas.

El capítulo 4 se centra en el desarrollo empírico del proyecto donde se incluye una breve descripción de los set de proyectos que van a ser simulados y probados para las diferentes reglas así como un breve análisis de los resultados obtenidos.

Por último en el capítulo 5 se plantean las futuras lineas de investigación que complementen el estudio actual.

El orden de los capítulos seguidos en esta memoria no se corresponde con el del proyecto original, pero debido a la brevedad del mismo, se ha creido conveniente adecuarlo de esta manera para facilitar la comprension del documento para el lector.

Los objetivos para los que ha sido realizado este trabajo son dos. En primer lugar encontrar las reglas de prioridad que mejoren los resultados obtenidos por las reglas usadas en el Departamento de Logística de la Universidad Técnica de Múnich para la optimización de tiempos y presupuestos en sus proyectos. Los algoritmos realizados serán por tanto usados para la realización de los futuros proyectos que se vayan a llevar a cabo. El segundo objetivo que se persigue es la introducción del recurso área sobre el que futuros alumnos de la Universidad Técnica de Munich investigarán. Para ello se ha seleccionado una de las reglas de prioridad que mejor funciona que es la llamada Long Path Following (LFP) y se han realizado los proyectos una vez introducido el recurso área. Estos resultados servirán como base para la mejora de las reglas de prioridad que serán investigadas para la elaboración de los proyectos de logística y construcción que se llevan a cabo en el departamento.

2 Introducción

Dado un proyecto cuyas actividades requieren una cierta cantidad de recursos, materiales y tiempo no variables a lo largo del desarrollo del mismo, el objetivo principal para el director del proyecto, que dispone de una cantidad de recursos limitada por unidad de tiempo, es reducir su duración programando las actividades en el orden más favorable. Este es el llamado Resource-Constraint Project Scheduling Problem (RCPSP) y las razones de buscar la minimización de la duración del proyecto son las siguientes:

- La mayoría de los pagos se efectuan al final del proyecto y por tanto para reducir la cantidad de capital inmovilizado es importante concluir el mismo en el menor tiempo posible.
- La calidad de las estimaciones disminuye con la distancia en el futuro para las que están hechas debido a la incertidumbre de la información y a los cambios en el marco de trabajo.
- Terminar el proyecto lo antes posible reduce la posibilidad de sobrepasar fechas límite.
- Cuanto antes se termine un proyecto, antes se liberan recursos para realizar nuevos proyectos o emprender nuevas acciones económicas.

Es por tanto de vital importancia como puede observarse, la realización del proyecto en el mínimo tiempo posible. La forma de abordar el RCPSP es asignando a cada actividad un determinado valor y de acuerdo a este valor dichas actividades obtienen una prioridad con respecto a las otras que marca el orden de realización de las mismas. Este procedimiento de asignar diferentes valores a cada actividad se llama ´Priority Rule´ o en español Regla de Prioridad. Como resumen, el problema comprende la selección y realización de las actividades apropiadas cuando muchas compiten por los mismos recursos.

3 Marco teórico

3.1 Sistema multi-agente

El sistema multi-agente es un sistema compuesto por múltiples agentes inteligentes que interactúan entre sí en un entorno determinado. Es usado para resolver problemas que son imposibles o muy difíciles de resolver usando un único agente. Los agentes son considerados programas independientes que controlan sus propias decisiones y operan siguiendo la percepción del entorno para conseguir múltiples objetivos.

El gráfico siguiente muestra como se aplica el sistema multi-agente para la resolución del RCPSP. Los Agentes Proceso son las actividades del proyecto y tienen información de duración, recursos necesarios, sucesores y predecesores etc. Los Agentes Recurso tienen información sobre su estado (libre, bloqueado o activo), tipo de recurso etc. El Blackboard es el centro donde se intercambia la información y hace de intermediario entre los distintos agentes proporcionando la información necesaria para que los agentes tomen las decisiones. El documento original en el capítulo 5.4 amplía y detalla la explicación sobre el sistema multi-agente.
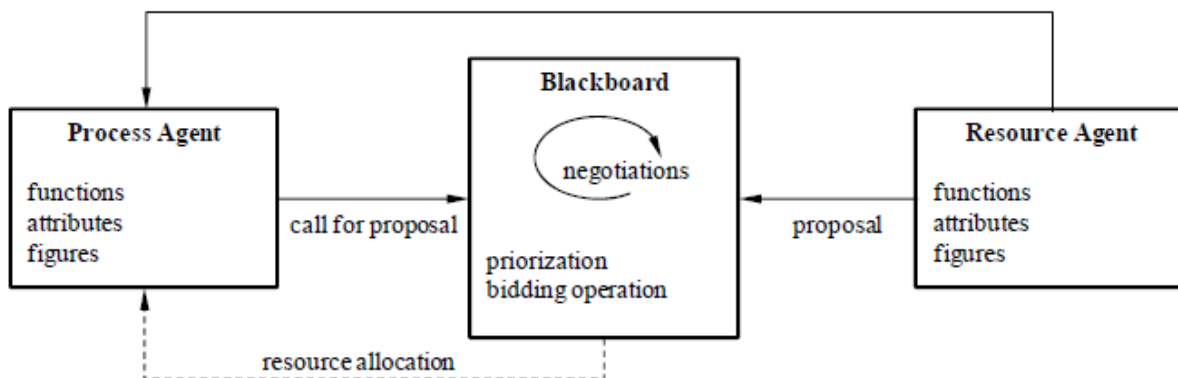

Figura 3.1: Sistema multi-agente para la ejecución de proyectos.

3.2 Reglas de prioridad

Como ha sido comentado en el capítulo 2, las reglas de prioridad son la herramienta usada para solucionar el RCPSP. El funcionamiento de las reglas es el siguiente. A todas las actividades realizables, es decir cuyas predecesoras han sido realizadas y terminadas, se les asigna un valor dependiendo de la regla de prioridad elegida. Estos valores dependen de características de las actividades como su duración, recursos requeridos o número de actividades sucesoras entre otras. En el capítulo 4.3.1 del documento original, puede encontrarse la explicación con ejemplos para cada una de las 18 reglas de prioridad que han sido estudiadas tras la lectura de la documentación y estudios de los autores más expertos en el tema. Una vez que todas las actividades realizables tienen asignado su valor, son ordenadas de mayor a menor prioridad y comienza la asignación de recursos

para la realización de las mismas. El proceso se volverá a repetir en el próximo punto de negociación, cuando las actividades que están siendo llevadas a cabo terminen y liberen los recursos necesarios para seguir con la realización del proyecto.

3.3 Recurso Área

Es un recurso que ha sido introducido por primera vez en este estudio y trata de facilitar la programación de las actividades de un proyecto en el que el área donde es realizado es limitada. Esta pensado especialmente para proyectos a realizar dentro de una empresa o recinto cerrado en el que los movimientos entre máquinas o lugares sean limitados o para la realización de obras de construcción en el que actividades concretas deban ser hechas en una zona determinada como por ejemplo la instalación de una piscina.

Debido a que los proyectos que han sido realizados carecían de dicho recurso, ha tenido que ser creado para que la simulación pudiera llevarse a cabo. El proceso de como se ha realizado puede leerse en el capítulo 7.3.3 del documento original.

4 Estudio empírico

4.1 Modelos de proyectos

Para dar validez y rigurosidad a los estudios realizados con diferentes reglas de prioridad, se crearon en 1997 una serie de conjuntos de proyectos llamados J30, J60, J90 y J120. Los 3 primeros estan formados por 480 proyectos distintos con 30, 60 y 90 actividades útiles respectivamente y con 4 tipos distintos de recursos. El set de proyectos J120 esta formado por 600 proyectos con 120 actividades útiles cada uno y 5 tipos de recursos distintos.

Cada una de las 10 reglas de prioridad estudiadas han sido utilizadas para la realización de los proyectos que forman los sets J30, J60, J90 y J120. Además, se han ejecutado los proyectos con 10 ventanas de tiempo (explicado en capítulo 5.4.4 del documento original) distintas por lo que al final la cantidad de proyectos realizados ha sido superior a los 200.000, dato que demuestra la rigurosidad y calidad del estudio llevado a cabo.

4.2 Reglas estudiadas

De entre las 18 reglas que han sido incluidas de manera teórica en el documento original, se han seleccionado 10 para ser utilizadas en la simulación de los proyectos. A continuación se van a explicar de una manera concisa las reglas implementadas en el software. Una explicación mas detallada con tablas e imágenes puede ser consultada para cada regla en el capítulo 4.3.1 del documento original.

- Greatest Cumulative Resource Requirement (GCRR). Obtienen mayor prioridad aquellas actividades con mayor requerimiento de recursos tanto para su realización como para la de todas sus sucesoras.
- Long Path Following (LPF). Asigna la mayor prioridad a aquellas actividades cuya suma de su duración más la duración de todas sus actividades sucesoras que estén en el camino crítico sea la mayor.
- Resource Scheduling Method (RSM). Escoge la actividad que induce el mínimo retraso en las actividades que están compitiendo en ese instante por los recursos disponibles.
- Great Number Inmediate Successors (GNIS). El valor asignado es el número de actividades sucesoras que tiene cada una y aquella con mayor valor obtiene la mayor prioridad.
- Great Number Successors (GNS). La forma de asignar valores y obtener mayor prioridad es como en GNIS pero no se tiene solo en cuenta las actividades inmediatemente sucesoras sino todas las actividades que dependen de la actividad seleccionada para ser realizadas.
- Improve Resource Scheduling Method (IRSM). Como el propio nombre indica, se trata de la regla RSM mejorada. La mayor prioridad es obtenida teniendo en cuenta no solo el retraso inducido por una actividad sino por un grupo de actividades.
- Worst Case Slack (WCS). La mayor prioridad es dada a aquellas actividades que tienen menor holgura teniendo en cuenta tanto la propia actividad como sus sucesoras.
- Average Case Slack (ACS). La actividad seleccionada tiene la mayor mayor holgura media teniendo en cuenta tanto la propia actividad como sus sucesoras.
- Minimum Slack (MinSLack). La mayor prioridad es dada a aquellas actividades que tienen menor holgura.

- Latest Finish Time (LFT). El valor asignado a cada actividad corresponde con su tiempo de terminación más lejano. La actividad con menor valor obtiene la mayor prioridad.

4.3 Resultados y conclusiones

Los resultados han sido comentados individualmente en el documento original para cada set de proyectos. En esta breve memoria se muestra la gráfica proporcionada tras el análisis de los datos obtenidos para el set de proyectos J30. La similitud de las gráficas que pueden verse en el capitulo 6 del documento original, muestra que el comportamiento de las reglas es similar independientemente del set de proyectos estudiado y que por tanto una regla que arroje mejores resultados para por ejemplo, el set de proyectos J30, tendrá un comportamiento similar para el resto de sets.
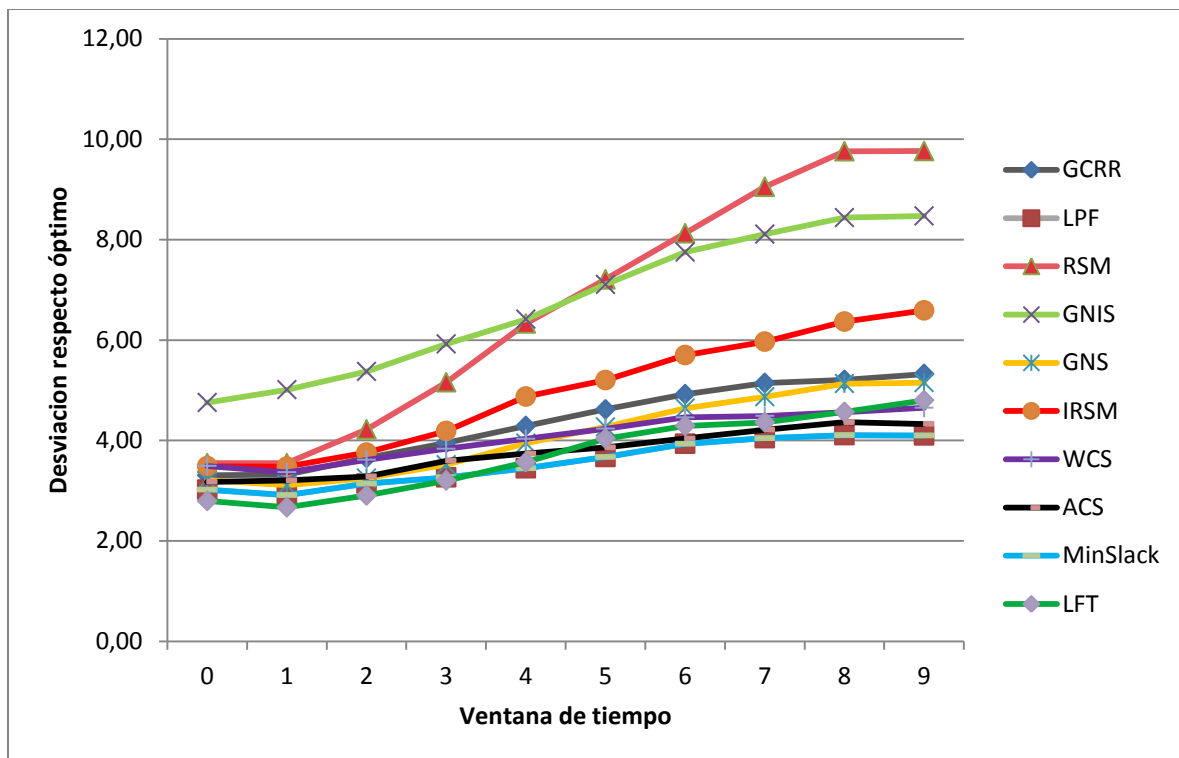

Figura 4.1: Resultados del set J30.

En la gráfica el eje de abcisas representa los distintos valores de la ventana de tiempo. El eje de ordenadas muestra la desviación media en unidades de tiempo de los 480 proyectos que forman el set J30 con respecto al valor óptimo para los proyectos estudiados. Cada línea representa el comportamiento de sus respectivas reglas de prioridad. Cuanto menor es el valor, más efectiva es la regla de prioridad debido a que la desviación con respecto del óptimo es menor. Por tanto, podemos decir que reglas como RSM o GNIS arrojan resultados muy pobres mientras que las reglas que mejor han funcionado han sido MinSlack, LPF o LFT. Los resultados pueden verse mas extensa y detalladamente en el documento original para cada un de los sets estudiados.
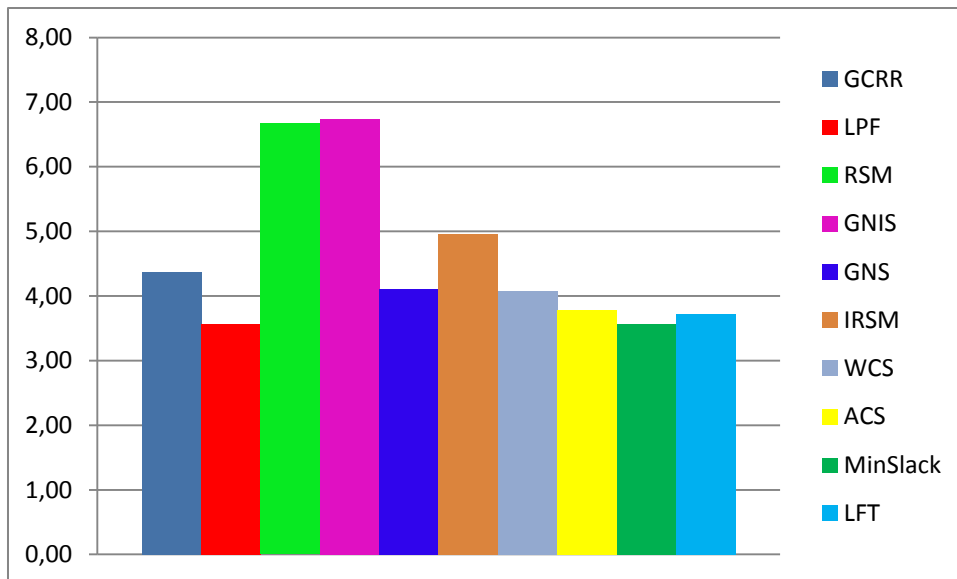
Figura 4.2: Desviación media para las distintas priority rules set J30.

La figura 4.2 muestra la media de las desviaciones con respecto al óptimo para todas las reglas. Como puede observarse, las reglas de prioridad que muestran menor desviación con respecto al óptimo son LFP, MinSlack y LFT y por tanto son consideradas en este estudio como las reglas que mejores resultados ofrecen. Debe remarcarse sin embargo, que pueden no ser las que mejores resultados obtengan para un proyecto concreto, es por eso importante que el director del proyecto simule el mismo con varias reglas y escoja la ordenación mas favorable, es decir la que requiera de menos tiempo para la conclusión del proyecto.

Con respecto al recurso área, los resultados obtenidos muestran una duración mucho mayor de los proyectos llevados a cabo, pero debido a que es un recurso que ha sido por primera vez estudiado en este trabajo no es posible compararlos con otros estudios previamente realizados por otros autores. Estos resultados servirán para la comparación con distintas reglas de prioridad enfocadas en el recurso área que estan siendo desarrolladas en el Departamento de Logística de la Universidad Técnica de Múnich.

5 Futuras investigaciones

Se ha probado en este documento que las reglas de prioridad que mejor funcionan son aquellas que utilizan el camino crítico para asignar valores a las actividades. La regla LPF da prioridad a aquellas actividades que están en el camino crítico en cada tiempo de negociación. Procedimiento parecido es llevado a cabo por la regla de prioridad MinSlack y como se ha comprobado también muestra buenos resultados. Otras reglas que también muestran buenos resultados han sido WCS y ACS cuya asignación de valores también está relacionada con el camino crítico. Debido a esto, se considera que los gestores de proyectos que quieran desarrollar nuevas reglas de prioridad deberían enfocar sus estudios en métodos que asignaran valores relacionados con el camino crítico.

Como puede verse en el capítulo 4.4 del documento original, cuando dos actividades obtienen el mismo valor y por tanto tienen la misma prioridad, sería necesario la introducción de una nueva regla que se usase para romper estas igualdades. Este método eliminaría la ejecución aleatoria de una u otra actividad que es el método que se utiliza actualmente. Sería por tanto importante comprobar que pareja de reglas de prioridad arrojarían mejores resultados cuando fueran utilizadas para realizar proyectos.

