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An optimization-based framework for concurrent planning of multiple projects and supply chain : application on building thermal renovation projects

Shadan Gholizadeh Tayyar

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Shadan GHOLIZADEH TAYYAR

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Centre Génie Industriel - IMT Mines Albi

Directeur de Thèse :

Jacques Lamothe

Jury :

Stéphane Dauzère-Pérès, Professeur, Mines Saint-Étienne, Rapporteur

Lionel Dupont, Professeur, IMT Mines Albi, Co-Directeur

Séverine Durieux, Maître de Conférences, Université Clermont Auvergne, Examinatrice

Jacques Lamothe, Professeur, IMT Mines Albi, Directeur

Samir Lamouri, Professeur, Arts et Métiers ParisTech, Président

Raul Poler, Professeur, Universitat Politècnica de València, Rapporteur

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“Every story starts with an idea, but it is the characters that move this idea forward.” This is an excerpt of a book by Michael Scott entitled “The Alchemyst”. As with the stories, every thesis work also triggers and progresses by its characters. These characters are the players without whose effort and support any single word of the work would never exist... Multitude people have had a part in my thesis story. I can only single out a few characters by name to express to them my sincere gratitudes.

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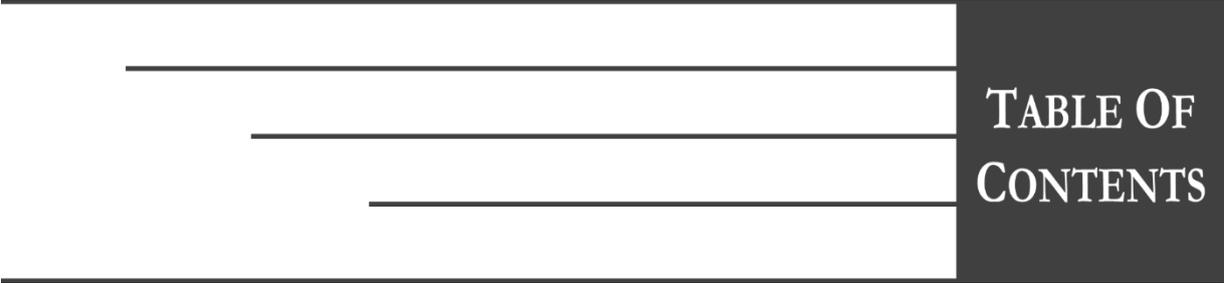


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General Introduction

Over the last six decades, the importance of project management and scheduling as a means for achieving profit and staying competitive has been proven to many organizations. Subsequently, the issues involved in project management and scheduling have drawn the attention of many managers and researchers in both practice and academia. A deterministic project comprises a set of activities to be processed by following technical/technological precedence, while a set of pre-determined criteria needs to be satisfied through the accomplishment of these activities. Motivated by real world situations, most projects are constrained by limitations, such as the availability of the resources required (resource factors), seen in (Afshar-Nadjafi et al., 2015), or imposed deadlines or time windows (time factors), discussed in (Khoshjahan et al., 2013). Additionally, in many practical project planning cases, it is very often the case that more than one single project need to be performed simultaneously (Browning and Yassine, 2010). Taking extant restriction factors into consideration, the management and concurrent scheduling of multiple projects is becoming more and more challenging for organizations, particularly when they need to make decisions on how capital is allocated amongst the projects (Singh, 2014). In such cases, efforts are generally focused on planning, so that the limited resources can be assigned to the multiple projects in a way that satisfies the executive expectation of optimal performance.

In implementing projects, various types of resources are required at the worksite to make progress in processing activities. One class of these resources could be those that are consumable, such as construction products and raw materials (Dodin and Elimam, 2001). These resources are generally supplied to the project worksites by individual suppliers or via a network of inter-related actors, known as a supply chain network. This network collaborates to produce and deliver the required resources of the projects to their worksites. During recent decades, demand management policies have led companies to try to reduce the burden of inventory, especially for products with high value and low demand (Stevenson et al., 2005) (Gunalay, 2010). This intention has seen the emergence of policies involved in “pull” systems, such as Just-In-Time (JIT) and Continuous Replenishment Program (CRP) approaches. For pull systems using these approaches, production and procurement of the products are totally dependent on definitely confirmed demand. In such systems, whilst inventory is kept to a minimum, materials/products are supplied to the end-use destinations in the right quantity and at the expected time. Accordingly, in many of these cases of project scheduling, which we shall call *pull-type project scheduling* over the course of this study, procurement of the consumable resources to the project worksites is conducted on the basis of the pull strategies used in Just-in-Time approaches. A pull-based condition for these projects is defined as the circumstances where stocking high-value consumable resources is not allowed on the project worksites and the procurement of these resources is only fulfilled on the basis of the demand that is generated by the triggering of the activities requiring the resources. Therefore, in projects that are conducted using pull-type conditions, until agreement on determining the start date (schedule) of the activities demanding the supply chain network resources is not reached, it is strictly unworkable to determine an optimal plan for production and procurement of the resources by the

manufacturers and suppliers of the supply chain. Figure 1 schematizes how the scheduling of the activities affects the operation of the supply chain in procurement of the resources at the project worksites in a Just-in-Time manner. On the basis of the figure, an appropriate start date can be determined for the activities from their feasible time windows. Once such a time is determined, the information regarding the quantity of production and transportation of the required resources can be given to the actors of the supply chain by those downstream (worksites) to those upstream (suppliers of the raw materials). In the figure, events B, C and D relate to the operations of the supply chain in procuring the resources for the worksite with only one single actor of each type, i.e. one single raw material supplier, one intermediate products supplier and a manufacturer of the final product. It is clear that in cases where more than one single actor exists in the supply chain, especially with limited capacity constraints, the decision to assign production and transportation operations to the potential actors will become more crucial in achieving optimal performance.