En lo concerniente al recurso del tipo área que ha sido introducido por primera vez en este estudio, se deberian crear nuevas reglas de prioridad para la realización de este tipo de proyectos de manera que ordenaran las actividades de una forma más eficiente y que por tanto mejorasen los resultados que se han obtenido.

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Diplomarbeit

Evaluation of different priority rules for resource allocation in project scheduling

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November 2012

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1 Abstract

In this document, the Resource-Constraint Project Scheduling Problem (RCPSP) is going to be faced. It refers to the management of any project in which the amount of resources per unit time is limited and hence, it is not possible to schedule simultaneously every parallel activities but have to been prioriticaly chosen and executed. The main goal is to schedule the activities in the best order to make the duration of the project as short as possible taking into account not only the resources, duration and necessary materials but also the predecessors and successors tasks.

To solve it a set of mathematical methods called Priority Rules are used. The way they work is assigning every task a value which determines the order of choice and execution for all of them.

In this section a compilation of most of the Priority Rules that actually exist are going to be studied and explained with the help of an easy and short example of project to illustrate the reader how values are assigned to every activity and how are then they scheduled.

The next step will be the simulation of the, according to the checked papers, 10 best Priority Rules and will be analyzed and compared for 2040 different projects in order to make the study as accurate as possible.

The last part of the study will be the introduction of a new type of resource that has been called as Area´s resource. It consists in the introduction of a new constraint in the scheduling of the activities. It would be helpful when the project must be realized in a certain place with a limited area as for example the inside surface of a firma or the area in a building work. Every activity would have assigned a fixed place where they would be executed, as a concrete machine in a firma or a concrete crane while building. So as long as a running activity is using this place the task could not be executed and hence, the order of scheduling the activities may vary. It is considered that this resource would be very helpful and used in construction´s projects as well as in the layout planification of companies.

2 Acknowledgments

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3   Introduction

3.1 Problem and Motivation

Project planning and scheduling has become an important management tool for to-day´s complex business and manufacturing systems. Models and methods from pro-ject planning play a vital role in such different tasks as, e.g. the re-design of business and work processes and finite scheduling of manufacturing systems (cf. (Adelsberg and Kanet, 1991; Tobias, 1991; Stadtler and Wilhelm, 1993)). The core of project planning is the Resource-Constrained Project Scheduling Problem (RCPSP). It adresses the question of how activities which are interrelated by technological and multiple capacity constraints have to be time-phased in order to accomplish a pre-specified management goal. [Kol-96]

Assuming a complete project with a limited number of activities which everyone of them needs a certain amount of resources, material and have a estimated duration which are not supposed to vary during the course of the project, the main goal for a project manager that has limited resources available for every period of time is to reduce the makespan of the project scheduling the activities in the best proper or-der.

The objective of makespan minimization is due to several reasons:

- Most of the income payments are made at the end of the project, there-fore to reduce the amount of tied up capital is important to finish the pro-ject as early as possible.

- The quality of forecasts decrease with the distance into the future for which are made becasuse of data uncertainty and environment changes.

- Finish the product as soon as possible reduces the possibilities of dead-lines violation.

- The earliest the project is finished, the earliest the resources available are freed to undertake new projects or new economic actions. [Kol-96]

In order to deal with the problem of the RCPSP many different studies and efforts have been undertaken. The way to solve the problem is assigning every activity a determined value according to its priority and execute them in the proper order. The procedure of assigning the different values for every task is called `Priority Rule´. To sum up, the problem involves choosing and executing the „proper" activities when several compete for the same resources.

To solve the RCPSP problem in a proper way, project managers prefer the heuristic dispatching rules rather than the exact or optimal ones. This question lies on the fact that exact procedures are limited in the size of the project due to the complexity and the big amount of operations the algorithm sould carry out with. Hence, it is not possible to calculate a big project with this procedures in a reasonable amount of computation time [Sim-96]. In the other hand priority rules have the advantage of being intuitive and very robust and much faster in terms of computational effort. Besides, available software provides the project manager the opportunity to define its own priority rules and therefore the possibility to choose the most appropiate one for the project that sould be carried out.

3.2 Objective

The main goal of this document is to give the reader an insight into the working of the project management and specifically in the RCPSP as well as to introduce the problem of the Area´s resource.

This document will offer information about the obtained results for the different priority rules and could be used to choose the most appropiate one according to the characteristics of the project the reader sould face with.

The objective of this writting will be also to introduce the Area Resource to the cientific comunity in order to make possible to solve in the best propper way those building work´s projects which are highly affected by surface constraints.

3.3 Methodology

Through this pages the reader will find after this introduction in capter 3 an historical review of project management and specifically the RCPSP. 18 priority rules have been studied and detailed as well as clarified with examples of two different projects. At the end of this chapter a short explanation of why those 10 different priority rules have been chosen to be implemented could be also read.

Chapter 4 focuses on the software used to implement the different priority rules, explaining also the importance of simulation not only in project management but also in plannification and production.

Chapter 5 is left to explain and to analyze the obtained results as well as to yield the conclusions for the studied priority rules.

Chapter 6 begins with the section of the Area´s resource. In this chapter an introduction to the resource is going to be done. The chapter follows with a small section of theory and explanation. The most important part is to now how the resource in the implementation was done and moreover what can it improve.

Chapter 7 yields the conclusion for these new resource for the different priority rules that have been studied.

To finish, chapter 8 is left to specify the suggested future investigations paths the scientific community sould develop.

4 State of the Art & Related work

4.1 Historical review on project management

Until 1900s civil engineering projects were managed by architects, engineers and master builders themselves and is not till 1950s that organizations started to use project management tools sistematically in their projects. [You-05]

Two people were essencial in the development of project management tools. The first one is Henry Gantt, called the father of planning and control techniques, who developed the Gantt Chart, one of the most important project management tools. The second one is Henri Fayol for his creation of the five management functions (to forecast and plan, to organize, to command, to coordinate and to control) that form the foundation of the body of knowledge associated with project and program management. [Wit-03]

In the 1950s born the new era of project management. It became recognized as a distinct discipline. At that time the Critical Path Method (CPM) was developed as a new project scheduling model. Not less important was also the development of the Program Evaluation and Review Technique (PERT) and both were quickly spread into many enterprises.

In 1967 the International Project Management Association (IPMA) was founded in Europe as a federation of several national project management associations. Two years later, in 1969, the Project Management Institute was formed in the USA. [Cle-06]

4.2 Resource-Constraint Project Scheduling Problem

The Resource-Constraint Project Scheduling Problem (RCPSP) involve assigning jobs or tasks to a resource or set of resources with limited capacity in order to meet some predefined objective. [Yan-01]

Resource constraints relate to the lack of adequate resources which may force parallel activities to be performed in sequence. [PSU-05a]

Projects can be classified from a scheduling point of view as either time constrained or resource constrained. The time constrained project is the one that in situations where the critical path is delayed the addition of resources can bring the project back in the schedule time and hence complete the project in the required date. In this situations the project manager must decide whether to increase the amount of resources used to achieve the project in the scheduled time is worth or not. On the other hand, a project is resource constrained if the level of resource availability can not be exceeded. In these type of projects a delay is permitted but the manager must schedule the activities in order to reduce the makespan to the minimum possible. The focus of scheduling in this situations is to allocate the available resources in the best way in order to reduce the delay of the project. [PSU-05b]

There are two mainly kinds of RCPSP, the single-mode and the multi-mode scheduling problem.

In the single-mode RCPSP for every activity, both duration and its requirement for a set of resources are fixed and hence, only one execution mode is available for any activity. The project is generally considereed as a network of activities which can be represented as a Graph G(N,A) where the nodes represent activities and the arcs in the graph represent precedence relationships. That means that if arc (i,j) exists, activity i must be finished before activity j is allowed to begin. Two kinds of relation could exist between this two activites. First one is that activity j can be started at any time following completion of activity i or the second one are cases in which activity j has a time window to be scheduled after or before completion of activity i. [Yan-01]

In the multi-mode RCPSP the main difference with regard to the single mode is that activities do not have a fixed duration and resource requirement but a fixed work content. That means that if for example activity i has a work content of 10 resource-period of time the activity could be realized in 10 periods of time using 1 resource (mode 1) or may be done in 5 periods of time using 2 resources simultaneously (mode 2).

The set of resources could be for both single and multi-mode RCPSP renewable or non-renewable. The renewable resources have usually the same availability for every

period of time whereas the non-renewable are limited and therefore depleted after a certain amount of consumption. []bibo yang]

4.3 Priority Rules

Priority rules were created to deal with the resource-constrained project scheduling problem, triying to offer a mathematical, intuitive and robust solution to it. As the RCPSP belongs to the NP-hard problems, both exact and heuristic approches have been developed. Due to the complexity and the big amount of operations the algorithm sould carry out, exact procedures are not usually used to solve RCPSP in big projects.

Priority rules are not exact procedures, however they yield a good solution for the scheduling of the activities in a project in a much less amount of algorithm operations than the exact procedures. The effectiveness of every priority rule has a small dependence on the duration and resources of every activity in a project, hence it is not possible to say that one concrete priority rule is the best one and yields the best results for every project.

4.3.1 Theory and explanation of the priority rules

In this chapter 21 different priority rules are going to be explained and detailed with two different brief projects examples in order to clarify and make it easy for the reader to understand. Some characteristics of every priority rule have been explained as well.

The first example used is one with five parallel activities and two different kind of resources, A and B. The duration, as well as the necessary resources for every activity are shown inside a circle for all of them. For every single period of time, the available amount of resources is equal to one for both resources A and B. The left part of every activity will be used to clarify the priority value of the corresponding activity and thus the order of execution. The activity with the maximum priority will have had painted the five lines, the second activity four lines, the third will have three and so on. The reader is recommended to draw the project in a separate sheet in order to follow the examples and explanations in an easier way.
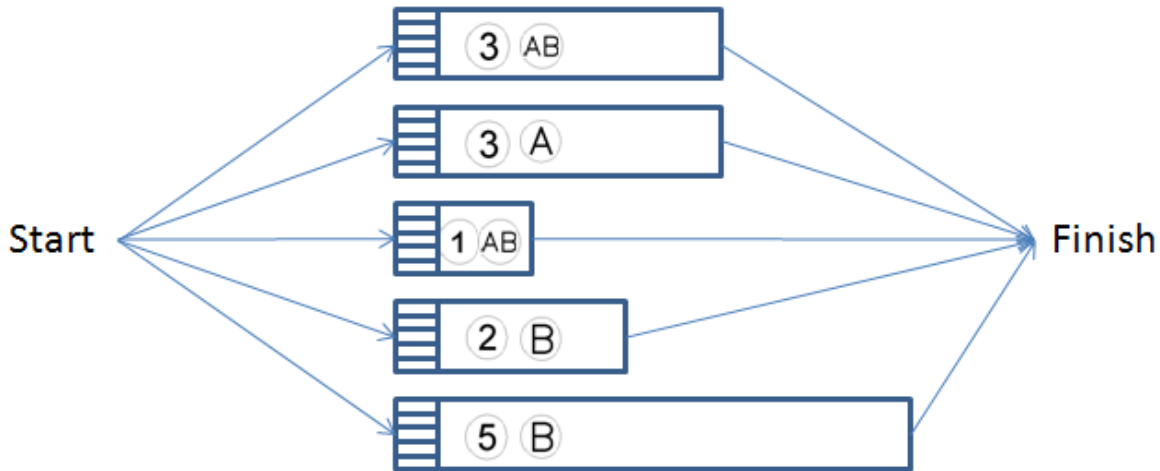
Figure 4-1: First project example

As an example, the first activity has a duration of three periods of time and needs a unit of both resources.

.1   Resource Scheduling Method (RSM)

The RSM is a classical priority rule undertaken in different studies like Davis and Patterson 1975 [Dav-75], Boctor 1990 [Boc-90] and Kolisch 1996 [Kol-96].

The priority value for every activity is assigned as follows. The activity with the highest priority is the one that induces the minimum delay when scheduled to the rest of activities in the decision set (AP_n) beyond its Latest Start Time (LST). The formula used to calculate the delay for activity j according to the RSM priority value is

$$v(j) = max \ \{0, \ t_n + d - LST(i,j) \ \mathcal{E} \ AP_n\} \qquad \qquad (3\text{-}1)$$

and the activity with the minimum value is selected .

t_n is the scheduling´s time of the activities.

For the given example the LTS and duration for the tasks can be seen in the next table.

Table 4-1: RSM- Duration and Latest Start Time

Activity	Duration	LST
1	3	2
2	3	2
3	1	4
4	2	3
5	5	0

Once the LST is known, the value for the first activity is calculated by the RSM as follows.

$$v(1) = max \{0, t_n + d_1 - LST_2, t_n + d_1 - LST_3, t_n + d_1 - LST_4, t_n + d_1 - LST_5\} = max \{0, 0 + 3 - 2,$$
$$0 + 3 - 4, 0 + 3 - 3, 0 + 3 - 0\} = 3 \qquad (3\text{-}2)$$

The values for all activities as well as the priority in scheduling the activities are shown in table A-2

Table 4-2: First iteration for the RSM priority rule

Activity	Duration	LST	Value $v(j)$	Priority
1	3	2	max {0, 1, -1, 0, 3}=3	3
2	3	2	max {0, 1, -1, 0, 3}=3	3
3	1	4	max {0, -1, -1, -2, 1}=1	1
4	2	3	max {0, 0, 0, -2, 2}=2	2
5	5	0	max {0, 3, 3, 1, 2}=3	3

Then activity 3 is first scheduled. As there are no more available resources, the second iteration begins when activity 1 is finished, at $t_n=1$.

Table 4-3: Second iteration for the RSM priority rule

Activity	Duration	LST	Value $v(j)$	Priority
1	3	2	*max {0, 2, 1, 4}=4*	2
2	3	2	*max {0, 2, 1, 4}=4*	2
4	2	3	*max {0, 1, 1, 3}=3*	1
5	5	0	*max {0, 4, 4, 3}=4*	2

The next activity in been scheduled is now activity 4. As activity 4 needs only the resource of type B if another activity needs only resource A could be scheduled simultaneously. Thus the only activity that needs resource A is activity 2 and is then scheduled. The process continues and the project is finally scheduled as shown in the picture below with a total duration of 11 units time. Critical path is represented by the arrows involving activities 1,3,4,5.
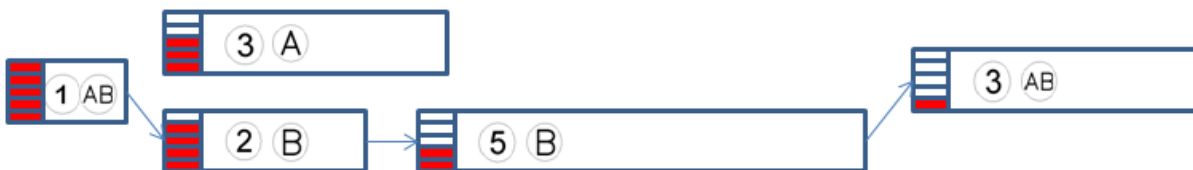
Figure 4-2: Project solution for the RSM priority rule

.2 Improved Resource Scheduling Method (IRSM)

It was created and published in [Kol-96]. This priority rule divides the set of activity pairs AP_n into three different groups:

- Generally Forbidden Pairs (GFP_n) contains the set of activities that due to resource constraints can never be scheduled simultaneously.
- Termporarily Forbidden Pairs (TFP_n) contains the set of activities that can not be scheduled simultaneously because of a lack of the resources available at the schedule time.
- Currently Schedulable Pairs (CSP_n) contains the set of activities that can be scheduled simultaneously at the schedule time.

The time in which a pair of activities will be scheduled simultaneously depends on the group they belong to. $\prod_{(i,j)}$ is the earliest time for any activity pair to be scheduled simultaneously and is calculated as follows. If the pair belongs to the GFP$_n$, $\prod_{(i,j)} = \infty$ and if it belongs to the CSP$_n$, $\prod_{(i,j)} = t_n$. For the activities in the TFP$_n$ group the $\prod_{(i,j)}$ must be calculated according to the following formulas.

$$\prod{'}_{(i,j)} = min\{\tau \quad \Sigma \; k_{hr} + \pi K_r \geq k_{ir+} k_{jr} \, , \; \tau = t_n \, , ..., \; T/ \; \}, \; (i,j) \; \in TFP_n \; and \; h \in A_n \, /FT_h <n \qquad (3\text{-}3)$$

$$\prod{}_{(i,j)} = max \; \{ \; \prod{'}_{(i,j)} \; / \; r \in R\}, \; (i,j) \in TFP_n. \qquad (3\text{-}4)$$

The earliest time to schedule activity j if activity i is started at t_n is for every kind of group of pairs as follows.

$$E(i,j) = min\{t_n + d_i \, , \; \prod{}_{(i,j)} \in AP_n\} \qquad (3\text{-}5)$$

Once $E(i,j)$ is calculated, the value assigned to an activity j is equal to

$$v(j) = max \; \{ \; 0, \; E(i,j)\text{-}LST_i \, /(i,j) \in AP_n\} \qquad (3\text{-}6)$$

and the activity with the minimum value is selected. That means that the scheduled activity induces the minimum increase of the precedence based lower bound for the not chosen activities in the decision set.

In order to clarify and make easy for the reader to understand this priority rule, a new example will be shown.

In the first iteration $t_n = 0$ and as none of the resources have already been used, there are only two different cases of pairs to study, GFP$_n$ and CSP$_n$.

An example of GFP$_n$ can be studied with the pair of activities 1 and 3 and as told above.

$$\prod{}_{(1,3)} = \infty \qquad (3\text{-}7)$$

$E(1,3) = min\{t_n + d_1 \, , \; \prod{}_{(1,3)} \in AP_n\} = min\{0 + 3 \, , \; \infty \; \in AP_n\} = 3$ that means that scheduling activity 1 that has a duration of 3 periods of time, induces a delay of 3 periods of time to the activity 3.

An example of CSP$_n$ can be studied with the pair of activities 2 and 4.

$$\prod{}_{(2,4)} = 0 \qquad (3\text{-}8)$$

$E(2,4)=min\{t_n + d_2, \prod_{(2,4)} \in AP_n\}= min\{0 +3, 0 \in AP_n\} = 0$ that means that scheduling activity 2 that has a duration of 3 periods of time, does not induce a delay in the activity 4.