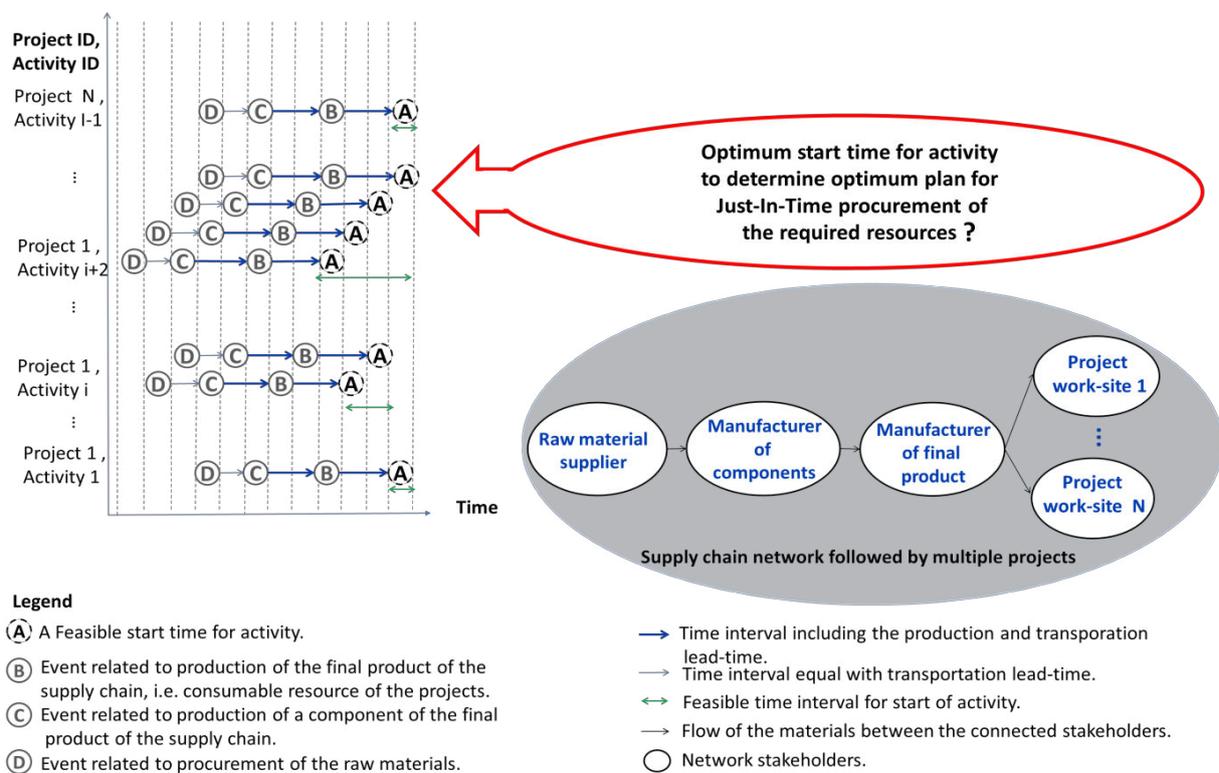


Figure 1- Effect of activity schedules on determining an operating plan for actors of the supply chain.

As well as consumable resources, a set of the non-consumable resources such as labor or machinery, need to be on hand at the worksites during the execution of the project. In fact, determination of the start date for conducting each activity also requires the presence of these non-consumable resources in the required quantity. With regard to the restrictions in performing the activities, such as the time windows or imposed deadlines as well as the project scheduling

objectives, an ensuing challenge which comes up is to define a plan for scheduling activities that addresses the issues on the availability of non-consumable resources.

In addition to the issues of decision making in scheduling activities and resources, there are concerns today about the protection of the environment and its natural resources, and the need for sustainable development has clearly become an unavoidable issue for organizations in their decisional procedures (Hurt and Thomas, 2009) (Robichaud and Anantatmula, 2011). A review of works and studies on the subject of sustainability reveals that greening practices can range widely, from creating general environmental programs to their implementation and control. In this context, the management of the wastes generated in the use destinations, especially in the implementation and closure of architectural and construction projects, has become an important subject for organizations (Wahi et al., 2016) (Bakshan et al., 2017) (Ajayi et al., 2017). Pursuing this interest, any project scheduling arrangements need to include the collection and recycling of the wastes produced in the project worksites.

In aiming to define a modeling framework for planning projects determined in this way and linked to environmental concerns, a pioneer question (**Q.1**) that comes to mind is: **“What driving parameters could influence the determination of the start dates (schedules) of the activities within the projects that are supposed to be performed under the so-called pull-type circumstances? And what concerns need to be addressed in the corresponding modeling framework?”** Answering these questions leads the study to analyze the requirements for determining a planning model for such cases and thus establish the perimeter and hypothesis of the corresponding model. The motivation to plan the system to the optimal level of efficiency leads the study to look at taking advantage of mathematical modeling approaches used in Operations Research (OR). In this context, the second question that arises (**Q.2**), is **“How can the problem be presented mathematically and what methods can be applied to the model to solve its instance problems?”** Since any model using OR limits its applicability only to those managers who are familiar with this field, the question that arises next (**Q.3**) is **“How can the proposed model be made useable for those managers of organizations who are not experts in Operations Research.”** The answer might be to provide an online support system which gives users the possibility to exploit and utilize the proposed decision-making framework through the interfaces of a web-based application, to create their own projects and run them to find the right solution.

The present research work is interested in answering the three afore-mentioned questions through a research project which is called CRIBA (standing for Construction et Rénovation Industrialisée Bois et Acier). The CRIBA project involves the business of industrializing processes for thermal renovation of buildings in France. Its main intention is to reduce significantly the total energy consumption of the buildings by the use of highly-insulated prefabricated panels. The panels are to be shipped to the worksites and installed on the external facades of the buildings for covering and insulation. In this framework, several executive projects, each encompassing renovation activities for a set of building complexes, have been defined with a view to implementing Just-in-Time procurement of the panels to the worksites. With respect to scheduling the executive projects of the CRIBA project, the present work is being conducted to provide a decision-making

framework and a support tool for SYRTHEA, the company responsible for coordinating the projects and providing creative ideas in industrializing the operations and configuration of the panels.

The present report is organized into six main chapters (Seventh chapter is a resume of the report in French). The logical structure of the study, which has been depicted in Figure 2, is determined based on the research methodology presented in (Blessing et al., 2009). In consonance with this methodology, four parts are set out:

- *Definition*: the objective of this step is to define the research context and show the motivation of the study in its context. Within this step, the researchers are interested in answering several questions related to the research topic, so as to clarify the current situation regarding the problem. In the main, the questions deal with key issues of the problem, influencing factors, objectives and restrictions whose answers will enable the researchers to define a more precise problem set. In this step, a preliminary review of the literature will be opportune.

Within Chapter 1 of the current dissertation, the main context of the research is presented by an introduction to project management. Next, the phase of the Project Management Process (PMP) in which the study has been positioned is identified. While reviewing the literature, the chapter clarifies the research requirements in the context of scheduling for so-called pull-type projects. Subsequently, it develops the perimeter of the study by examining the driving factors for decision making in project scheduling. Finally, it determines the main assumptions of the planning mode in the context of the CRIBA project.

- *Descriptive Study I (DS-I)*: this step provides a vision and better understanding of the approaches proposed in the literature and helps the researchers to obtain the know-how required to define their methodology in representing the model of the problem as well as the appropriate solution procedures.

Chapter 2 and Chapter 3 review respectively the literature on project scheduling problems and green supply chain planning problems. In this context, studies of the early literature in project scheduling and developments in each field of research are outlined in Chapter 2. During this chapter, various extensions of project scheduling problems are reviewed and different aspects of the models are highlighted. Different solution methodologies that are used for solving project scheduling problems are described. Within Chapter 3, the concepts and interest in planning for green supply chain networks are discussed. On the basis of the synthesis obtained from the model aspects from Chapter 2 and Chapter 3, the requirements for developing a new modeling framework in the context of planning for so-called pull type project scheduling problems are outlined and the main assumptions of the problem are defined. Exploring the literature, the proper solution methods are also chosen in order to solve the instances of the proposed model.

- *Prescriptive Study (PS)*: the outcome of the preceding step is used in order to engender the representative model of the problem and show the results obtained by using the solution methodology/methodologies.

Chapter 4 presents the optimization model that is proposed to respond to the requirements of the study. It also outlines the methods that are used for solving the instance problems of the model.

The representation of the web-based tool, which is implemented to support the proposed optimization model, is described in Chapter 5.

- *Descriptive Study II (DS-II)*: mainly, this part provides a critical review on the study and presents the perspectives for future research.

Chapter 6 of the current dissertation is dedicated to these statements on the conclusion and perspectives for future development.

Through this structure, Chapter 1 aims to prove insights to answering question **Q.1**. Subsequently, Chapters 2, 3 and 4 deal with answering the second question, **Q.2**, and the last question of the study, **Q.3**, is investigated in Chapter 5.

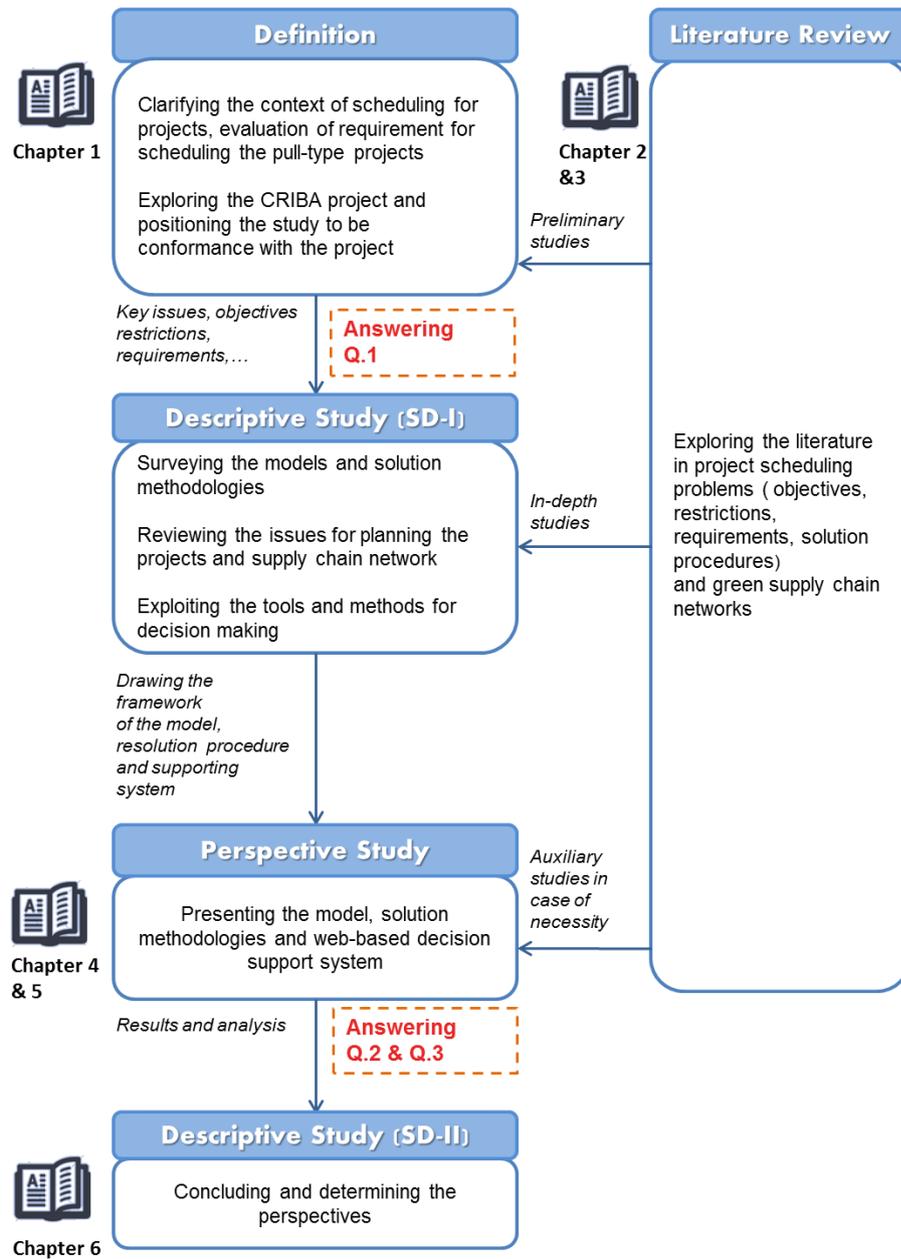


Figure 2- Organization of the research in the dissertation.

“The beginning of knowledge is the discovery of something we do not understand.”
Frank Herbert

1. Context and problem statement

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1.1 Chapter introduction

The main objective of the current chapter is to provide a vision on the research and practical context of the study and to investigate the planning requirements. To this end, Section 1.2 presents an informative introduction to the *project management* realm and outlines its different phases. Considering that *project planning* is a key phase of research in this study, Section 1.2.1 outlines the major steps that need to be streamed within the planning for the projects. Section 1.3 discusses the issues around procuring the consumable (non-renewable) resources for the project and puts forward the ideas of the research in *scheduling for the so-called pull-type projects*. Section 1.4 introduces the specificities of *the CRIBA project*, which is the research case of the study. It defines the main *concept of the CRIBA project* as well as its different objectives and highlights the *position of the research* in the context of the project.

1.2 The project management process

Projects are often undertaken as a means to achieve a company's commercial and business plans. According to the given definitions by (Shtub et al., 1994) (Meredith and Mantel, 1995) (Spinner, 1997) the term "project" can be described as a set of one-time activities with deterministic or stochastic processing time that should be realized completely under the presence of a set of given restrictions. These restrictions can be understood in terms of the technological/technical executive precedence of the activities and/or the availability of resources. Furthermore, the execution of these activities is supposed to be carried out by satisfying a set of pre-defined objectives and criteria. In the main, these objectives are the minimization of total execution cost, the minimization of the project completion time and the maximization of project quality. Once execution of all of the activities is accomplished, the project will be terminated.

On the basis of distinctive characteristics such as duration ranges (i.e. execution horizon on the strategic, tactical and operational levels) or organizational boundaries (single managing organization or joint-venture and partnering), the projects can be determined in different scopes and assigned to the managers. From the definition stage of the project to the completion stage, most projects go through similar phases. These phases collectively form the project management process (PMBOK Fourth Edition, 2008). Depending on the organization and also on the specific nature of the project, project management phases may differ slightly from one project to another. However, the process can usually be summarized as depicted in Figure 3.