Once calculated $E(i,j)$ for every pair of activities, it is possible to assign the proper value according to the IRSM priority rule to every activity and hence the priority for all of them. This is done in the table below.

Table 4-4: First iteration for the IRSM priority rule

Activity	Duration	LST	Value $v(j)$	Priority
1	3	2	*max {0, 1, -1, 0, 3}=3*	4
2	3	2	*max {0, 1, -1, -3, 0}=1*	1
3	1	4	*max {0, -1, -1, -2, 1}=1*	1
4	2	3	*max {0, 0, -2, -2, 2}=2*	3
5	5	0	*max {0, 3, -2, 1, 2}=3*	4

As both activities 2 and 3 have the same priority it will depend on the software to schedule one or the other in first case. In the example here shown the study will be carried out scheduling activity 3 in first place, but at the end of it both possibilities will be represented.

Scheduling activity 3 do not allow to schedule any other activity simultaneously therefore the second iteration must be started at $t_n=1$ when it would has finished. The values for the second iteration are represented in the table below.

Table 4-5: Second iteration for the IRSM priority rule

Activity	Duration	LST	Value $v(j)$	Priority
1	3	2	*max {0, 2, 1, 4}=4*	3
2	3	2	*max {0, 2, -2, 1}=2*	1
4	2	3	*max {0, 1, -1, 3}=3*	2
5	5	0	*max {0, 4, -1, 3}=4*	3

The next activity in been scheduled is now activity 2. As activity 2 needs only the resource of type A if another activity needs only resource B could be scheduled simultaneously. Thus the activities that need resource B are 4 and 5 and as task 4 has more priority than 5 then is scheduled. The process continues and the project is finally scheduled as shown in the picture below with a total duration of 11 units time. The new Critical path considering resources is represented by the arrows involving activities 1,3,4,5.
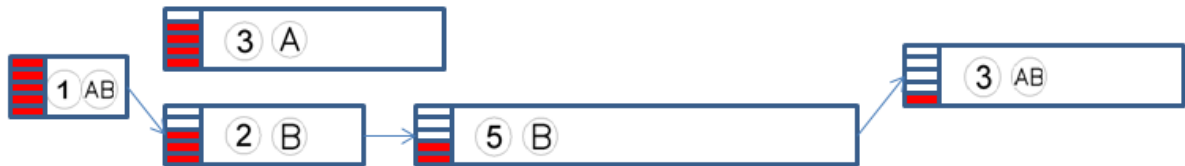
Figure 4-3: First solution for the IRSM priority rule

Figure 4-4: Second solution for the IRSM priority rule

.3 **Minimum SLacK (MSLK)**

It is a classical priority rule that gives preference to those activities which are in the critical path or whose LST is close to the schedule time. The value is given according to the formula

$$v(j) = LST_j - t_n \qquad (3\text{-}9)$$

and the activity with the minimum value is selected. [Kol-96]

For the given example the values for the first iteration ($t_n=0$) can be seen in table A-6

Table 4-6: First iteration for the MSLK priority rule

Activity	Duration	LST	Value $v(j)$	Priority
1	3	2	*2-0=2*	2
2	3	2	*2-0=2*	2
3	1	4	*4-0=4*	5
4	2	3	*3-0=3*	4
5	5	0	*0-0=0*	1

Then activity 5 is first scheduled. As it only requires resource from type B, activity 2 is also scheduled. After finishing activity 2, as none of the remaining tasks employs only resource A, the second iteration will be started at $t_n=5$. The process continues scheduling activity 2, after that 4 and activity 3 is left for the end. Critical path is represented by the activities 5, 3, 2, 1 and the duration is 11 periods of time.

Figure 4-5: Project solution for the MSLK priority rule

.4 Worst Case Slack (WCS)

This priority rule was created and first published in Kolisch (1996). It combines concepts used in the IRSM with the fundaments of the MSLK. The priority value assigned to every activity according to the WCS is as follows.

$$v(j) = LST_j - max \{ E(i,j)/(i,j) \in AP_n\}. \tag{3-10}$$

With $E(j,i)$ the earliest time to schedule activity j if activity i is started at t_n calculated in the same way as fort he IRSM. The activity with the minimum value is selected. [Kol-96]

The WCS priority rule would solve the example as follows.

Table 4-7: First iteration for the WCS priority rule

Activity	Duration	LST	Value $v(j)$	Priority
1	3	2	2- max {3,3,3,3}=-1	2
2	3	2	2- max {3,3,0,0}=-1	2
3	1	4	4- max {1,1,1,1}=3	5
4	2	3	3- max {2,0,2,2}=1	4
5	5	0	0- max {5,0,5,5}=-5	1

Then activity 5 is first scheduled. As it only requires resource from type B, activity 2 is also scheduled. After finishing activity 2, as none of the remaining tasks employs only resource A, the second iteration will be started at $t_n=5$. The process continues scheduling activity 2, after that 4 and activity 3 is left for the end. Critical path is represented by activities 5, 3, 2, 1 and the duration is 11 periods of time.
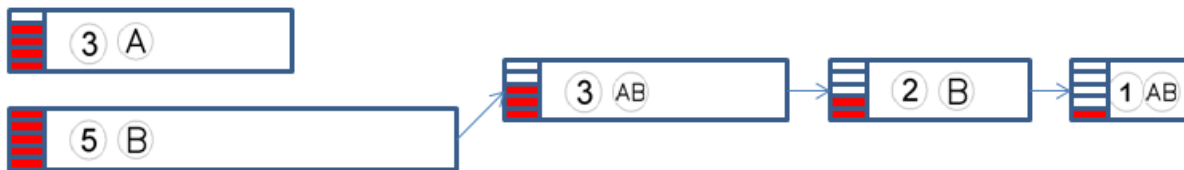

Figure 4-6: Project solution for the WCS priority rule

.5 Average Case Slack (ACS)

It is also created and first used in [Kol-96]. It combines as well concepts used in the IRSM with the fundaments of the MSLK. The priority value assigned to every activity according to the ACS is

$$v(j) = LST_j - \frac{}{} \Sigma_{(i,j) \in APn} E(i,j) \tag{3-11}$$

D_n is the number of activities in the decision set and the activity with the minimum value is selected.

For the given example the values for the first iteration ($t_n=0$) can be seen in table 3-8

Table 4-8: First iteration for the ACS priority rule

Activity	Duration	LST	Value $v(j)$	Priority
1	3	2	$2-¼(3+3+3+3)= -1$	2
2	3	2	$2-¼(3+3+0+0)= 1/2$	3
3	1	4	$4-¼(1+1+1+1)= 3$	5
4	2	3	$3-¼(2+0+2+2)= 3/2$	4
5	5	0	$0-¼(5+0+5+5)= -15/4$	1

Now activity 5 is first scheduled. As it only requires resource from type B, activity 2 is also scheduled. After finishing activity 2, as none of the remaining tasks employs only resource A, the second iteration will be started at $t_n=5$. The process continues scheduling activity 2, after that 4 and activity 3 is left for the end. Critical path is represented by the activities 5, 3, 2, 1 and the duration is 11 periods of time.
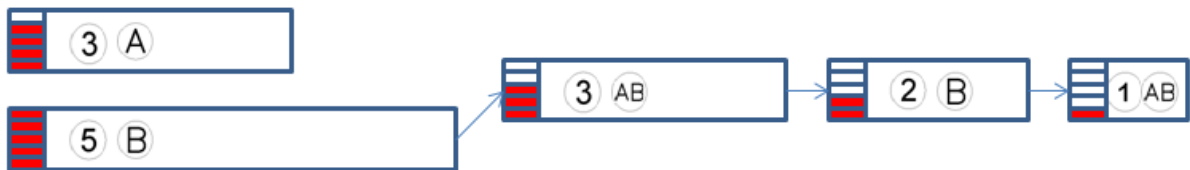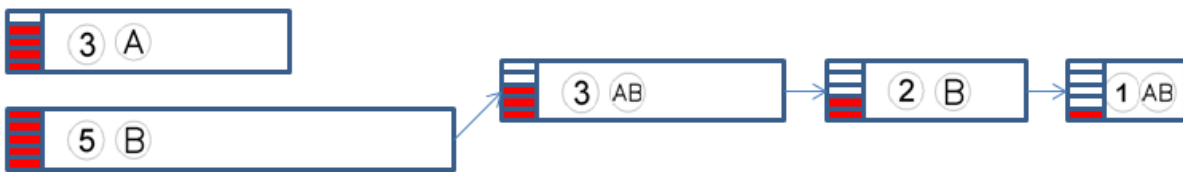

Figure 4-7: Project solution for the ACS priority rule

.6   Shortest Processing Time (SPT)

It is a classical priority rule that gives priority to the shortest activities. The value is calculated with the formula

$$v(j) = d_j \qquad\qquad (3\text{-}12)$$

and the activity with the minimum value is then scheduled. [Sim-96]

In the studied example, the first iteration is again calculated for $t_n=0$ and the values obtained as well as the priority are shown in the following table.

Table 4-9: First iteration for the SPT priority rule

Activity	Duration	LST	Value $v(j)$	Priority
1	3	2	*3*	3
2	3	2	*3*	3
3	1	4	*1*	1
4	2	3	*2*	2
5	5	0	*5*	5

In the first iteration the actvity 3 is the first in been scheduled. The project will follow executing in $t_n=1$ activity 4 and 2. Later in $t_n=3$ activity 5 would be scheduled and the last one would be activity 1. The critical path has a duration of 11 periods of time and is represented by activities 1, 4, 5, 1.

Figure 4-8: Project solution for the SPT priority rule

.7 Maximum Activity Duration (MaxDur)

It is another classical priority rule that in opposition to the SPT gives priority to the longest activities. The value given to every task is calculated with the formula

$$v(j) = d_j \tag{3-13}$$

and the activity with the maximum value is then scheduled. [Sim-96]

In the studied example, the first iteration is again calculated for $t_n=0$ and the values obtained as well as the priority for every task are shown in the table 3-10.

Table 4-10: First iteration for the MAxDur priority rule

Activity	Duration	LST	Value $v(j)$	Priority
1	3	2	3	2
2	3	2	3	2
3	1	4	1	5
4	2	3	2	4
5	5	0	5	1

In the first iteration the activity 5 that has a duration of 5 periods of time will be first scheduled. As it only needs resources from type B, activity 2 will also be executed. Then activity 1 will be scheduled in $t_n=5$ and activities 4 and then 3 will be left for the end. The project duration is 11 periods of time and critical path is formed by tasks 5, 1, 4 and 3.
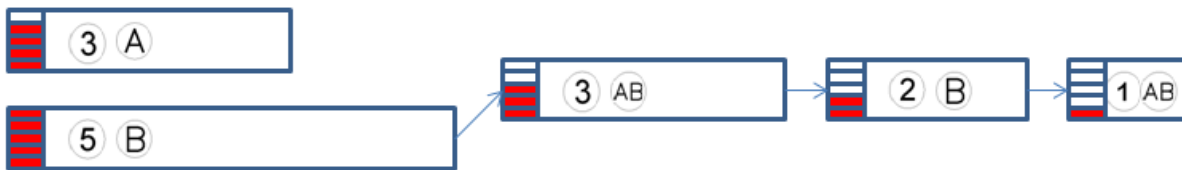
Figure 4-9: Project solution for the MAxDur priority rule

.8 Greatest Resource Demand (GRD)

This priority rule was developed to avoid potencial bottlenecks actvities. It takes into account not only the amount of resources the activity needs but also the duration. The value is assigned to every task according with the formula

$$v(j) = d_j \sum_{k=1 \text{ to } K} R_{jk} \qquad (3-14)$$

being R the number of resources per period time and k the different types of resources and the activity with the maximum value is first scheduled. [Sim-96]

The GRD priority rule would solve the example as follows.

Table 4-11: First iteration for the GRD priority rule

Activity	Duration	LST	Value $v(j)$	Priority
1	3	2	$3*1+3*1=6$	1
2	3	2	$3*1=3$	3
3	1	4	$1*1+1*1=2$	4
4	2	3	$2*1=2$	4
5	5	0	$5*1=5$	2

The first iteration yields that the activity with the most priority is task 1. Then, according to the values given, activity 5 would be the next one. At the end, the critical path would be formed by activitites 1, 5, 3 and 4.
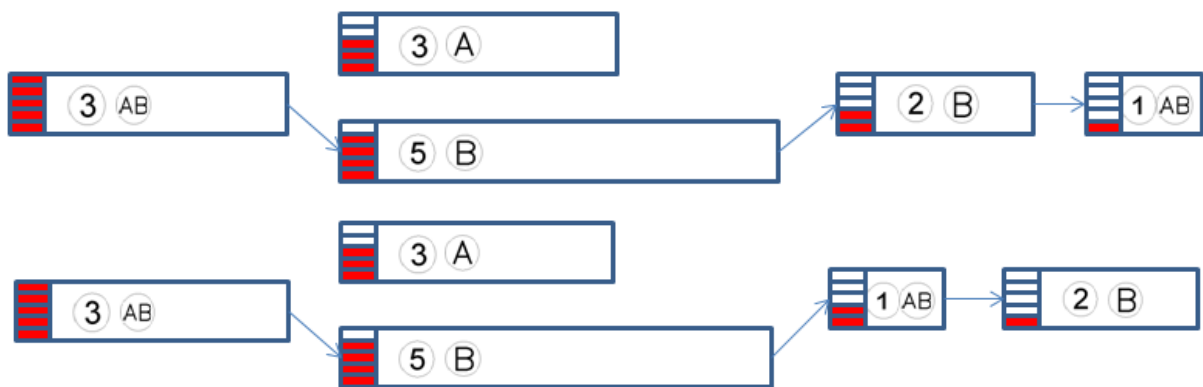
Figure 4-10: Project solutions for the GRD priority rule

Because of the same value that activities 3 and 4 have, both ways of scheduling the activities could be used.

.9 Minimum Resource Requirement (MRR)

This priority rule has the same principle as the GRD and the formula used to assign values is the same but now priority is given to those activities with the minimum value. [Bou-03]

For the given example the values for the first iteration ($t_n=0$) can be seen in table A-11.

Table 4-12: First iteration for the MRR priority rule

Activity	Duration	LST	Value $v(j)$	Priority
1	3	2	*3*1+3*1=6*	5
2	3	2	*3*1=3*	3
3	1	4	*1*1+1*1=2*	1
4	2	3	*2*1=2*	1
5	5	0	*5*1=5*	4

As both activity 3 and 4 has the same priority, two different ways of making the proyect can be carried out. Both duration and activities in the critical path are the same for the two different ways of execution.
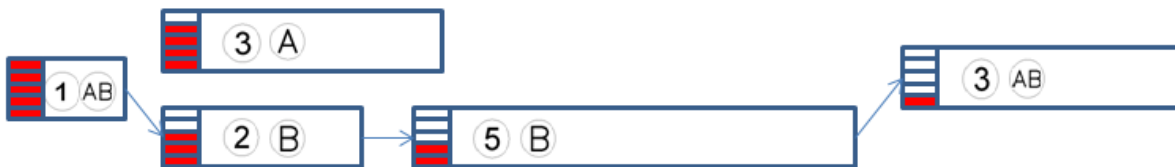
Figure 4-11: Project solution for the MRR priority rule scheduling first activity 3

Figure 4-12: Project solution for the MRR priority rule scheduling first activity 4

As commented at the beginning of this chapter, another example will be used in order to clarify and explain in a more detailed way the remaining priority rules. In this second example the duration and necessary resources could also be seen inside a circle for every activity and the total amount of resources per unit time is as with the previus example 1 for both resource A and B. The main different now is the introduction of activities that have successors and predecessors tasks. As well as with the previous project, the activity with the highest priority will have five lines painted

and the one with the lowest priority only one. The new example can be seen in the figure below.
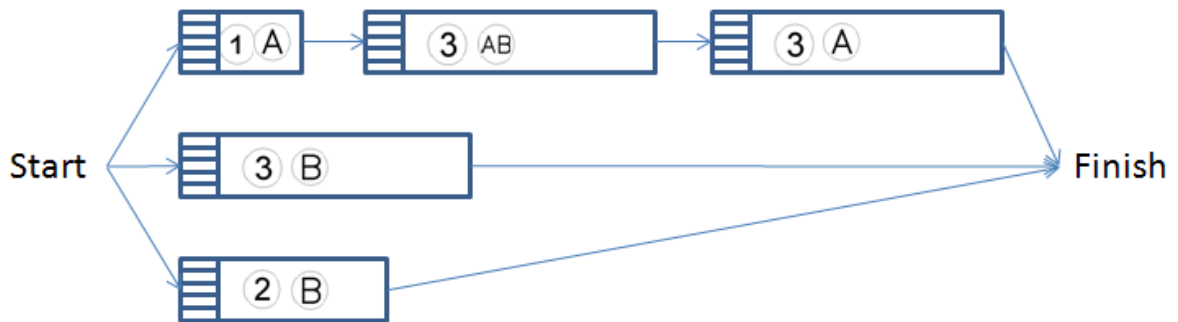
Figure 4-13: Second project example

The numeration for the activities is from up to down and left to right hence activity 1 is the activity with duration 1 and the activity 5 the activity with duration 2 and necessary resource of type B. The reader is again encouraged to draw the project in a separate sheet.

The following table shows the duration LST and Earliest Star Time (EST) for every activity.

Table 4-13: Duration and LST for the RSM priority rule

Activity	Duration	LST	EST
1	3	0	0
2	3	1	1
3	1	4	4
4	2	4	0
5	5	5	0

.10 **Minimum Early Finish Time (MinEFT)**

According to this priority rule, the values for every tasks are their Early Finish Time (EFT) so they must be calculated by backwards pass. The EFT is the Early Start Time (EST) plus the duration of the activity. This priority rule hence depends not on the schedule time (t_n). The formula then used for the assgined values is:

$v(j) = EST_j + d_j$ or directly $v(j) = EFT_j$ (3-15)

And the activitity with the minimum value is then selected. [Sim-96]

Using the new example, the first iteration $(t_n=0)$ will assign values as follows.

Table 4-14: First iteration for the MRR priority rule

Activity	Duration	EST	Value $v(j)$	Priority
1	1	0	0+1=1	1
2	3	1	1+3=4	4
3	3	4	4+3=7	5
4	3	0	0+3=3	3
5	2	0	0+2=2	2

As can be seen in the table, the activity with the highest priority is activity 1. Activity 5 because of the availability of resources could be scheduled simultaneously. Then the second iteration would be at $t_n=2$ and activity 4 will be scheduled. As long as activity 2 has not yet been finished activity 3 can not be scheduled at the same time with activity 4. The graphic below shows the way of performing this project. Finally, it has a duration of 11 periods of time and activities in the critical path are 5, 2, 3 and 4.
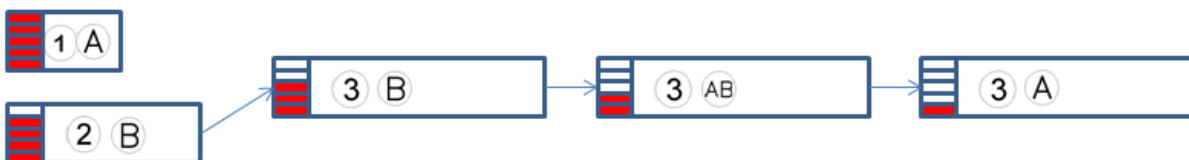

Figure 4-14: Project solution for the MinEFT priority rule

.11 **Greatest Cumulative Resource Requirement (GCRR)**

With this priority rule, priority is given to those activities which need a bigger load of work content for completing not only them but also their successors. The formula then used is

$$v(j) = d_j \Sigma_{k=1 \text{ to } K} R_{jk} + \Sigma_{n=1 \text{ to } N} (d_n \Sigma_{k=1 \text{ to } K} R_{nk}) \qquad (3\text{-}16)$$

The first term is the duration times the amount of every resource the activity needs for its completion and the second term the duration times the amount of resource for all its successors. The activity with the maximum value is selected. [Kum-98]

For the given example, the first iteration is as shown in the table 3-15. $t_n=0$ and the available activities in being scheduled are 1, 4 and 5.

Table 4-15: First iteration for the GCRR priority rule

Activity	Duration	EST	Value $v(j)$	Priority
1	1	0	$1*1+3*2=7$	1
4	3	0	$3*1=3$	2
5	2	0	$2*1=2$	3

Then the first activity in been scheduled is activity 1. As there are remaining resources available, activity 4 will be scheduled simultaneously.

The second iteration will continue with activities 2 and 5 as follows.

At $t_n=1$ neither activity 2 nor 5 can be scheduled because of resource inavailbility, then the next schedule time will be at $t_n=3$ when activity 4 would have already been finished .

The second iteration is shown in the table 3-16.

Table 4-16: Second iteration for the GCRR priority rule

Activity	Duration	EST	Value $v(j)$	Priority
2	3	1	$3*2+3*1=9$	1
5	2	0	$2*1=2$	2

As activity 2 has now the highest priority and there are enough resources available to it, is therefore scheduled. The process follows and at $t_n=6$ the remaining activities are 3 and 5. Now priority will be for activity 3 but due to resource disponibility, both activities 3 and 5 will be scheduled simultaneously. Thus the project duration will be 9 periods of time and the critical path is formed by activities 4,2,3. The solution of the project could be sawn in the figure below.

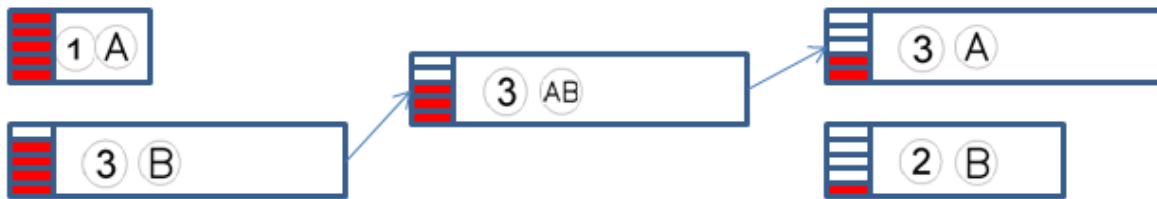**Figure 4-15: Project solution for the GCRR priority rule**

## .12 Smallest Cumulative Resource Requirement (SCRR)

The formula used to assign values to every activity is the same as for the Greatest Cumulative Resource Requirement but in this case the activities chosen are those whose value is the smallest. [Kum-98]

Hence for the given example the appropiate solution according to the SCRR is as follows.

Table 4-17: First iteration for the GCRR priority rule

Activity	Duration	EST	Value $v(j)$	Priority
1	1	0	*1*1+3*2=7*	3
4	3	0	*3*1=3*	2
5	2	0	*2*1=2*	1

The highest priority is given to activity 5 which is then scheduled. As there are no available resources for activity 4 to be scheduled simultaneously with activity 5, in the first iteration activity 1 will also be scheduled. Following the process as explained, the SCRR yields the following solution. Critical path is now delimited by activities 5, 2, 3 and 4 and the duration of the project is 11 periods of time.
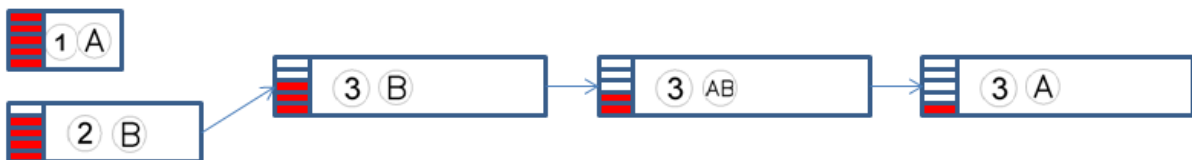
Figure 4-16: Project solution for the GCRR priority rule

.13 Greatest Number of Successors (GNS)

This priority rule focuses on the number of succesors every activity have. The value assigned then is simply the total (not only inmediate) number of successors and the activity with the biggest value is then chosen. Hence, this priority rule gives priority to those activities that has a big amount of successors in order to eliminate or reduce possible bottle-ties. [Kum-98]

Scheduling the example project according to this priority rule will be as shown below.

Table 4-18: First iteration for the GNS priority rule

Activity	Duration	EST	Value $v(j)$	Priority
1	1	0	*2*	1
2	3	1	*1*	2
3	3	4	*0*	3
4	3	0	*0*	3
5	2	0	*0*	3

As can be sawn the highest priority yields on activity 1 an hence is first scheduled. The problem now is that both activity 4 and activity 5 due to resource availability could also been scheduled and have the same priority. Hence two different solutions for the project could be reached. Both solutions are shown in the figures below.

Figure 4-17: First solution for the GNS priority rule

Figure 4-18: Second solution for the GNS priority rule

The first one involves scheduling activity 4 first and has a duration of 9 periods of time whereas scheduling activity 5 simultaneously with activity 1 will decrease the duration in 1 period of time.

The critical path in the first solution is formed by activities 4, 2 and 3 and in the second solution by activities 5, 2 and both 3 and 4.

.14 Smallest Number of Successors (SNS)

As for the previous priority rule, the value for every task is assigned according to the number of total successors but the difference here is that the activity with the highest priority is the activity with the minimum instead of the maximum number of successors. [Kum-98]

Then for the given example the solution of he project would be as follows.

Table 4-19: First iteration for the SNS priority rule

Activity	Duration	EST	Value $v(j)$	Priority
1	1	0	*2*	5
2	3	1	*1*	4
3	3	4	*0*	1
4	3	0	*0*	1
5	2	0	*0*	1

Both activity 4 and 5 has the highest priority but due to a lack of the amount of resources only one of them could be first scheduled. So again 2 differents ways of solving the project could be reached.
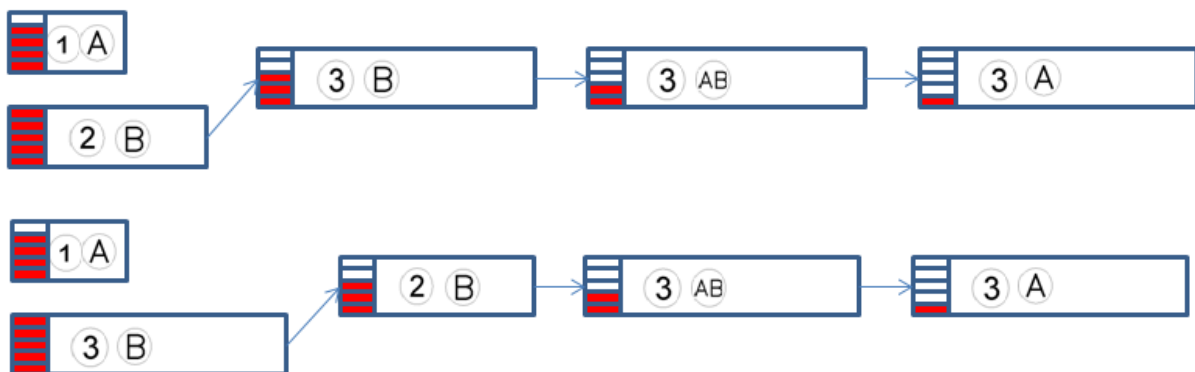

Figure 4-19: Two possible solutions for the SNS priority rule

As can be shawn, duration for both is 11 periods of time and therefore none of them yields good results.

.15 Rank Positional Weight (RPW)

It is a classical priority rule that focuses in the duration of the activty and the duration of all its successors. Hence, this priority rule gives usually priority to those activities which have many successors with a long duration. The value then given for every activity is the sum of its duration plus the duration of all its successors as can be san in the formula below. [Kum-98]

$$v(j) = d_j + \Sigma_{n=1 \ to \ N} \ d_n \ where \ N \ is \ the \ total \ number \ of \ successors. \qquad (3\text{-}16)$$

The table below shows the result for the first iteration for the studied project example.

Table 4-20: First iteration for the RPW priority rule

Activity	Duration	EST	Value $v(j)$	Priority
1	1	0	$1+3+3 = 7$	1
2	3	1	$3+3=6$	2
3	3	4	3	3
4	3	0	3	3
5	2	0	2	5

Then the activity first scheduled is activity 1 and simultaneously is also executed activity 4. The process follows then with activity 2 and at the end activities 3 and 5 will be scheduled simultaneously. The project duration is 9 periods of time and the activities in the critical path are now 4, 2 and 3.

Figure 4-20: Project solution for the RPW priority rule

.16 **Long Path Following (LPF)**

It is another classical rule that focuses in the duration of the activities and the duration of all its successors but the difference with the RPW is that takes only into account not all the successors but only those that will be in the critical path for the evaluated activity. That means starting with the evaluating activity which is the longest path among all its successors to accomplish the project. Hence, this priority rule gives priority to those activities in the critical path. [Sti-78]

For the given example, the project would be solved as follows.

Table 4-21: First iteration for the RPW priority rule

Activity	Duration	EST	Value $v(j)$	Priority
1	1	0	$1+3+3 = 7$	1
2	3	1	$3+3=6$	2
3	3	4	3	3
4	3	0	3	3
5	2	0	2	5

As can be sawn to finish the project from the point of view of activity 1, the path to accomplish the project is adding to its duration the duration of activity 2 and 3. The difference with the RPW could be clearly sawn in the following example. The reader has to imagine that another activity of duration 4 (activity 6) in parallel with activity 3 is now added. The value that the RPW would assign to activy 1 would be 7+4=11 but according to the LPF the value would be determined between the maximum of the two possible paths to accomplish the project. The first path will be as sawn before involving activities 1, 2 and 3 and would have a duration of 7 periods of time. The second path would be involving activities 1, 2 and now instead of activity 3, activity 6 and hence the duration would be of 8 periods of time. As 8 is bigger than 7, the value that the LPF would assign to activity 1 would be 8.

Following now with the studied example (without activity 6) activity 1 with a value of 7 would have the highest priority and therefore would be first executed. Simultaneously with activity 1, task 4 would also be scheduled. The solution for the project would be as follows.

Figure 4-21: Project solution for the RPW priority rule

The total duration for the project is 9 periods of time and the activities that form part of the critical path are now 4, 2 and 3.

.17 **Great Number of Inmediate Successors (GNIS)**

In this rule the priority is given to the activity that has the largest number of inmediate successors. It is a easy and functional priority rule that try to avoid bottle-ties. [Kum-98]

As done with the previous priority rules, a example for the studied project will be solved.

Table 4-22: Iteration for the GNIS priority rule

Activity	Duration	EST	Value $v(j)$	Priority
1	1	0	*1*	1
2	3	1	*1*	1
3	3	4	*0*	3
4	3	0	*0*	3
5	2	0	*0*	3

Both activities 1 and 2 have the highest priority but in this case as activity 2 is a successor from activity 1, only activity 1 can be scheduled. But in the oder hand activity 4 and 5 have the same priority and hence two differents solutions could be reached as can be sawn in the figure below.
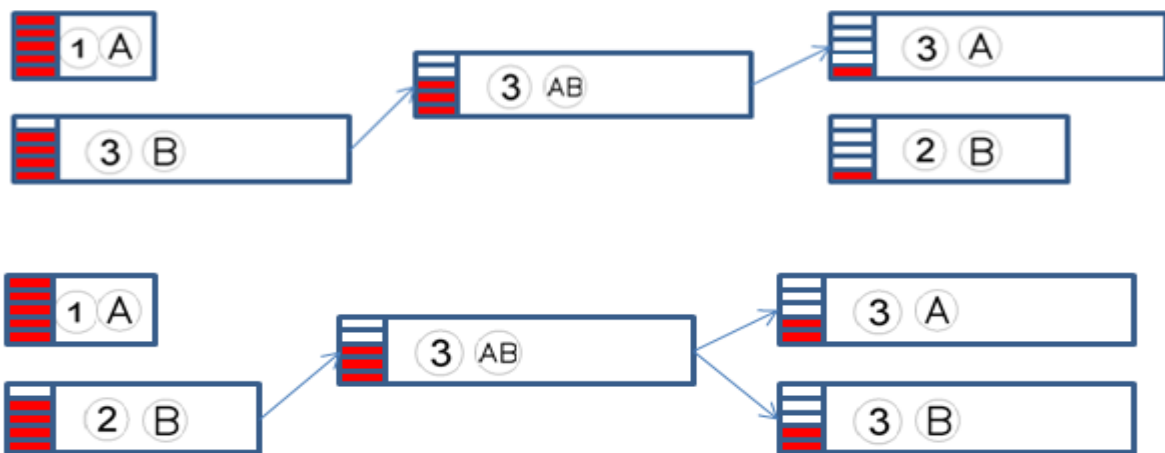
Figure 4-22: Project solutions for the GNIS priority rule

In the example the second solution yields better results with a duration of 8 periods of time instead of 9.

.18 Smallest Number of Inmediate Successors (SNIS)

The way this priority rule assigns values to the activities is the same as the previous priority rule but the activity with the minimum successors is now chosen. [Kum-98]

It is not a very efficient rule as the reader could see at the end of the example.

Table 4-23: Iteration for the GNIS priority rule

Activity	Duration	EST	Value $v(j)$	Priority
1	1	0	*1*	4
2	3	1	*1*	4
3	3	4	*0*	1
4	3	0	*0*	1
5	2	0	*0*	1

As with other examples, according to the priority of the different activities, two possible solutions can be reached. The first solution is scheduling activity 4 firstly as well as due to resource availability activiy 1. The second solution would be schedul-

ing in first place activity 5 as well as activity 1. The two possible solutions have the same duration and can be sawn in the figure below.
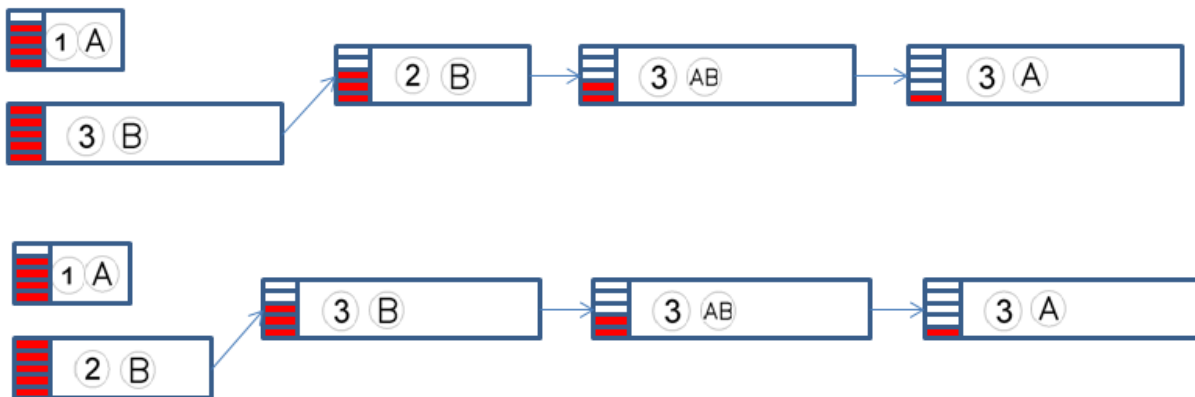

Figure 4-23: Two possible solutions for the SNIS priority rule

As can be sawn, duration for both is 11 periods of time and hence, none of them yields good results.

4.3.2 Selection of the chosen priority rules

In this document, 10 different priority rules have been implemented and studied with the help of the software Plant Simulation.

According to the paper from Kum Khiong Yang [Kum-98]:

The results show that project environment affects only the performance differences but not the grouping of the better dispatching rules. The greatest number of successors, rank postional weight, greatest cumulative resource requirement and minimum activity slack dispatching rules consistently perform better than the other dispatching rules, unaffected by the accuracy of the estimated activity durations.

Hence, those priority rules have been studied with the exception of the Rank Positional Weight that has been replaced by the Long Path Following priority rule because of their similarity and because was already used in the Technische Universität München as well.

The other activities performed are resource scheduling method, improved resource scheduling method, worst case slack and average case slack because according to Kolisch [Kol-96] were some of the best priority rules.

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The latest finish time priority rule has also been implemented due to two different reasons. First reason is that it assigns values in a very easy way and hence it is very easy to implement. The second and more important is because it requires a low amount of computational calculations and therefore as it yields not bad solutions it is a good priority rule to use to compare with solutions reached by other priority rules.

5 About Plant Simulation

In this chapter a quick overlook on the simulation software plant simulation is given. Afterwards the existing Multi-Agent System (MAS) for project scheduling is introduced

5.1 Introduction

Plant Simulation is a computer application developed by Siemens for modeling, simulating, optimizing, visualizing and analyzing the flow of materials and logistic operations in production systems.