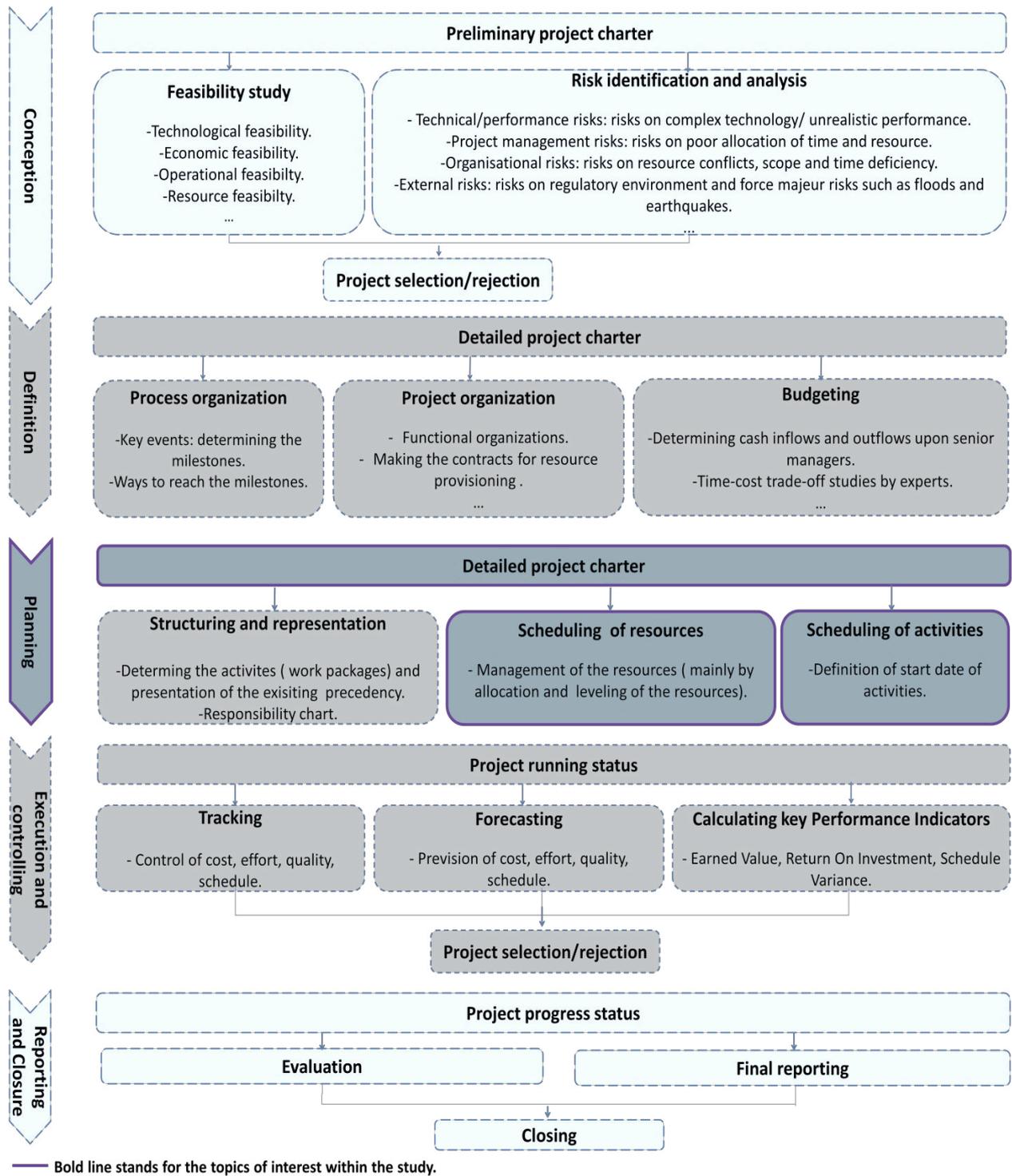


Figure 3- The project management process, (adapted from (Klein, 1999) and (PMBOK Fourth Edition, 2008)).

As this study is positioned within the Project Management Process (PMP), in this section we give a short description of the different phases of this process. According to Figure 3, these phases come under five headings:

(1)- *Conception*: as described by (Cleland, 1999), during the conception phase a project is analyzed in its preliminary features from the viewpoints of feasibility and risk. Based on the result of these analyses, the organization decides whether to go ahead with the project or not.

(2)- *Definition*: Once a project has been accepted as feasible, the definition phase can begin. A more precise understanding of project should be provided during this phase. According to (Abdul-Kadir and Price 1995), poor specification of projects will prove to be expensive for the organization in the later phases. Generally, three major matters are treated within the definition step: *i*. Process organization: referring to (Dvir et al., 2003), the main intention in this step is to define key milestones for achieving goals at different time points of the planning horizon, *ii*. Project organization: this serves to determine the functional organizations that will work together to carry out the project (Canonic and Söderlund, 2010) and *iii*. Budgeting, a step to define the expected incoming and outgoing cash flows, which are associated with every milestone (Ammar, 2011).

(3)- *Planning*: The planning phase is of interest in the current research study. (Klein, 1999) (Levitt, 2000) and (Ciutiene and Meiliene, 2015) describe planning as being at the heart of good management. Its main goal is to ensure that all works of the project are integrated and thus ensure the quality of the project for the owners, as well as its on-time completion and economic benefit. Most commonly, efforts in this step focus on establishing either a multilevel tree or a network-based representation of the activities/work packages (Structuring and representation). It also involves specifying the start and end dates of the activities (Scheduling for activities) by considering precedence levels for each activity, and assignment of the required resources to each activity during its process (Scheduling for resources). More principles involved in the planning phase are outlined in Section 1.2.1.

(4)- *Execution and control*: during this step the activities of the projects are executed and monitored. Most often, the progress is measured in terms of time (schedule) and cost. Depending on the achieved progress and forecasts for required efforts, the current status of the project is updated and adapted. Within this phase, performance data are described and reported by using well-known key performance indicators such as Earned Value (EV), Return On Investment (ROI), Schedule Variance (SV) and so on. For complementary information about the practices in this phase, see (Albert P.C. Chan and Ada P.L. Chan, 2004).

(5)- *Reporting and closure*: final evaluation and reporting is regarded as a way to learn from the experience gained throughout the execution of the project. Once this reporting phase is completed, the project can be closed.

1.2.1 Principles of project planning

The aim of this section is to provide a vision of different issues in the planning phase and to present the roles that are associated with project planning managers.

As stated above, project planning can be categorized under three topics: *i*- Structuring and representation, *ii*- Scheduling for resources, and *iii*- Scheduling for activities. Parts *ii* and *iii* of this phase relate to our research work. The main purposes of every part are described in the following:

1.2.1.1 Structuring and representation

In this context, the content of the project is presented as a series of manageable activities (or work packages) and then these activities are inter-related on the basis of the governing technological or procedural precedence (Wiley et al., 1998). The point to consider in the structuring and representation step is to particularize whether several multiple projects are supposed to be executed simultaneously or whether there is only one single project to be planned. When dealing with multi-project structuring, this can be carried out by two approaches: 1- a single-project approach and 2- a multi-project approach (Lova and Tormos, 2001).

In the first approach all the projects are joined together to make a single mega project. Several models have been used to join the multiple projects together. As seen in Figure 4, either every project is undertaken in parallel or they are joined together via a serial flow. Regardless of the chosen strategy, two starting and ending dummy nodes should be added to complete the final network. Within this approach, one single critical path is formed in the scheduling network. It is worth remembering that the critical path is the longest sequence of activities which determines the shortest time to complete a project.

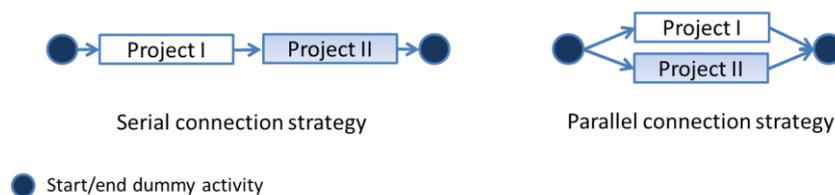


Figure 4- Single-project approach: serial and parallel linkage, adapted from (Lova and Tormos, 2001).

In a multiple-project approach, projects are individually treated in parallel. In this approach each of the projects can maintain its own critical path, as presented in Figure 5. Therefore, using a common pool of resources, each project is scheduled and optimized separately.

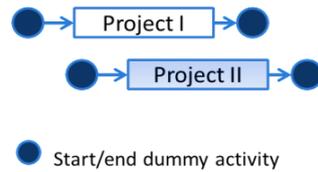


Figure 5- Multi-project approach, adapted from (Lova and Tormos, 2001).

Both single-project and multiple-project approaches can produce different schedules. According to (Browning and Yassine, 2010), compared to a single-project approach, the multiple-project approach is more realistic and presents great opportunity for improvement in the planning of the projects.

Having dealt with structuring the multiple projects, the next step is to present the context of the project(s) in the form of manageable work packages or activities. For this purpose, reasonable execution size and the level of complexity are factors in constituting the group of work packages or single activities. Since the method of forming the activities network is not the point of our study, we have omitted more in-depth details and, for further information, we refer the reader to the principles of preparing a Work Breakdown Structure (WBS) discussed in (Burghardt, 1997).

Subsequently, the interrelation of activities (work packages) needs to be determined and presented within the structuring and representation phase. Mainly, four types of precedence are determined, comprising finish-to-start, start-to-start, start-to-finish and finish-to-finish. Finish-to-start is the most commonly used relationship in project planning. It implies that an activity can only start after all its predecessor activities in the relationship have been completed. Similarly, start-to-start means that the sink activity in the relation cannot start before the source activity starts. By a start-to-finish relation, the sink activity in the relationship cannot finish before the source activity starts. Likewise, the finish-to-finish precedence states that the source activity in the relation must be completed before the sink activity can finish. In the literature, the project scheduling problems under these four types of precedence are termed as generalized project scheduling problems (Elmaghraby and Kamburowski, 1992).