Plant Simulation allows comparing different production alternatives, by means of computer simulations. It is broadly used in both small and multi-national enterprises in order to achieve the best plan layout, capacity and dimensions for the plant and logic control. [PSim-10]

5.2 The necessity of simulation

The computer simulation of an industrial process can be defined according to the Merrian-webster dictionary as „ the imitative representation of the functioning of one system or process by means of the functioning of another". Here remains the most important advantage in comparison with the experimentation: It is possible to obtain a good knowledge of the behaviour of the process system without a direct experimentation. [Mer-12]

The optimization of the production in every company is the key element for a medium and long term future viability due to the need of cost reducing and fully exploiting the resources at its disposal, providing mathematically safeguarded entrepreneurial decisions. Optimization can set the difference among a leader enterprise and the rest of the competitors in the market, that is why companies are using nowdays all technological, logistical and economical possibilities within their reach. [McL-01]

The computer model allows the user to run through `what if scenarios´ without the need of having to experiment with the real production environment, and even more important, while planning phase long before the real systems exists, provide good evidence of the future system behaviour helping to choose the best production method and plan layout. [McL-01]

5.3 Plant Simulation in the thesis

Within the field of the ressource-constrained project scheduling problem many different priority rules have been developed in order to reduce the project makespan. In this thesis the supposed best ten priority rules had been done and evaluated.

The algorithm created for this purpose consists mainly on two stages. The first stage is common for all priority rules and is related to the construction of the activities which are part of the project and their characteristics of duration, necessary resources and material as well as the assignment of their predecessors and successors activities. The second stage deals with the problem of scheduling every single task in a proper way in order to diminish the makespan. The way of achieving it is by simply assigning different values for every activity in order to affect their execution order, which is different for every priority rule studied

In order to be as rigorous as possible 480 different projects with 30, 60 and 90 activities and 600 projects with 120 activities have been carried out, altogether 2040 different projects for every single priority rule.

After all, a new kind of resource called as `Area resource´ has been introduced to deal with the problem of the logistic in the scheduling of projects. As explained before, the algorithm consists again on two stages with the only difference that now the new requested resource is introduced as a new characteristic of every task in the first stage and scheduled in the second according to each priority rule. [Hor-12]

5.4 Multi-Agent Scheduling System

A Multi-Agent System (MAS) is a system composed of multiple intelligent agents that interact with each other within an environment. It is used in problems that are impossible or extremely difficult for an individual agent to solve. [Sun-04]

The agents are self-contained programs which control their own decisions and operate to reach one or multiple objetives acting according to their perception of the environment.

5.4.1 Process agent

The process agents represent each activity of the project and hold the necessary information such as predecessors and successors, duration and the amount of material and resources they need. They are also provided with their respective start and completion dates.

The process agent has mechanisms to control and interact with the incoming information. These information comes from a central place and the agent processes it and accordingly operates and manipulates its state. The different states of process agents can be sawn in the table 1of Horenburg 2012 .

state	description	operations
blocked	preconditions not met	wait for predecessors
admitted	preconditions met for negotiations	registration at blackboard and call for proposals
accepted	resources allocated	wait for resources & predecessors' completion
active	resources allocated and working	finish activity in duration p_j, update successors
complete	activity finished	deallocation of resources

Figure 5-1: Different states of process agents [Hor-12d]

These states can varied according to the states of predecessors and successors and the negotiation of resources due to the interaction of process agents among each other.

5.4.2 Resource agent

Unlike the traditional approaches that used resources not as intelligent entities, in this study the path initiated in [Hor-12d] has been followed. Resources are now considered as intelligent entities which have specific functions and variables and thus, participate in the decision making. There are usually two types of resources:

- Renewable- resources available for every period of planning such as workers or machinery.
- Non-renewable- limited amount of resources which are not reusable as for example material.

Each resource agent is either renewable or non-renewable and hence, they differ in the attributes and variables and can change among three states that are free, active and reserved. [Hor-12d]

5.4.3 Bidding system

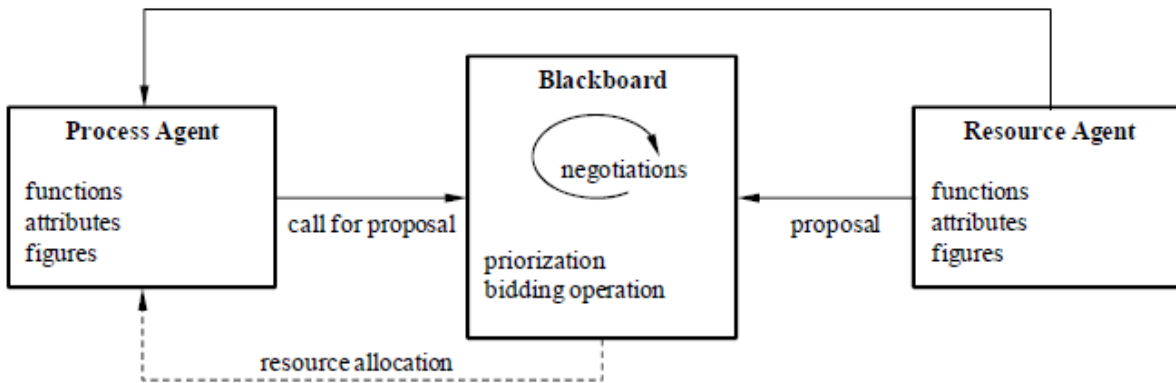The bidding system can be explained following the figure 1 of Horenburg 2012.

Figure 5-2: Multi-Agent system for project scheduling [Hor-12d]

The process agent and the resource agent have been already explained. The blackboard is the central sytem that facilitates the negotiation among process and resource agents and provides priority to the different process agents following the different priority rules.

For each negotiation time, the process agents request proposals to the blackboard and those whose state is admitted, are given a value according to the priority rule used in the blackboard. These process agents then negotiate on resource allocation while considering existing constraints. Then, the resource agents whose state is free, choose in first place the process agents with the highest priority. After the completion of the negotiation, the remaining resource agents are moved to the central resource pool , from where new proposals may be placed on the blackboard.

5.4.4 Time Window

It has been created to reserve resources to potentially more critical processes that would be admitted in the negotiation of the resource allocation in the incoming frame´s time. Traditionally, the resources were allocated immediately after the conclusion of prior activities, and with this method the necessary resources to realize an activity with high priority whose predecessors are not already finished would be re-

served. In this scenario, the time window is the frame´s time at which an activity can change its state to admitted as soon as all its predecessors reach this time. That means that if an activity could enter in the negotiation at time 17 because all its predecessors are already finished by this time, if the time window is 3, the activity will enter in the negotiation at time 14 and if the priority of this activity is the highest, the necessary resources would be reserved till time 17 in which the activity would be scheduled. Acting in this way, provides activities with high priority the inmediately allocation of resources. [Hor-12d]

5.4.5 Implementation of priority rules

The priority rules are the functions that provides different values to the process agents that are in the negotiation of resources. Once the values are assigned to each activity, the blackboard gives the priority to the activities and the allocation of resources begin. The available free resources agents are first offered to the activity with the highest priority. If the amount of necessary resources is enough, the resources are assigned to the activities and both process and resource agents change their state to active. The process continues assigning resources to the next activity with the highest priority. It is repeated till the amount of process or resource agents are finished. Once the process is finished, begin the execution of the activities. The next negotiation point begin when any of the running activities is completed and hence, change its state to complete. The state of the associated resource agents adquire the status of free as well and therefore, would be included in the next negotiation.

5.5 Example of simulation

As told in the chapter 3.3.2 IRSM is one of the priority rules that is going to be studied. In order to prove that the algorithm has been implemented in the proper way an example is going to be shown. It corresponds to the project which has parameter 1 and instanz 1 of the J30 set of projects and has been scheduled following the IRSM priority rule. This priority rule has been chosen because is one of the most difficult to implement and because it is the base used to schedule projects with the ACS and WCS priority rules. The non-dummy activities are numbered from 2 to 31 and the dummy activities are those numbered with 1 and 32 at the beginning and at the end of the figure. The arrows represent the successors and predecesors.
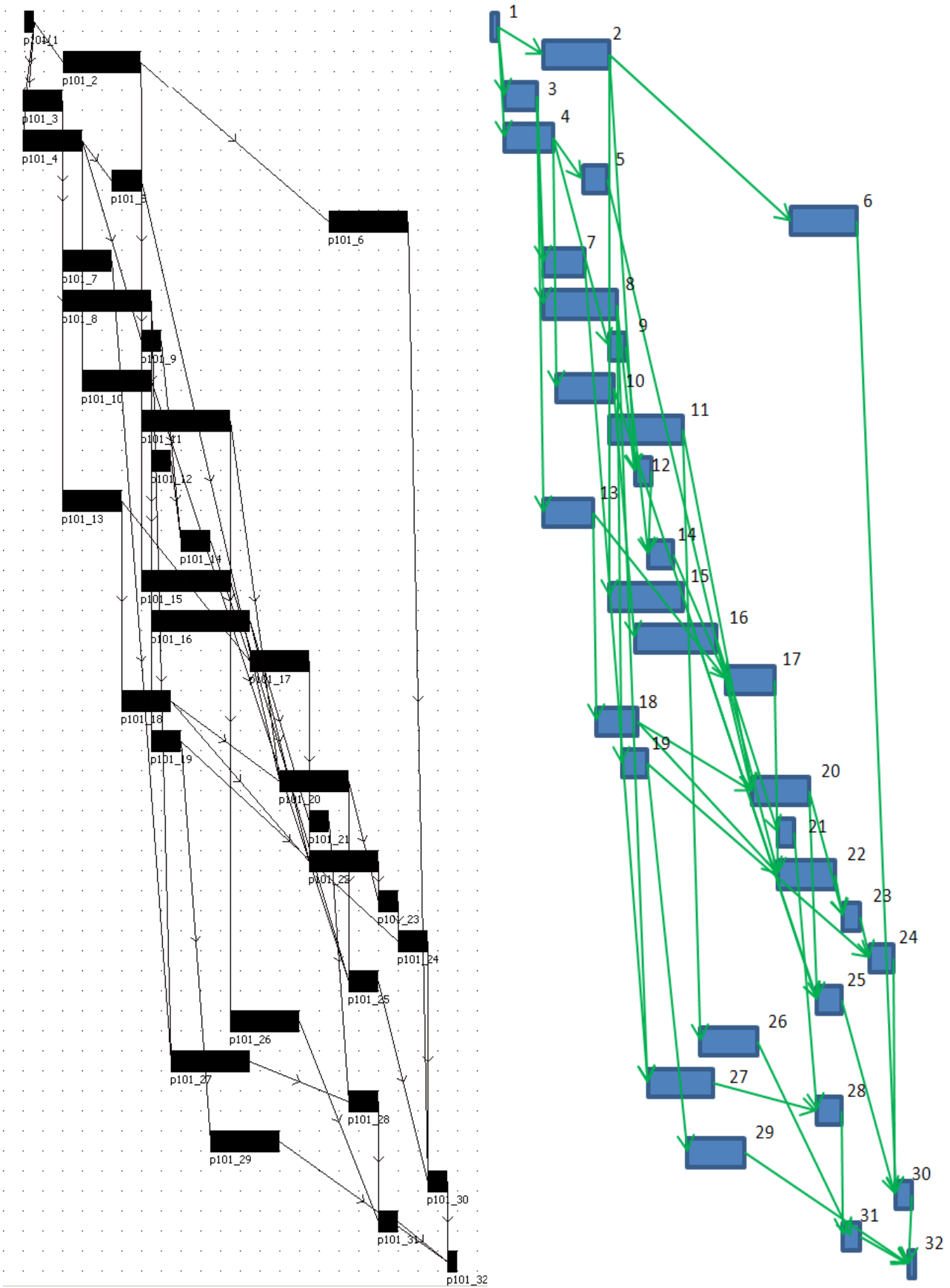
Figure 5-3: Result´s comparison of the IRSM

As can be sawn the result is the same and thus it can be said that the algorithm is done in the proper way. In the figure A-21 the reader could see that there are 32 activities but activity p101_1 and p101_32 correspond to the activities Start and End which in the self-calculated case are no numbered.

As an small example, activity 1 (Start) has three successors that are activities 2, 3 and 4 so in the first iteration both three could be selected. Activity 2 has a duration of 8 units of time and its Latest Finish Time (LFT) is 7. The duration for activities 3 and 4 is 4 and 6 and the LFT is 0 and 1 respectively. The values then assigned to the activities are:

$$v(2) = max \{ 0, 8, -1\}=8 \qquad (4-1)$$

$$v(3) = max \{ 0, -3, -1\}=0 \qquad (4-2)$$

$$v(4) = max \{ 0, -7, 0\}=0 \qquad (4-3)$$

The activity selected is the one that induces the minimum increase of the precedence based lower bound for the not chosen activities in the decision set. In the example above, activity 3 and 4 have then the maximum priority. As there are enough resources for both of them but not for activity 2 as well, activities 3 and 4 are first executed.

The next scheduling time is at t=4, when activity 3 is finished. Now the activities that are available to be scheduled are 2, 7, 8 and 13 and the values assigned to them:

$$v(2) = max \{ 0, -16, -9, -8\}=0 \qquad (4-4)$$

$$v(7) = max \{ 0,-3, 0, - 8\}=0 \qquad (4-5)$$

$$v(8) = max \{ 0, -3, -16, -8\}=0 \qquad (4-6)$$

$$v(13) = max \{ 0, -3, -16, 0\}=0 \qquad (4-7)$$

As can be sawn, the value for every activity is the same and hence, all of them have the same priority. As there are enough resources to schedule all of them simultaneously, at time t=4 activities 2, 7, 8 and 13 are executed. The procedure continues at the scheduling time t=6, when activity 4 is just finished. At this scheduling time activities 5, 9 and 10 are ready to be executed. Now activity 10 is executed and the projects goes on.

The reader is encouraged to follow the procedure by itself in order to finish the project and check its results with the obtained here.

The project is finally accomplish after 43 units of time, which for this problem is the minimum time.

As the reader could have sawn in the second iteration, the values assigned to the four activities were the same and hence, the priority is not clearly defined. That was not cause for concern because the amount of resources available was enough to schedule all of them at the same time. A possible way to solve this problem would be explained in the chapter 8, when talking about future investigations paths.

6 Results and Conclusions

As told in chapter 3.3.2 ten different priority rules have been implemented and studied for the J30, J60, J90 and J120 standard set of projects.

The J30, J60, J90 and J120 were generated by Kolisch and Sprecher in 1997 with the program ProGen network generator in order to be used in future investigations to standardize the study of the RCPSP among others. They are available in the website http://129.187.106.231/psplib/. The J30, J60 and J90 problem sets all have 480 projects with four resource types and 32, 62 and 92 activities but the first and the last activity which represent the beginning and the end of the project has neither duration nor resource requirements and therefore it is said that for the J30, J60 and J90 the number of non-dummy activities is 30, 60 and 90. The J120 problem set is composed of 600 different projects with five resource types and 120 non-dummy activities. (references)

6.1 Results and conclusions for the J30 set of projects

Table 6-1: Average deviation from optimum for different time windows, J30

| TW	GCRR	LPF	RSM	GNIS	GNS	IRSM	WCS	ACS	MSLack	LFT
0	3,30	3,02	3,55	4,75	3,21	3,49	3,49	3,18	3,02	2,79
1	3,32	2,91	3,55	5,01	3,11	3,48	3,37	3,20	2,91	2,67
2	3,65	3,14	4,22	5,37	3,25	3,76	3,61	3,28	3,14	2,90
3	3,95	3,26	5,16	5,92	3,51	4,19	3,83	3,60	3,26	3,20
4	4,29	3,44	6,33	6,41	3,94	4,87	4,03	3,74	3,44	3,57
5	4,62	3,67	7,21	7,11	4,27	5,20	4,23	3,86	3,67	4,03
6	4,92	3,93	8,13	7,75	4,64	5,70	4,46	4,04	3,93	4,29
7	5,14	4,04	9,05	8,11	4,87	5,97	4,49	4,21	4,04	4,36
8	5,20	4,10	9,76	8,44	5,13	6,37	4,56	4,36	4,10	4,57
9	5,32	4,10	9,76	8,47	5,15	6,59	4,65	4,33	4,10	4,80
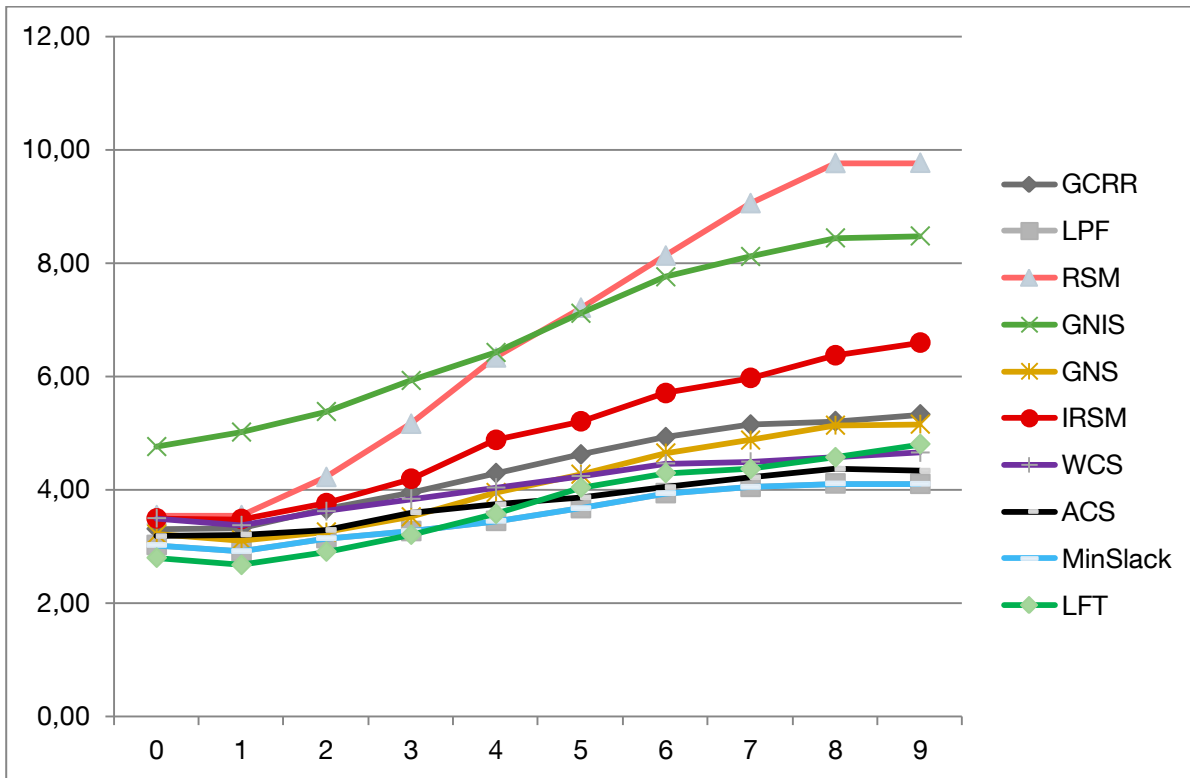
Figure 6-1: Average deviation from optimum for different time windows, J30

The table shows for every studied priority rule the average deviation from the optimum solution for ten different values of time window. The way of doing it is as follows. For the 480 different projects which the J30 problem set is composed of, the projects have been executed using a selected priority rule for the same time window value and this has been repeated for the different values of time window and for every priority rule, that means 4800 projects for every priority rule, 48000 projects altogether. Consequently, the table yields the efficiency of every priority rule to face projects with different time windows. The graphic clarifies and gives form to the numbers in order to make a visual representation of the results. The x axis represent the different values of time window whereas the y axis represent the average deviation from optimum.

As can be seen, the efficiency for every priority rule diminishes as the value of the time window increases. Remarkably negative is the effect of this increase in the duration of the projects scheduled using the RSM and GNIS priority rules. Those priority rules are then not adequate to solve projects in which high values of time windows are required. In addition to this low efficiency with high values, with low values of time window there is an appreciable difference of two periods of time in compari-

son with the other rules used and hence, it is possible to state that RSM and GNIS priority rules are not the right priority rules to execute the J30 set of projects or at least they are not as good as the oder rules used.

Lightly better are the results obtained while executing projects with IRSM. Although at the beginning the deviation from optimum is not big, as long as the time window values increase, the IRSM yields poor results.

Better results than the three priority rules previously analyzed are yielded by GCRR and GNS. Both two have a similar behavior suffering an increase of 2 periods of time along the values of the time window. The deviation from the optimum at the beginning of the chart is about 3 periods of time whereas at the end, with values of time windows of 8 and 9, the deviation is around 5 periods of time. They are not the priority rules that better solutions offer, but in comparison with the previously studied rules (RMS, GNIS and IRSM) the efficiency is much higher.

The WCS and ACS priority rules yield little bit better results than the obtained by GCRR and GNS. For this two priority rules the increase of the deviation from the optimum along the different values of time window is only of 1 period of time, starting with a deviation around 3 periods of time and finishing with a deviation of 4 periods of time for the values of time window 8 and 9.

According to the chart, LFT and MinSlack as well as LPF are the priority rules that better solutions offer for the studied projects. Nevertheless the behavior along the different values of time window is very different. Although LFT yields the better solution for projects with values of time window of from 0 to 3 with an average deviation from the optimum smaller than 3, the increase of the deviation along the chart has a steep slope that makes the rule inefficient for big values of time window.

On the other hand, the results obtained using the MinSlack and LPF priority rules show the opposite behavior. At the beginning, the duration of the projects carried out is not the shortest one, but as can be seen, the effectiveness of these priority rules do not depend highly on the different values of time window and hence, from values bigger than 4 the solutions offered are the best ones. Although the results are exactly the same, that means that the activities are ordened in the same way, the way of assigning values as can be seen in the chapter 3.3.1 to the activities is different for both of them.

Table 6-2: Average deviation from optimum over all time windows, J30

	GCRR	LPF	RSM	GNIS	GNS	IRSM	WCS	ACS	MSLack	LFT
Average	4,37	3,56	6,67	6,73	4,11	4,96	4,07	3,78	3,56	3,72

Then as a conclusion, this J30 project experiment reject the WCS, RSM and GNIS as a way to obtain good results when scheduling this type of projects. The results obtained using the other priority rules shows no big differences. Although for small a values of time windows the LFT yields the better results, LPF and MinSlack have a smaller general average deviation and hence if the time window for a project is not clearly specified it would be better to schedule the project using LPF or MinSlack instead of the other rules.
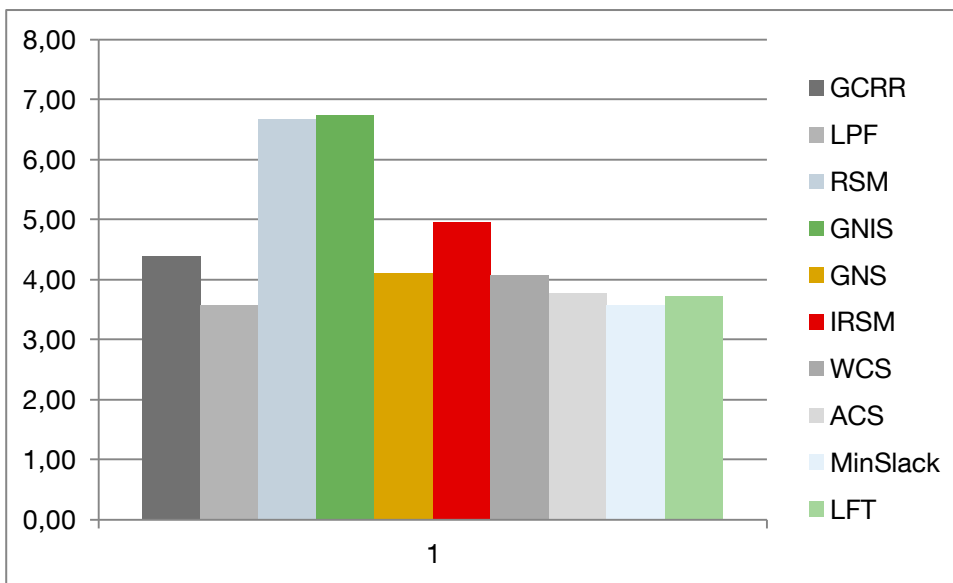
Figure 6-2: Average deviation from optimum for th J30 set of projects.

6.2 Results and conclusions for the J60 set of projects

Table 6-3: Average deviation from optimum for different time windows, J60

TW	GCRR	LPF	RSM	GNIS	GNS	IRSM	WCS	ACS	MSLack	LFT
0	5,26	4,85	6,03	7,65	5,20	6,17	5,33	5,17	4,85	4,93
1	5,33	4,57	6,71	8,39	5,07	6,27	5,08	4,71	4,57	4,69
2	5,68	4,62	8,18	9,21	5,52	6,75	5,09	5,03	4,62	4,88
3	6,31	5,02	9,79	10,26	6,03	7,97	5,51	5,15	5,02	5,39
4	6,90	5,49	12,25	11,55	6,54	8,82	5,74	5,72	5,49	6,07
5	7,53	5,76	14,56	12,70	7,25	9,67	6,05	5,65	5,76	6,55
6	7,96	6,06	16,35	13,49	7,58	9,96	6,25	6,00	6,06	6,96
7	8,12	6,19	17,71	13,94	7,90	10,61	6,41	6,08	6,19	7,36
8	8,16	6,33	18,77	14,36	8,21	10,65	6,57	6,24	6,33	7,57
9	8,21	6,34	18,61	14,74	8,11	11,29	6,64	6,20	6,34	7,71
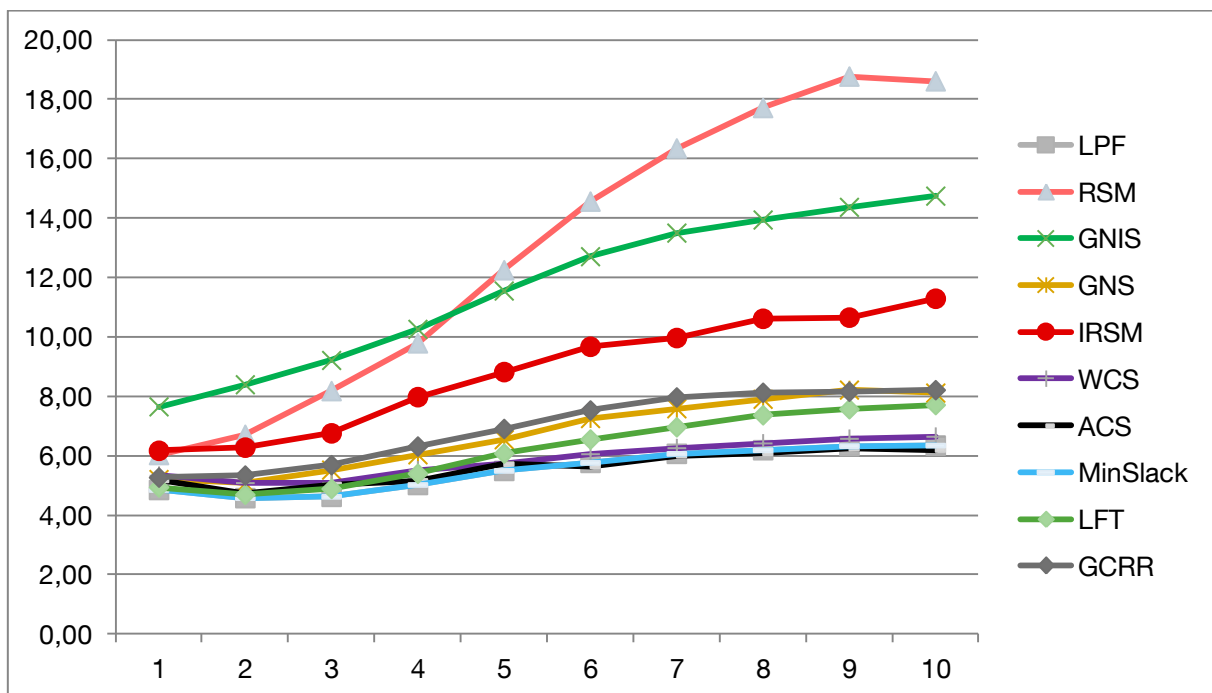
Figure 6-3: Average deviation from optimum for different time windows, J60

They way of proceeding is the same as with the J30 project. Although the average deviation from the optimum for every priority rule is bigger, it does not mean that the priority rules do not work properly for this set of projects. As the projects consist now of 60 non-dummy activities, the duration of the project is longer and hence, the deviation from the optimum in general terms is bigger. Though the percentage deviation from the optimum stays as before.

As with the J30 set of projects, RSM and GNIS yield poor results not only for big values of time windows but also for small ones. The priority rule GNIS have a continous slope during the whole chart, whereas the RSM offers better results at the beginning but the increase of the deviation along the different values of time window is much bigger and at the end the results obtained are even worst. Then, it is possible to state that RSM and GNIS priority rules are not the right priority rules to execute the J60 set of projects or at least they are not as good as the oder rules used.

The IRSM yields better results than the three priority rules previously commented. For small values of time windows, the average deviation from the optimum is 6 periods of time but at the end of the graphic the deviation reaches up to values around 10 which is then clearly worst than the priority rules that would be explained below.

GNS and GCRR have now a similar behavior. At the beginning of the chart, they offer good results but the increase along the different values of time windows is a little bit more notable than the remaining priority rules.

Unlike the conclusions obtained for the J30 set of projects, now the LFT can not be considered as one of the best priority rules. The results obtained for small values of time windows are still good, but the increase of the deviation from the optimum along the chart is considerably bigger than for the best priority rules.

LPF and MinSlack yield again the same results during the whole chart. They offer the best solutions for the four first values of time window and for big values the increase of the deviation from the optimum reach values of 6 periods of time which as can be seen in the chart, is smaller than for the already commented priority rules. Hence, for this set of projects they kept as two of the best priority rules studied.

The ACS shows a different behavior as the LFP and MinSlack priority rules. Whereas for the first values of time window LPF and MinSlack yield the better solutions, the

results obtained for values bigger than 3 are lightly better and thus it is also considered as one of the best priority rules.

Table 6-4: Average deviation from optimum J60

	GCRR	LPF	RSM	GNIS	GNS	IRSM	WCS	ACS	MSLack	LFT
Average	6,95	5,52	12,89	11,63	6,74	8,82	5,87	5,60	5,52	6,21

Then as a conclusion, this J60 project experiment reject the RSM and GNIS as a way to obtain good results when scheduling this type of projects. The results obtained using the other priority rules shows no big differences. The minimum average deviation from the optimum is obtained when scheduling the projects with the priority rules LPF and MinSlack. Lightly bigger is the average deviation of the ACS and WCS and therefore both four priority rules could be used to schedule this kind of projects.
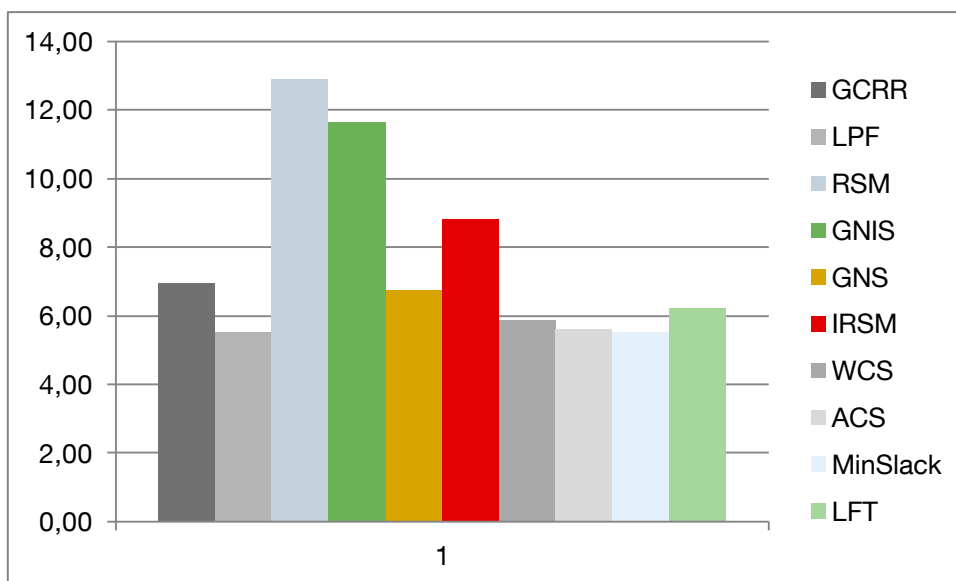
Figure 6-4: Average deviation from optimum for th J60 set of projects.

6.3 Results and conclusions for the J90 set of projects

Table 6-5: Average deviation from optimum for different time windows J90

TW	GCRR	LPF	RSM	GNIS	GNS	IRSM	WCS	ACS	MSLack	LFT
0	5,88	5,46	7,22	9,34	6,09	6,98	5,76	5,96	5,46	5,40
1	5,86	5,08	8,24	10,16	5,86	7,40	5,51	5,69	5,08	5,04
2	6,43	5,65	10,64	11,65	6,40	8,11	6,04	6,04	5,65	5,71
3	7,31	6,13	13,55	13,61	7,36	9,25	6,36	6,39	6,13	6,53
4	8,35	6,62	16,71	15,02	8,16	10,12	6,94	6,75	6,62	7,29
5	8,73	7,11	20,02	16,56	8,84	11,22	7,29	7,19	7,11	8,05
6	9,10	7,34	22,37	17,74	9,24	11,99	7,49	7,43	7,34	8,70
7	9,35	7,42	24,24	18,36	9,49	12,18	7,78	7,46	7,42	9,00
8	9,55	7,54	25,05	18,44	9,69	12,07	7,99	7,47	7,54	9,17
9	9,53	7,40	24,25	19,08	9,90	12,42	7,87	7,39	7,40	9,30
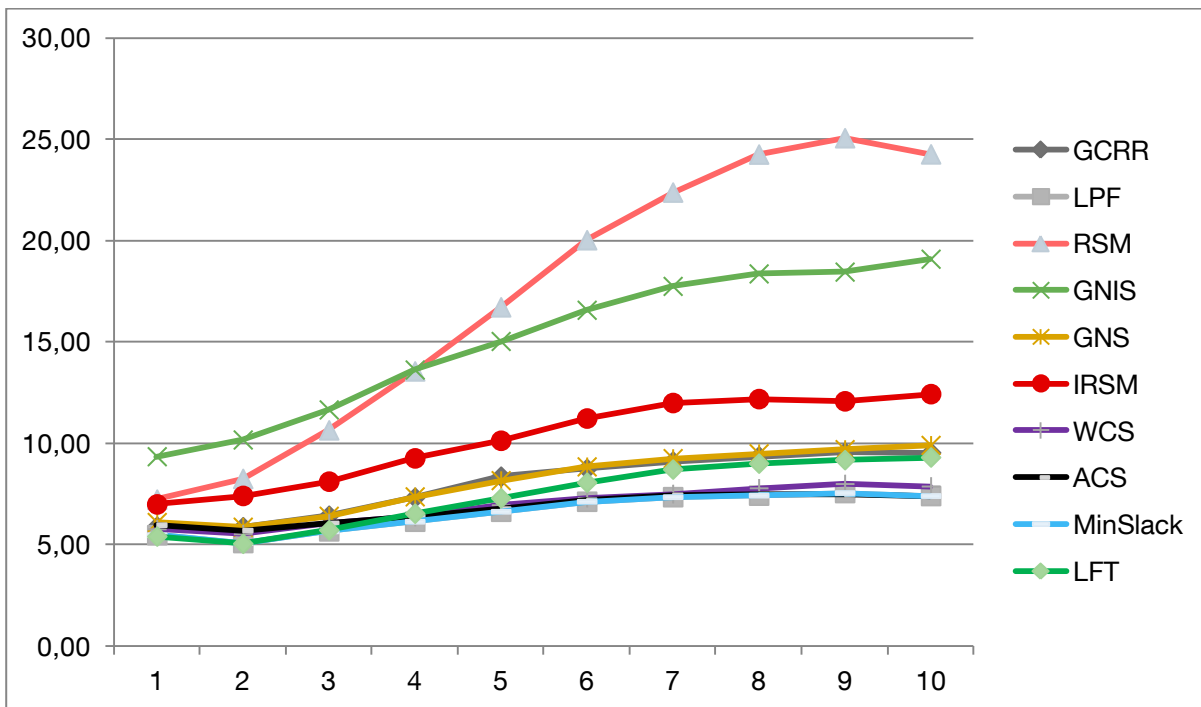
Figure 6-5: Average deviation from optimum for different time windows J90

The chart for the J90 set of projects shows the same behaviour as for the cases studied before. For the worst priority rules, the increase in the deviation from the optimum is very big along the different values of time window whereas for the best ones, although there is also an increase in the deviation, it is never bigger than 10 periods of time.