In generalized project scheduling problems, as is the case in the majority of practical situations, there is considered to be a minimum (maximum) time lag, which corresponds to a minimum (maximum) time interval between the start (finish) of the source activity and the finish (start) of the target activity. Project planning problems with minimum and maximum time lags are respectively known as minimal time lag and maximal time lag project planning problems (Węglarz et al., 2011). A negative minimal time lag implies that the corresponding activities may be overlapping. It is worth noting that any type of generalized precedence can be transformed into another type (Bartusch et al., 1998.), except for the case where there is more than one activity-processing mode. The transformation formulas are given in Chapter 4, and they are applied to our solution approach as well.

In order to present the relevance of the activities in the form of a network-based representation, two representative modes have been used: Activity-On-Node (AON) and Activity-On-Arc (AOA), seen in Figure 6. As a matter of fact, selecting an appropriate representation is an actual step in network analysis of project planning problems (Hartmann and Briskorn, 2010).

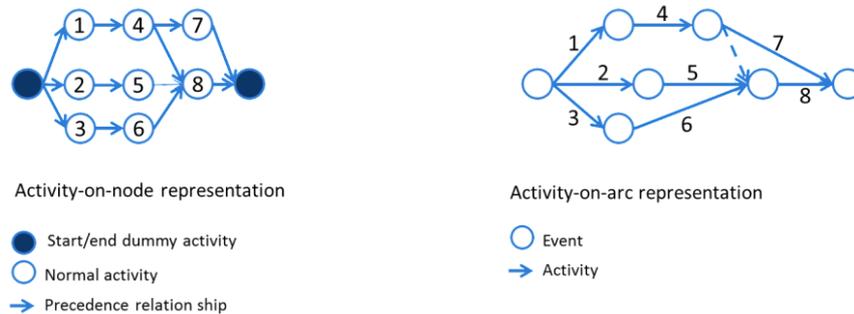


Figure 6- Activity-On-Node and Activity-On-Arc representation.

In AON, the activities and their related parameters are depicted within the nodes and the precedence relations are drawn by directed arcs. In this representation, dummy nodes are used to determine a single start and end for the project. Furthermore, dummy activities are deployed to preserve the precedence between the activities. Project planning with minimum makespan as well as cost minimization objectives are depicted by the AON networks.

In contrast to AON, in the AOA networks, nodes illustrate execution events and arcs are used to represent the activities. Since the AOA representation provides more simplicity and ease in analysis of the network data, it is widely regarded as presenting the problem with a view to maximizing net present value of money where cash inflows or outflows associated with different events may be involved. As with AON, in applying the AOA representation, the use of dummy activities is recommended in order to avoid creating false precedence between activities.

In our study, we deal with the planning of multiple projects where application of the multi-project approach for project structuring is of interest. The modeling framework encompasses four types of generalized precedence wherein a minimal time lag is associated with each of the precedence relationships. As regards the objective function, which is determined for minimizing the total cost of the execution of the project, the AON representation is used to establish the network-based representation.

1.2.1.2 Scheduling for resources

Basically, the various sorts of project planning resources are categorized in two types, renewable and non-renewable resources.

Renewable resources are those resources that are available at their initial amount in the time periods of the planning horizon and they are not depleted by usage (Węglarz et al., 2011). Units of the relevant resources are released immediately after the accomplishment of the activities to which they were assigned. Therefore, these resources can be used by other activities after release. Typical examples of renewable resources include labor and equipment. Project scheduling with renewable resources has been extensively studied in the literature, by (Pritsker et al., 1969) as the first research study, and (Krüger and Scholl, 2009) (Kellenbrink and Helber, 2015) and as the most recent ones on scheduling for resources in multiple projects, and the work of (Ranjbar et al., 2013) in single-project planning. The main idea in the scheduling of renewable resources is to allocate the bounded units of the resources to the activities so that the criteria of the problem have been satisfactorily met. The demand from the activities for these resources can be investigated either by measuring units of the resources that are required to be on hand during the processing time of the activity or by the workload (intensity) that is required to accomplish a specific activity (Kis, 2005).

On the other hand, a resource is considered as non-renewable if it is depleted by usage (Węglarz et al., 2011). Therefore, it cannot be assigned to any other activity. Examples of these resources may be construction materials or capital. Integrating the procurement of non-renewable resources in project scheduling problems was initially investigated by (Aquilano and Smith, 1980). The aim of this work was to define a procedure to plan the sequencing of the non-renewable resources for the project through the possible time windows for their acquisition. As with the other seminal study, (Dodin and Elimam, 2001), the authors consider rewards/penalties and discounts for ordering non-renewable resources and define a resolution procedure. The main goal in planning for non-renewable resources is to define a plan for ordering (transportation of) the resources and define a procedure that handles the procurement of the resources for the project.

In real world cases, projects are commonly constrained by several factors. Mainly, these factors are regarded in terms of *resource* and *time*. The constrained *resources* imply the limited amount of resources that are on hand for performing the project(s). The corresponding models focus on scheduling for “resource constrained projects” (Pritsker et al., 1969). On the other hand, the bounded *time* factor could be stated as the time point(s) that are imposed on the project(s), such as a deadline for completion. In models known as “time constrained project scheduling problems” (described in Section 2.3.2) an additional amount of resources may temporarily have to be added to the project (Dekro and Herbert, 1989) in order to meet the deadline that is imposed for completion.

In this study, our intention is to take advantage of both resource constrained and time constrained project scheduling problems and apply them in a unified model in order to define a framework for scheduling multiple projects which builds up a trade-off between time and resource factors with a view to minimizing the total cost of the execution of the projects. In this study, we deal with planning for both renewable and non-renewable resources.

1.2.1.3 Scheduling for activities

Because of the precedence relations between the activities and the factors restricting scheduling, start and end dates of the activities can be determined through solution procedures. To determine the appropriate dates, various solving methodologies have been developed and applied to project scheduling problems. Optimization resolution methodologies produce results where a schedule is called time-feasible if it satisfies all precedence and time restrictions. On the other hand, a schedule is fully feasible if it satisfies all the constraints on time and precedence relations as well as on resource availability constraints. In this regard, an optimal (global optimum) schedule is a feasible solution in that it is determined based on the given objectives (criteria). The optimal solution can be obtained by a set of methods that are known as exact procedures. In contrast to the global optimum solution, a semi-optimal solution does not present the most suitable feasible solution, but rather one that is most suitable within a particular neighborhood of values (Węglarz et al., 2011). Depending on the working mechanism used, the algorithms procedure, with so-called meta-heuristic and heuristic algorithms (discussed in Sections 2.7.2, 2.8.2 and 2.9.2) produces optimal or near-optimal solutions.

Within the current study, two different solution methodologies are applied for solving the proposed modeling framework. The first solution methodology, which is based on exact methods (a description of these methods is included in Section 2.9.1), generates the optimal results for scheduling of the activities and planning of the system. An additional meta-heuristic-based procedure is studied in the second step. Basically, it seeks to produce semi-optimal solutions rather than a global optimal. Nonetheless, the application of the developed procedure is useful for the scheduling of large projects with very many activities in which exact solving methods fail to generate optimal results due to the NP-hard nature of the problem, (the complexity issues in solving NP-hard problems are outlined in Section 2.4).

1.3 Requirements for scheduling pull-type projects with environmental aspects

A viable scheduling technique must show promise as an aid in determining appropriate start times for the activities based on the (i) *Inherit restrictions in executing the activities* and also on the (ii) *Constrained*

availability of the resources. *Inherit restrictions* are the limiting factors that emerge in the executive characteristics defined either in precedence relationships between the activities or the supposed time windows for their processing. On the other hand, *constraints in availability of the resources* involve concerns about the limited amount of the resources that are totally on hand and can be allotted to the activities in the required quantities. Having considered the two types of resources, renewable and non-renewable, scheduling in this regard could be divided up into two distinct aspects as follows:

- i. Scheduling for the available quantity of renewable resources to allocate them to the activities with the aim to meet the expected objectives and satisfy the constraints on performing the project.
- ii. Defining a plan to acquire the required non-renewable resources at the project worksites to be able to schedule the activities with the proper start times.

i.) In the literature, scheduling for renewable resources is covered in a large body of works on both resource constrained and time constrained project scheduling problems. In the standard form of resource constrained project scheduling problems, activities can only be executed in one single mode requiring a given fixed duration to process and a given quantity of resources. Starting with (Elmaghraby, 1977), this assumption is generalized to allow several alternatives for performing the activities. In the model presented, each alternative (mode) reflects a feasible way to accomplish the underlying activity and each alternative possesses a given processing time and the requirement for the resources, as well as a use cost. This extension constitutes the basic approach to multi-mode problems seen in (Kolisch and Drexel, 1997) (Zhu et al., 2006) (Tareghian and Taheri, 2007) (Tiwari et al., 2009) (Coelho and Vanhoucke, 2011) (Asta et al., 2016), wherein the aim is to choose the appropriate modes of accomplishing the activities so that the objectives in scheduling the projects are met and the constraints of the availability of the resources, as well as the precedence relationships, are satisfied. Moreover, the same idea has been used in the case of problems that are generally termed as time/cost trade-off problems (TCTP). In TCTP, the project is due at a given deadline whilst multiple modes of processing the activities are also used. The goal in these problems is to find an appropriate schedule which minimizes the total cost of running the project by choosing the modes of the activities which cost less and meet the deadline of the project (Vanhoucke et al., 2002) (Hadjiconstantinou and Klerides, 2010). The applicability and efficiency of the trade-off problems have drawn the attention of many researchers in theoretical and practical studies. (Węglarz et al., 2011) provides a comprehensive survey of the works in this field.

In our modeling framework, the study is interested in taking the advantage of “trade-off problems” in determining “balanced” solutions and applying their concepts to project scheduling problems with one single mode of processing the activities:

- In the current study the activities are supposed to be due for completion at a given deadline. To meet the deadline, a supplementary limited amount of renewable resources are assumed to be rented and added over the time periods in which the requirement

for the resources may exceed the quantity available. In fact, the aim of this assumption of making trade-offs is to enable the modeling framework to decide either to pay for renting supplementary quantities of the renewable resources and avoid paying high penalty costs for late delivery, or vice versa, that is, to pay low penalty costs instead of shelling out the high rental cost for additional amounts of the resources that need to be added to meet the given due-date (Gholizadeh-Tayyar et al., 2016a).

ii.) Besides of scheduling for renewable resources, this study also needs to examine planning for acquiring the non-renewable resources of the projects. Referring again to the literature, works on planning for non-renewable resources have not been widely presented and further new research is needed to find decision-aiding tools that adequately conform to real world conditions. In this regard, the main focus in this study is on the issue of acquiring the right quantity of non-renewable resources at the right time and in the right place for projects that are performed under so-called pull-type conditions, as supposed for the CRIBA project.

In traditional approaches, project scheduling and ordering of materials were treated separately. Firstly, appropriate schedules were determined for the activities and then a material ordering plan was drawn up to conform to the generated schedules. However, as has been demonstrated by project planners, any initial planning of the project that does not take materials management factors into account results in unexpected delays and subsequently leads to higher costs (Aquilano and Smith, 1980). Given this potential outcome, several authors have expressed caveats about the exclusion of material ordering issues in determining schedules for the activities and resources. As a pioneer work, (Aquilano and Smith, 1980) states the need to include the order lead-time for the materials in scheduling activities, as well as the records of the amount of storable materials at the project worksites. In a later work by Smith-Daniels and Smith-Daniels, (Smith-Daniels and Smith-Daniels, 1987a), the authors consider the aspect of cost in planning the project and integrate material ordering issues. In their study, they take into consideration the various existing sorts of cost and they determine the schedule on the basis of a trade-off between these costs. The cost term in their study comprises the cost due to delay in the project completion and the costs related to ordering and holding of the materials. Following on from the work of (Smith-Daniels and Smith-Daniels, 1987b), the works of (Dodin and Elimam, 2001) (Sajadieh and Shadrokh, 2009) (Zoraghi et al., 2012) (Fu, 2014) (Tabrizi and Ghaderi, 2015) (Tabrizi and Ghaderi, 2016) use models with the same aim: to take into consideration the effects of cost in yielding settled schedules in the planning of a project with material-ordering issues.

By reviewing the literature (presented in detail in Section 3.3), we note that previous works deal with these problems on the assumption that it is possible to stock materials at the project worksites and basically do not consider the issues of Just-In-Time procurement of non-renewable resources. Therefore, the problem that arises is to define a modeling framework that corresponds to these additional constraints. A suitable modeling framework could be provided by determining *how* to establish the appropriate schedules for defining the start dates for activities in such cases and *how*

to define a procurement plan which incorporates shipping the resources to the project worksites. These two ‘how’ questions are investigated in the following three paragraphs:

- *1- Influencing factors of multi-project schedules on material ordering:* according to the executive characteristics for performing the projects, factors such as the given time windows for executing activities, precedence relationships and also dedicated due-dates for completion of activities constitute restrictions which inductively affect the operations of suppliers in providing the required resources. Considering demands that can be generated by the triggering of the activities, the just-in-time procurement of the resources to project worksites necessitates integrating the project scheduling facts into the resource procurement and supplying issues. Since the products of manufacturers (the non-renewable resources of projects) are commonly used on project worksites, the issues of projects scheduling are linked to the planning for production and transportation of these resources. Taking the definition given in (Chopra and Meindl, 2007) into account, the supply chain network is considered as a network of distinct organizations that work together with the aim of satisfying the final customer demand by producing products or providing services. Therefore, in the context of our work on the scheduling for pull-type projects, project scheduling issues will be integrated with the issues of the supply chain network responsible for producing and procuring the production resources to the projects (Gholizadeh-Tayyar et al., 2015).
- *2- Influencing factors of material ordering issues on scheduling for the multiple projects:* along with the influencing factors of projects schedules on material ordering, the characteristics of the supply chain, such as limited production, transportation and stock capacity affect the procurement of the products and consequently the schedules of the projects. Therefore, determining appropriate schedules for the activities inevitably necessitates including the effect of the driving factors of the supply chain as well. Besides, the influence of the supply chain on the projects becomes more serious when the products required at the worksites are customized and a significant variety of products modules need to be manufactured. In addition, in cases where there is a significant lead-time for transportation or production between the different actors, the operations of the supply chain network will influence the scheduling of the activities. In this context, in the centralized networks where certain given actors perform to supply the required items, the capacity that is negotiated with these actors definitively impacts the scheduling of projects activities at the work-sites.
- *3- Inherent influencing factors of projects on scheduling of the projects:* furthermore, the determination of proper schedules for the activities depends on some inherent influencing factors that are related to the projects themselves, such as the availability of the renewable resources. In our modeling framework, this issue can be addressed through assumptions made to build up a trade-off between time and resources. Indeed, in the corresponding modeling framework, defining a schedule for activities can be

affected by the repercussions of the trade-off between paying for supplementary renewable resources to meet the high-cost due-dates and paying for low-cost due-dates instead of disbursing for high rental cost of the resources.

Given the afore-mentioned points, a modeling framework that encompasses them can be stated by the integration of the *time-* and *resource-constrained multiple project* scheduling problems with a *typical supply chain network* planning model (Gholizadeh-Tayyar et al., 2015).