Again the priority rules that yield the worst results are GNIS and RSM. The efficiency of the RSM priority rule in the first two values of the x-axe is lightly smaller than for the other priority rules but as has been sawn in the previous charts, the slope along the different values of time windows is very steeply and hence the results obtained are very poor.

Lightly better results are achieved using the IRSM but again can not be considered as a very efficient priority rule due to its deviation of around 3 units of time in comparison with other more efficient rules.

GNS and GCRR yield good results starting with an average deviation from the optimum of around 6 units of time and accomplishing the projects with big values of time windows with a deviation smaller than ten.

LFT yield again the best results for the two first values of time window with an average deviation from the optimum of 5 periods of time. However as has been sawn in the results for the J30 and J60, again the efficience of this priority rule is hardly related with the values of time window and therefore, for bigger values the average deviation from the optimum increase considerably.

Very similar results are obtained when scheduling the J90 set of projects with the LPF, MinSlack, ACS and WCS. The increase of the average deviation along the x-axe is of only 2 periods of time and hence, better than the obtained scheduling the projects with LFT. In the table below the reader could see the average deviation for the different values of time window and it would help to decide wether is better to schedule the projects wit the LFT or with the other four priority rules.

Table 6-6: Average deviation from optimum J90

	GCRR	LPF	RSM	GNIS	GNS	IRSM	WCS	ACS	MSLack	LFT
Average	8,01	6,58	17,23	15,00	8,10	10,17	6,90	6,78	6,58	7,42

According to the table above, the priority rules that better results yield are MinSlack and LPF with a deviation of 6,78. Lightly worst is the duration of the projects obtained when scheduling them following the priority rules ACS and WCS with a deviation of 6,78 and 6,90 respectively. Although LFT yields the best results for small values of time window, as can be sawn the average deviation is quiet worst than for the other priority rules. This is due to its low efficiency with big values of time window and hence, can be stated that when the project manager does not know the time window of the project, it would be better to schedule it using for example LPF. As in the conclusions obtained for the J30 and J60, the worst priority rules and therefore the priority rules that are rejected are RSM and GNIS.
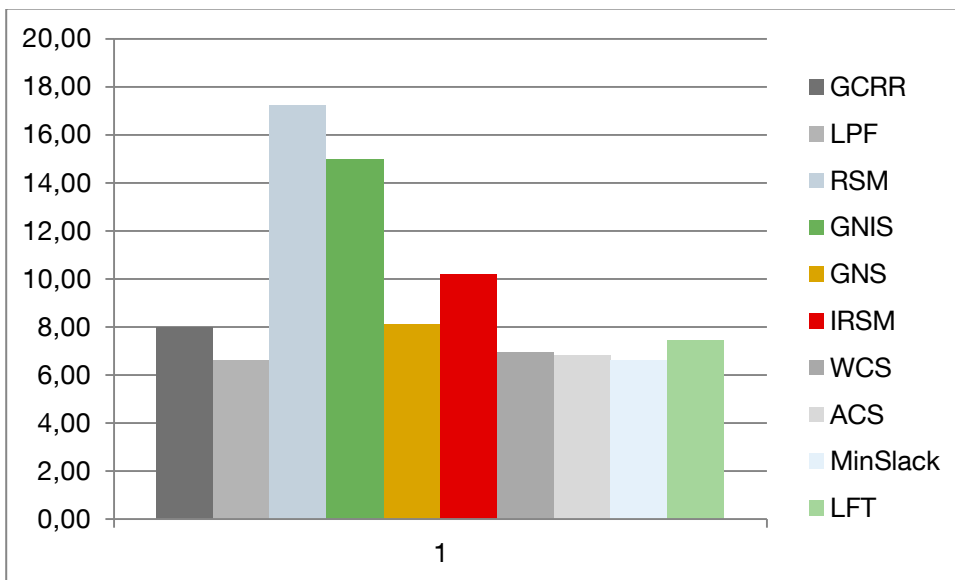
Figure 6-6: Average deviation from optimum for th J90 set of projects.

6.4 Results and conclusions for the J120 set of projects

Table 6-7: Average deviation from optimum for different time windows J120

TW	GCRR	LPF	RSM	GNIS	GNS	IRSM	WCS	ACS	MSLack	LFT
0	15,63	13,91	19,89	23,56	15,71	18,29	15,04	14,89	13,91	13,80
1	16,04	14,16	22,49	25,34	16,01	19,97	15,40	15,14	14,16	14,19
2	18,44	16,12	28,08	28,69	18,21	22,79	17,00	16,78	16,12	16,63
3	20,85	18,03	34,77	31,90	20,39	25,66	18,93	18,30	18,03	19,12
4	22,58	19,47	41,84	34,91	22,24	27,79	20,12	19,60	19,47	21,23
5	23,76	20,16	47,93	37,16	23,43	29,62	21,12	20,35	20,16	22,48
6	24,36	20,91	52,04	38,57	24,22	30,98	21,48	21,13	20,91	23,83
7	24,75	21,13	54,65	39,90	24,73	32,08	21,45	21,29	21,13	24,35
8	24,97	21,31	55,56	40,03	25,04	31,69	21,48	21,24	21,31	24,85
9	24,81	21,37	52,62	40,63	25,13	29,85	22,14	21,28	21,37	25,12
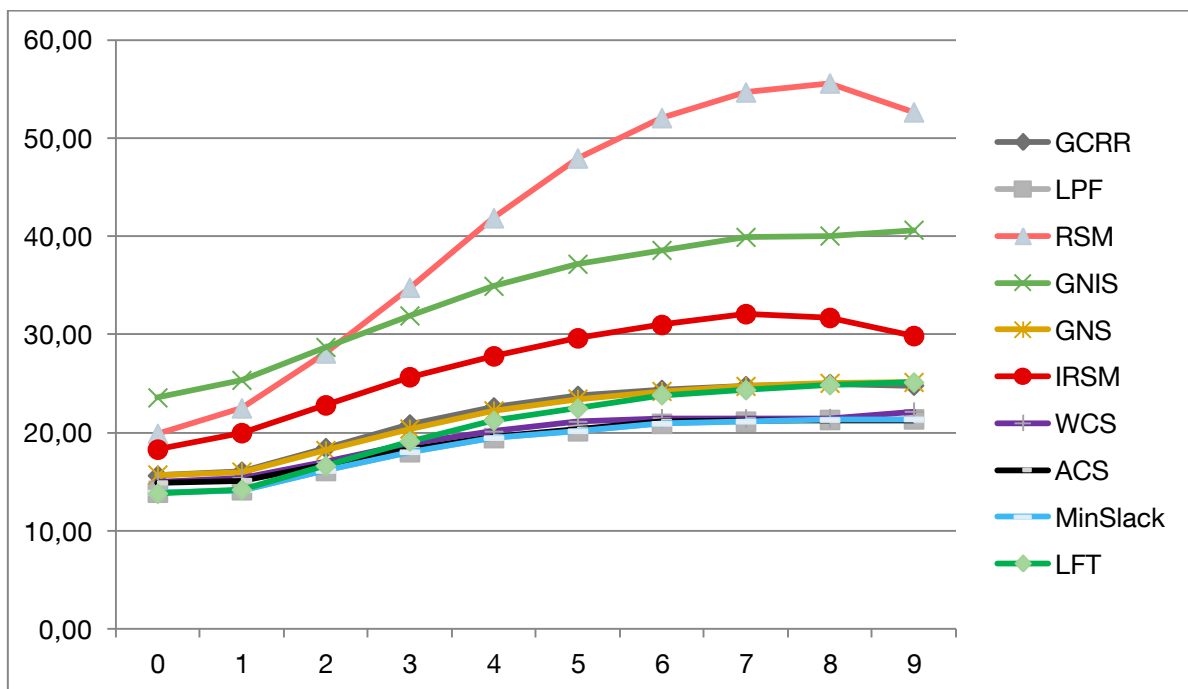
Figure 6-7: Average deviation from optimum for different time windows J120

As explained at the beginning of this chapter, the difference among the J120 and the J30, J60 and J90 is not only the number of activities every project is composed of but also the number of projects, 600 instead of 480, and the number of different resource types which is five for the J120 set of projects.

As can be sawn, the form of the chart bears a big resemblance with the previous graphs used to describe the J30, J60 and J90 set of projects. Again, the minimum values of average deviation from the optimum correspond with the minimum values of time windows being specially remarkable the deviation for the priority rules RSM and GNIS which are then rejected for the execution of this projects as well.

Lightly better results are obtained when scheduling projects using IRSM, though, there is a deviation of almost 10 units of time with the best priority rules and therefore, it should also not be used to schedule this sort of projects.

GCRR and GNS have a similar behaviour again along the whole chart. At the beginning the deviation from the optimum is 15 periods of time, which is only 1,5 units of time worse than the best priority rules, but for high values of time windows, the deviation is around 4 units of time.

LTF yield again the best results when scheduling projects with small values of time window, however in comparison with LPF or MinSlack, the difference is very little. For the biggest values of the x-axe the results obtained are similar to those achieved scheduling the projects with GNS and GCRR.

The best results are yielded again by LPF, MinSlack, ACS and WCS. As in the charts analyzed for the other set of projects, for this priority rules, the relation with the different values of time window is very little and hence, they achieve good results along the whole chart.

Table 6-8: Average deviation from optimum J120

	GCRR	LPF	RSM	GNIS	GNS	IRSM	WCS	ACS	MSLack	LFT
Average	21,62	18,66	40,99	34,07	21,51	26,87	19,42	19,00	18,66	20,56

As done for the other set of projects, the table A-28 shows the average deviation from the optimum for any value of time window. The best results are obtained again when scheduling LPF and MinSlack. Lightly worse, but also good, are those obtained using ACS and WCS. On the other hand, as told before, the priority rules RSM and GNIS should be rejected to execute this kind of projects.
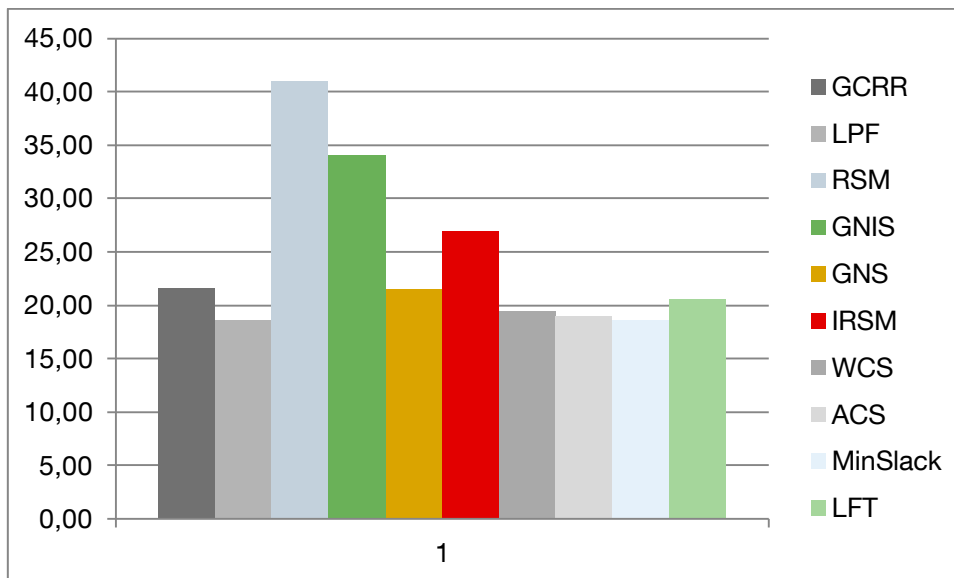

Figure 6-8: Average deviation from optimum for th J120 set of projects.

6.5 Conclusions

Acording to the obtained results, the best priority rules are LPF and MinSlack which although the way of assigning values is different, the order of scheduling the activities is the same and therefore it makes no difference to use one or the other. The two priority rules developed by Kolisch have also been proved themselves as hightly efficient ones. LFT has yielded the best results when scheduling the projects with small values of time window and hence, it should be used in executing those sort of projects. Not as efficient as the previous commented ones are GNS and GCRR, but the strong point of this priority rules is that they are easy to implement and the amount of computer calculations is then smaller. The worst results have been obtained using IRSM, GNIS and RSM.

In order to compare the results obtained in this document, the figure A-28 shows the results that appear in the table 5 of Kolisch 1996.

Table 9
Performance of priority rules for the ProGen-instances

	MEAN	STDDEV	MAX	#OPT	CPU
WCS	4.27	4.60	26.39	96	0.02
ACS	4.57	4.94	32.81	94	0.02
IRSM	4.66	4.83	27.03	95	0.02
LFT	4.83	4.77	22.37	85	0.01
MSLK	4.92	5.25	32.91	92	0.01
RSM	5.67	5.05	22.22	72	0.02
MTS	5.92	5.25	32.81	69	0.02
GRPW	9.22	8.17	41.86	58	0.01

Figure 6-9: Performance of priority rules [Kol-96]

Most of he priority rules that appear in this table have been studied in this paper. To help the reader with the notation, MTS is Most Total Successors which is the same as GNS and GRPW is Greatest Rank Positional Weight which has not been studied in this document.

For the studied cases, the mean is different than in our study because the projects used are different due to the non-existence of the standard set of projects J30, J60, J90 and J120 when they were studied.

Nevertheless, it is more interesting to highlight the different efficiency of the MinSlack priority rule which in this study could be sawn as one of the best priority rules but in the Kolisch appear as the fifth best rule.

Also remarkable is the fact that the WCS is lightly better than the ACS, results that are not shared in this document.

Another difference between the two papers is the behaviour of the MTS (GNS in this paper). Whereas in this paper the results obtained where good, the results obtained by Kolisch were supposed to be even worse than the RSM.

The last result that would be remarkable, would be the one that refers to the efficiency of the IRSM. According to this document, IRSM yield worse results than LFT something that is in opposition with the paper of Kolisch.

7 Area Resource

7.1 Introduction

As told in the chapter 2, a very important part of this document is the implementation of the Area Resource as an aditional resource constraint in the RCPSP. It involves an increase in the difficulty of the project solution but it also makes the scheduling problem to be more realistic and hence a better solution for the project manager can be reached.

7.2 Theory and explanation

In a common project there are many different activities and all of them have different execution characteristics that had to be done in a proper way. Some of them do not need to be executed in an specific area such as for example the purchase of some construction tools but many others like the installation of a big hydraulic press in a firm must be done in the place where it should carry out its work or can be previously assembled anywhere and then transported to its working place by a big truck that would need a big amount of free area to go through.

In all the literature read regarding the RCPSP, the usually resources taken into account are those related with workers, material, machines... However none of them are related with surface problems such as the previous problem of installation of a big press. Hence, this new resource tries to face common problems involving contruction projects or layout planning in most of the companies in which the availability of free area to execute a certain activity is of great importance.

Not only for the cases studied before has the area resource been created but also for the scheduling of activities which need a constant delivery of resources. Therefore those activities will need a free path available in order to be possible to communicate them with the store and in this case the necessary area would not be where the activity is physically done but the area needed to go from the store to the place of execution of the activity.

As the reader could see, the new resource opens a wide variety of possible constraints in order to make the simulation of projects as real as possible to allow the project manager to decide the best way in scheduling the activities to reach the project objective in the best proper way.

7.3 Method applied

In this document the case implemented with plant simulation is the one that refers to the area needed in the execution of an activity, like the hydraulic press commented in the chapter 6.2.

7.3.1 Requirements for the implementation

In order to realize the simulation with the surface resource, some functions and agents have to be added to those explained in the chapter 4.4 related to the multi-agent scheduling system. Thus, the resource agents related with the area as well as the necessity of surface where the process agent is going to be executed must be created. [Hor-12b]

7.3.2 Area´s resource agent

To make possible the implementation of the different projects in the computer, a new resource pool has been created. This resource pool is supposed to represent the area where the project is going to be executed. This area has been created as a matrix in which the free positions are represented with a 0 and with a 1 the already used ones. This resource pool is composed of the new area agents which work as the resource agents explained in the chapter 4.4.2. The possible states of this new agents is also free, active and reserved. Each agent corresponds to a cell in the matrix previously explained. When a certain agent changes its state to active or reserved, the associated matrix will change the cell whose position this agent represent, from 0 to 1, number which means "not free". Following the same process, when an agent gets the state free, the associated cell in the matrix will change to 0. [Hor-12c]

7.3.3 Implementation

Another matrix with the same dimensions has also been created for every activity but now the 1 represents the place where the activity should be carried out. The dimensions of the surface can be easily modified in the algorithm in order to provide the project manager a good tool to perform the most realistic scenario for his project. For the activities, as the tasks provided by the J30, J60, J90 and J120 test projects do not have this area resource it must also be created by the algorithm. The way of creating the necessary surface has been done as follows. Supposing the area of the project where is going to be executed as a matrix A(x,y) with x=y or not, the same matrix has been created for every activity. In order to delimitate the necessary area two different steps has been made. In the first step two integer variables have been calculated as normal functions with mean x/2 and y/2 and standadard deviation x/3 and y/3 respectively. After this calculation two positive values have been obtained and represent the "starting" point for the second step. In the second step two new integer variables have been created also with normal functions with mean 0 for both of them and standard deviation x/3 and y/3 respectively. Now the way of using this obtained values is as follows. Supposing that the values obtained in the first step are a and b, the point in the matrix A(a,b) would be the "starting" point of the necessary area. Thus A(a,b) will have now a value of 1 instead of 0. The net value of the variables calculated in the second step represent the x and y dimension of the area and the sign the direction. That means that if the value for the variables in the second step is -3 and 4 respectively starting in the point (a,b) the area for this activity is a 3 x 4 rectangle and the signus – represents that the area is occupied at the left of the x axe.