On the other hand, following the concerns over the increasingly negative impacts of human activities on the environment and the need to protect the environment and its natural resources, many industries and organizations are steering towards sustainable and green development (Musson, 2012) (Hwang and Ng, 2013) (Gosling et al., 2016). While the effects of scheduling for resources (specially for renewable resources) on project schedules are well documented in the literature, to the best of our knowledge, the effects of respecting the sustainability issues in planning to collect the produced wastes from the project worksites and transport them to recycling centers have yet to be determined in the form of a mathematical optimization of the problem. Therefore, in our study in order to make the decisional model responsible for *environmental concerns*, we suppose that the wastes produced in the worksites will be shipped to the appropriate recycling centers, which are located either in manufacturing units or in individual recycling departments, to be recycled and recovered. Figure 7 represents the different aspects of the modeling framework described above.

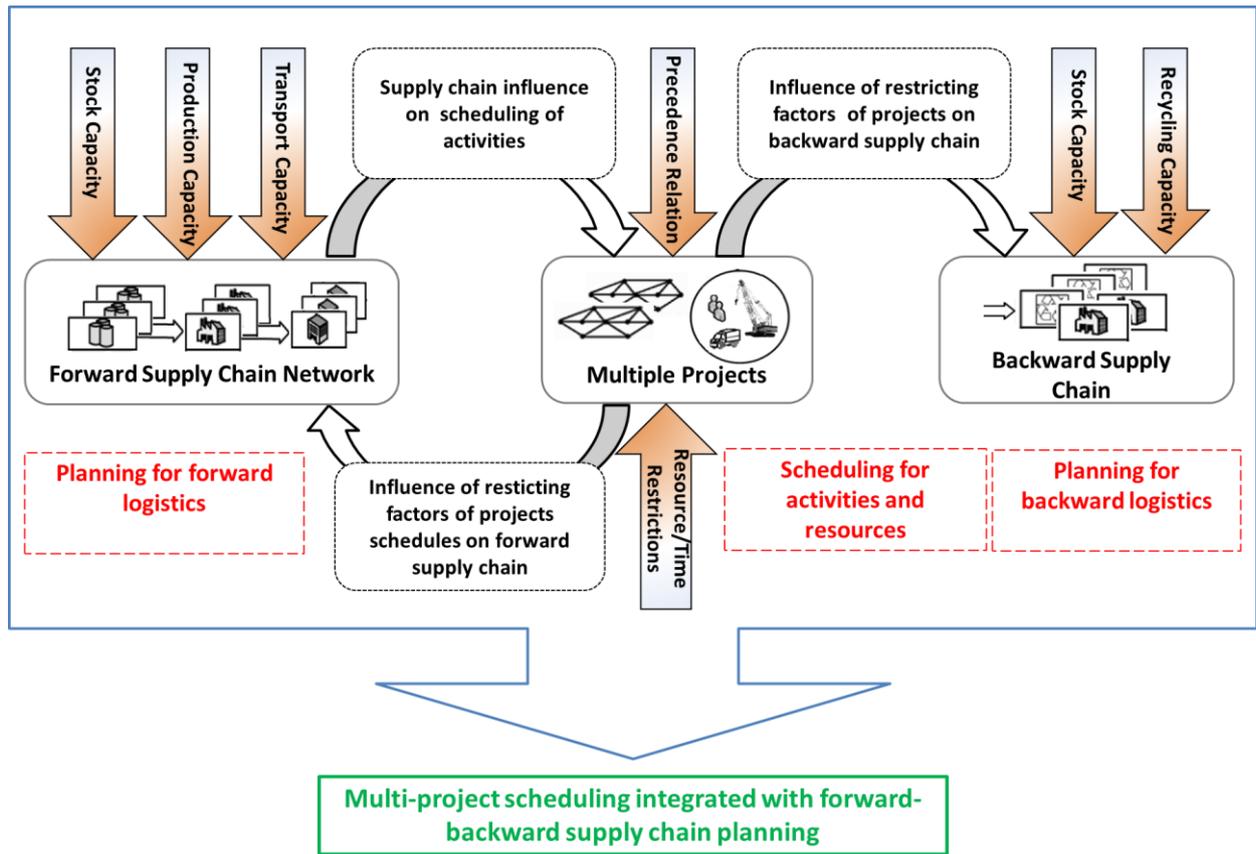


Figure 7- Presentation of the interacting factors of the supply chain and multiple projects in the modeling framework, adapted from (Gholizadeh-Tayyar et al, 2016a).

1.4 The CRIBA project

Because of the increase in human activities from the Industrial Revolution onwards, the emission of greenhouse gases (including CO₂, CH₄, N₂O, HFCs, PFCs, and SF₆) has risen significantly. According to statistics published by Goddard Institute for Space Studies, the average temperature of the Earth has gone up from 0.1 to 0.6 degrees Celsius between 1880 and 2000, as presented in Figure 8.

According to NASA Earth Observatory research, the rate of increase in temperature has nearly doubled in the last 50 years. Concerns about the rising temperature of the Earth have drawn the attention of scientists and managers to find either effective scientific solutions or make new policies for coping with the issue.

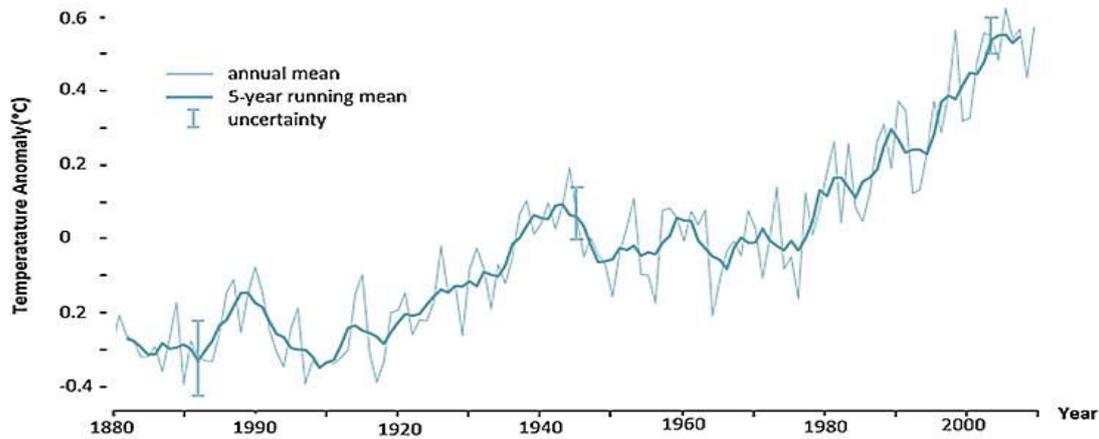


Figure 8- Global mean surface temperature, (from Goddard Institute for Space Studies, NASA Earth Observatory)

The global warning on the impacts of climate change began with the first world climate conference in Geneva, Switzerland in 1979 and continued with growing consensus at the conferences of Rio de Janeiro 1992, Kyoto 1997, Marrakech 2001, Montreal 2005, Nairobi 2006, Bali 2007, Copenhagen 2009, Cancun 2010, Durban 2011, Doha 2012 and Paris 2015.

The Earth Summit in Rio de Janeiro in Brazil led to the signing of the United Nations Framework Convention on Climate Change (UNFCCC). The Rio Declaration consisted of 27 principles intended to guide countries in sustainable development and also to set objectives for stabilizing the concentration of greenhouse gases in the atmosphere at a level that prevents dangerous anthropogenic interference with the climate system. Followed by the Kyoto protocol in 1997, the countries listed in annex B of the protocol, including most of the industrialized nations and countries in transition to a market economy, were committed to reducing their overall emission of greenhouse gases by at least 5% between 2008 and 2012, compared to the emission level in 1990.

In 2005, France made its commitments in sustainable development to follow the global warming reduction objectives. According to (Légifrance, 2005), the fight against climate change gives priority to policies in energy consumption that can reduce the emissions of greenhouse gases in the country by 3% per year. Consequently, the government has developed a climate plan, updated every two years, with all the national measures to tackle the issue of climate change. Following on from the 2005 legislation, in 2009 the French government decided to divide by four the emission of greenhouse gases in the country by 2050 (Légifrance, 2009). In line with this objective, since building sector generates 24% of the total emissions of the country due to consumption of 44% of the total energy, (CGDD - SOES, 2013), it is key to reaching the objectives pursued in climate change policy. See Figure 9.