In the studied example, the dimensions of the surface are 10 x 8 as can be sawn in the figure below.

	integer 1	integer 2	integer 3	integer 4	integer 5	integer 6	integer 7	integer 8	integer 9	integer 10
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0

Figure 7-1: Example area´s dimension

Then for the first step the value assigned to the first variable will be a random value of a normal distribution with mean=10/2 and standard deviation 10/3 and for the second variable mean=8/2 and standard deviation 8/3. Supposiing that the values obtained are a=6 and b=4 the starting point of the matrix will be A(6, 4) and therefore the matrix now will be as shown in Figure 6-2.

	integer 1	integer 2	integer 3	integer 4	integer 5	integer 6	integer 7	integer 8	integer 9	integer 10
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	1	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0

Figure 7-2: Result after first step

In the second step, the mean now for both variables c and d is 0 and the standard deviation is 10/3 and 8/3 respectively. The values obtained now are c=-4 and d=3 and hence the necessary area is a 4 x 3 rectangle with the "starting" point (6,4) and the final result is as follows.

	integ 1	integ 2	integ 3	integ 4	integ 5	integ 6	integ 7	integ 8	integ 9	integ 10
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	1	1	1	1	0	0	0	0
5	0	0	1	1	1	1	0	0	0	0
6	0	0	1	1	1	1	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0

Figure 7-3: Necessary area for the example activity.

8 Conclusions

The priority rule that has been selected to test the Area´s Resource is LPF due to the good results yielded. The way of proceeding has been the same as the one utilized in the chapter 5. The Area´s Resource has been tested also with the J30, J60, J90 and J120 set of projects. As the activities in this projects do not require the Area´s Resource, it has been created following the indications given in the chapter 6.3. For the J30, the algorithm has been executed for the 480 projects that it is composed of and has been repeated for the ten different values of time window. Altogether 4800 projects. The same procedure has been done with the J60 and J90 and finally with the J120, with the exception that the number of projects executed was 600 and then the sum of projects scheduled rises to 6000.

As this resource has never been studied, there are no papers to compare the results and there are also no optimal solutions for the projects executed. The conclusions are then going to be based in the difference of the deviation from the optimum for the set of projects with and without the Area´s Resource.

The tables used shows the average deviation from the optimum (mean), the total deviation from the optimum for the total amount of projects (sum) and the number of projects executed for every value of time window (NP).

In the left part of the table, the results represented are those that correspond to the execution of the project with the Area´s Resource whereas in the right side of the table correspond to the results without the resource.

8.1 Results for the J30 set of projects

Table 8-1: Results for the J30 with area

TW	Mean	Sum	NP		Mean	Sum	NP
0	31,59	15163	480		3,02	1449	480
1	31,46	15100	480		2,91	1397	480
2	31,70	15215	480		3,14	1507	480
3	32,19	15453	480		3,26	1567	480
4	32,76	15723	480		3,44	1653	480
5	33,23	15949	480		3,67	1761	480
6	33,80	16225	480		3,93	1888	480
7	34,16	16399	480		4,04	1941	480
8	34,33	16480	480		4,10	1970	480
9	34,36	16491	480		4,10	1967	480
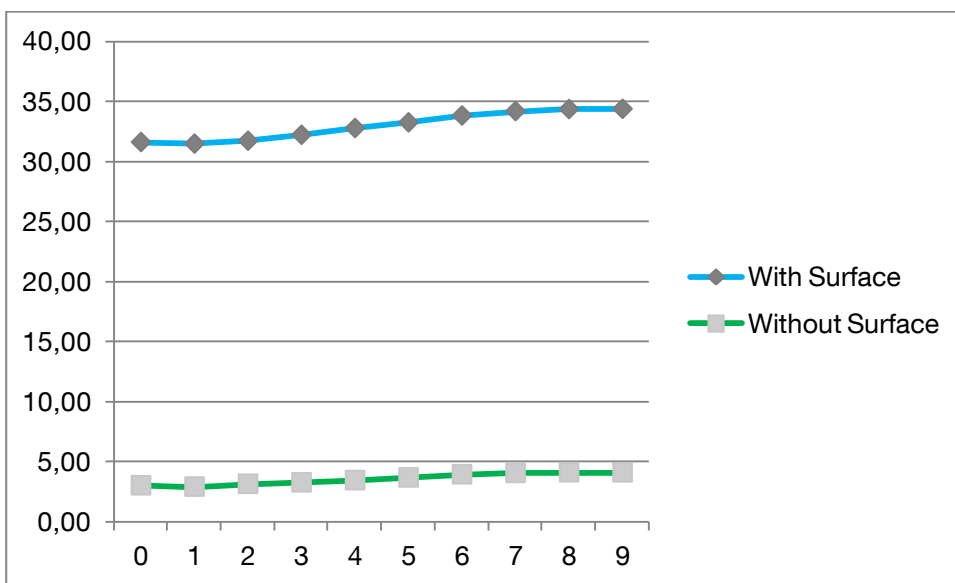
Figure 8-1: Chart for the J30 with area

Table 8-2: Rate for the J30 with area

Mean with area	Mean without area	Rate
32,96	3,56	9,25

The rate is the result of dividing the mean with area by the mean without area. Represent the per unit deviation that the mean with area is bigger than without area.

In this case, the rate is 9.25 and the deviation from optimum rises to 32.96 results that are clearly not good in comparison with the previously obtained.

8.2 Results for the J60 set of projects

Table 8-3: Results for the J60 with area

TW	Mean	Sum	NP		Mean	Sum	NP
0	70,03	33614	480		4,85	2327	480
1	69,93	33564	480		4,57	2195	480
2	70,83	33998	480		4,62	2216	480
3	71,90	34511	480		5,02	2408	480
4	73,28	35173	480		5,49	2635	480
5	74,56	35790	480		5,76	2765	480
6	75,48	36229	480		6,06	2911	480
7	76,38	36661	480		6,19	2970	480
8	76,64	36787	480		6,33	3036	480
9	76,86	36892	480		6,34	3044	480
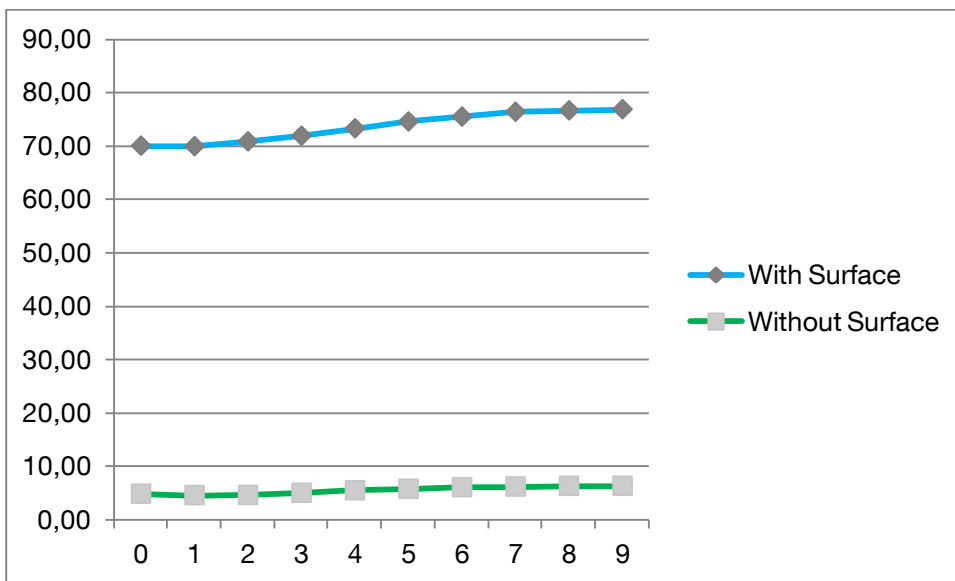
Figure 8-2: Chart for the J60 with area

Table 8-4: Rate for the J60 with area

Mean with area	Mean without area	Rate
73,59	5,52	13,33

8.3 Results for the J90 set of projects

Table 8-5: Results for the J90 with area

TW	Mean	Sum	NP		Mean	Sum	NP
0	104,23	50030	480		5,46	2622	480
1	102,56	49228	480		5,08	2437	480
2	104,08	49960	480		5,65	2714	480
3	105,71	50739	480		6,13	2942	480
4	107,00	51362	480		6,62	3178	480
5	108,63	52141	480		7,11	3415	480
6	109,97	52787	480		7,34	3523	480
7	111,14	53348	480		7,42	3560	480
8	111,53	53535	480		7,54	3621	480
9	111,97	53745	480		7,40	3550	480
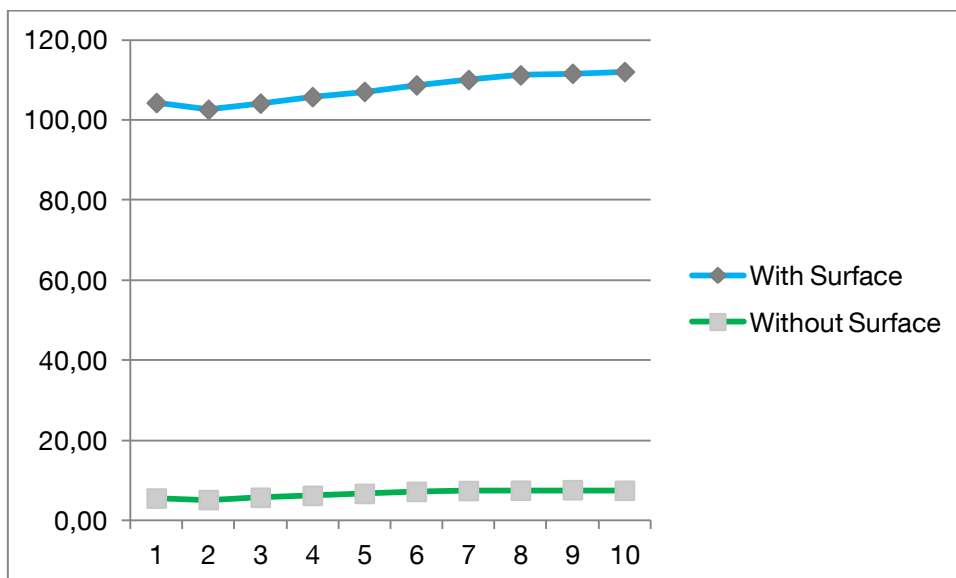
Figure 8-3: Chart for the J90 with area

Table 8-6: Rate for the J60 with area

Mean with area	Mean without area	Rate
107	6,58	16,38

8.4 Results for the J120 set of projects

Table 8-7: Results for the J120 with area

TW	Mean	Sum	NP		Mean	Sum	NP
0	139,75	83852	600		13,91	8344	600
1	137,52	82511	600		14,16	8496	600
2	139,10	83457	600		16,12	9670	600
3	141,24	84741	600		18,03	10816	600
4	144,29	86572	600		19,47	11679	600
5	145,31	87186	600		20,16	12096	600
6	147,07	88239	600		20,91	12548	600
7	148,12	88872	600		21,13	12679	600
8	148,69	89214	600		21,31	12784	600
9	149,07	89443	600		21,37	12823	600
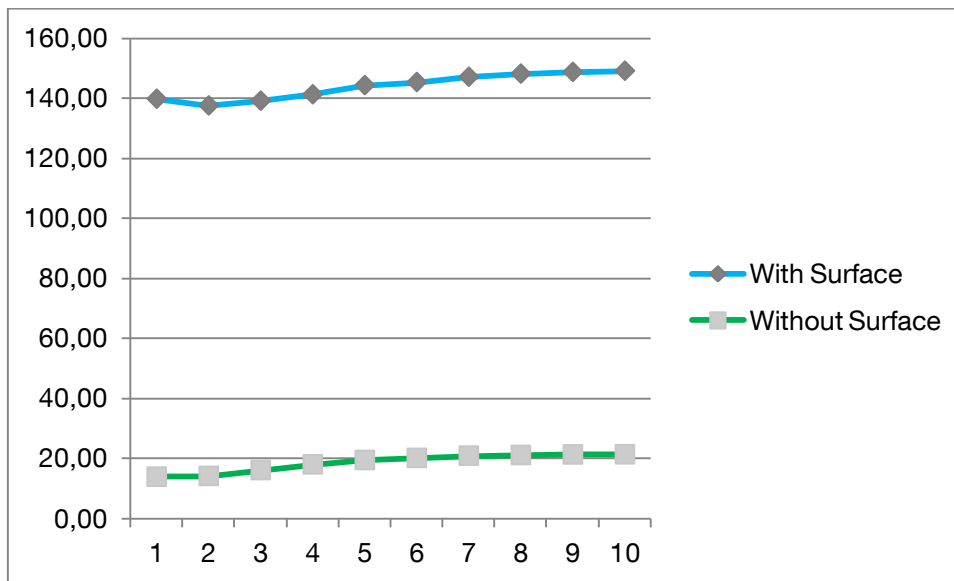
Figure 8-4: Chart for the J90 with area

Table 8-8: Rate for the J120 with area

Mean with area	Mean without area	Rate
144,01	18,66	7,72

8.5 Conclusions

The results obtained for every set of projects show a great deviation from the optimum as it was expected. This is due to two reasons. The first one is because the Area´s Resource for every activity has been created following a normal distribution with mean x/2 and standard deviation x/3 for a surface with length x and mean and standard deviation y/2 and y/3 for the surface with width y respectively. Hence, many of the activities use the same area or part of the same area and that is why not many activities can being simultaneously scheduled causing a much longer duration of the projects. The other reason is because it has not been used a priority rule which deals with the problem of the Area´s Resource. LPF is one of the best priority rules, but new priority rules should be developed in order to obtain better results when scheduling this type of projects.
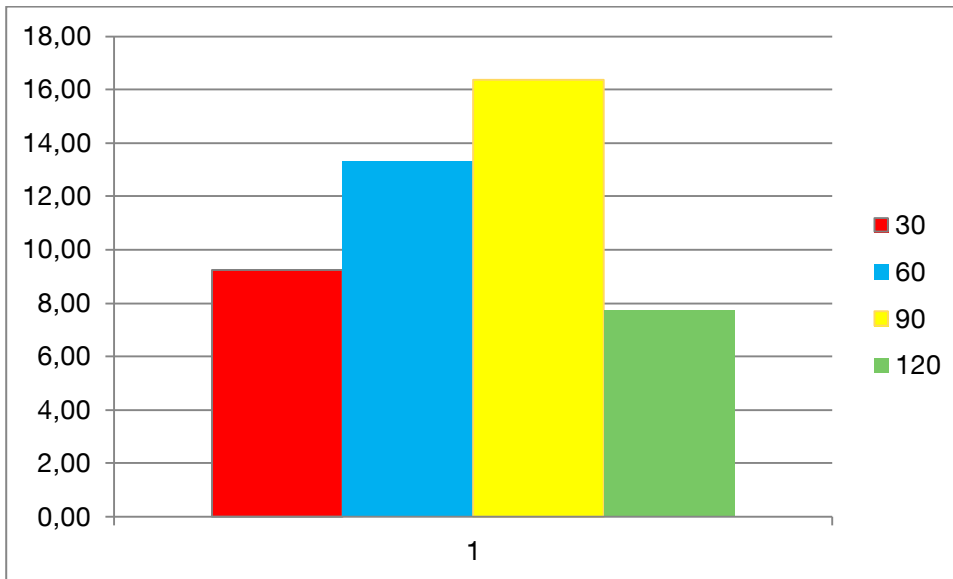
Figure 8-5: Rate for any set of projects

In the chart above it is represented the rate for every set of projects. It can be sawn that the rate grows for the J60 and J90 but for the J120 dimishes. This is because the average deviation from the optimum with area is very little for the J30, J60 and J90 and hence, a big average deviation with area involves big rates for this set of projects. On the other hand, the average deviation for the J120 set of projects for the priority rules without the Area´s Resource is considerably worse and therefore the rate between the projects scheduled with and without the Area´s Resource is smaller.

9   Future investigations paths

It has been proved in this paper that the priority rules that best work are those that use the critical path to assign values to the activities. LPF gives priority to those activities that are in the critical path in every scheduling time. MinSlack gives priority to the activities with the minimum slack and the available slack when an activity is in the critical path is 0, and that is why although the values are assigned in a different way, the results are the same. The other two priority rules that have also yield good results are WCS and ACS which tend to give priority to the activities in the critical chain. Due to this reason, the managers who want to develop new priority rules should focus its efforts in assigning values to the activities according with any characteristic related with the critical path.

As firstly introduced in the chapter 4.4, many times the value assigned to two ore more activities that compite for the resources is the same and the software then gives priority randomly to one of them.

It would be helpful and probably yield better results if a second priority rule is used. The main rule would be used as the primary criterion for activity sequencing and when two ore more activities would have the same value, the second priority rule would act as a tie-breaking. This method would avoid the randomly execution of activities when the values assigned are the same and hence, it would offer a unique activity ordering.

New studies should then be carried out with the goal of finding the pair of priority rules that best results yields when scheduling the projects using one as a primary criterion for value assigning and the other as a tie-breaking rule.

Regarding the new Area´s Resource which has been in this document firstly studied, new priority rules should be created in order to schedule this sort of projects more efficiently. A priority rule based on the necessary surface the activities need as for example an equivalent of the GCRR for this certain resource should be developed.

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Appendix A

1. Simluations

As far as not every single details can be quoted in this document, a copy of the files used for this simulation is attached In the CD-ROM.

The complete tables obtained in the simulations are attached as well.

Sworn Declaration

I hereby declare to have made the present work independently and without assistance from third parties. Thoughts and quotes that I have taken from other sources directly or indirectly are identified as such. I hereby agree that the work can be made available to the public through the department *Fördertechnik Materialfluss Logistik from the Technische Universität München*, Germany as well as through the Universidad de Zaragoza, Spain.

München, 1 November 2012

Fernando Alastuey González

Eidesstattliche Erklärung

Ich erkläre hiermit eidesstattlich, dass ich die vorliegende Arbeit selbständig angefertigt habe.

Alle aus fremden Quellen direkt oder indirekt übernommenen Gedanken sind als solche kenntlich gemacht.

Diese Arbeit wurde bisher keiner anderen Prüfungsbehörde vorgelegt.

München, 1. November 2012

Fernando Alastuey González