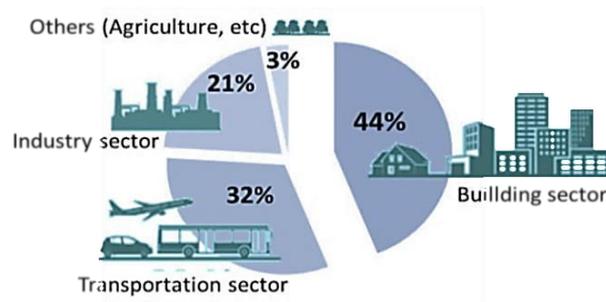


Figure 9- Energy consumption by sector in France (CGDD, 2013).

CRIBA (the initials come from the French terms “Construction et Rénovation Industrialisée Bois et Acier”) is a project created and funded by the ADEME agency for environment and energy management, (standing for l’Agence de l’Environnement et de la Maîtrise de l’Energie). ADEME has attempted to provide a scientific and applicable solution to reduce the total energy consumption level of buildings in France. Under the CRIBA project, energy consumption is targeted to fall to only 25 Kwh/m²/year in 500 000 habitations. To achieve this goal, buildings are supposed to be renovated from two points of view, from the inside and from the outside:

- The energy-efficient renovation of buildings from the inside involves establishing more efficient controlled mechanical ventilation systems as well as the replacement of heating and hot water systems by energy-saving ones.
- On the other hand, outside renovations involve covering the exterior facades of the buildings with industrialized pre-fabricated panels that contain new insulating carpentries. Covering the buildings with enveloping panels provides the possibility to insulate the buildings and thus reduce their energy transmission to the external environment. The panels are made up of different materials and components. The main composing elements are (i) insulation materials, (ii) wooden/steel frames (iii) joinery (doors, windows and shutters), and (iv) covering materials. A cross-section of the insulating panels is presented in Figure 10. The prefabricated panels embedded with the joinery are carried from the manufacturing centers to the project worksites to be installed on the buildings by use of appropriate metal fasteners and frames. Figure 11 depicts different steps that are followed to position the panels on the buildings. It is worth noting that the former carpentries of the buildings are removed after the installation of the insulating panels. The removed carpentries are supposed to be carried to the proper recycling centers to be recycled and reused in different industries for different purposes.

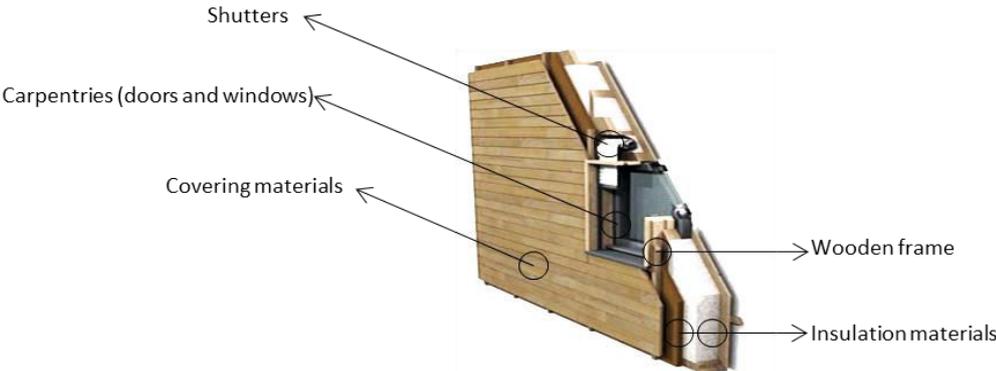


Figure 10- Prefabricated insulating panels integrated with the prefabricated carpentries.

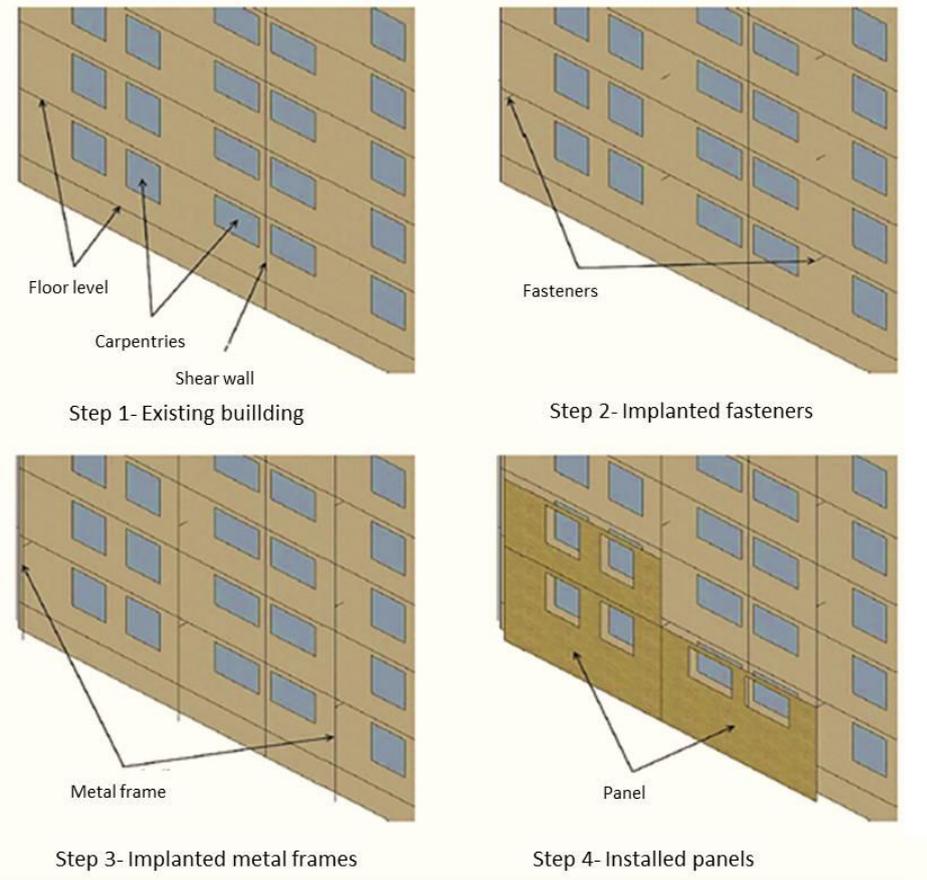


Figure 11- Steps for installing the insulating panels on an existing building, from (Falcon et al., 2013).

According to the demonstrator of the project (CRIBA project, 2010), the executive process of the buildings’ thermal renovation presents several major technological breakthroughs. Figure 12 summarizes the process of the thermal renovation of the buildings from the preliminary studies of the buildings’ situation to production and installation of the panels. With the aim to measure the dimension of the buildings and extract the information about the dimension of the panels as well the positioning of the carpentries on the facades, plotting of the buildings is done by use of drones. The drones are equipped with the existing techniques of laser scanning and photogrammetry enriched with photographic tools adapted to high-rise buildings and structures. On the basis of the information about the dimension of the panels extracted from the images, design and configuration of the pertinent panels will be accomplished. For this purpose a set of digital tools are used to help decision makers to evaluate different alternatives in the design and configuration of the cladding. On the basis of the results obtained from these analyses, manufacturing plans for the required panels and joinery are forwarded to the corresponding manufacturing centers. After that, the off-site prefabricated panels are directly sent in a just-in-time way from the warehouse of the manufacturing centers to the project worksites, based on the demand that is created in the worksites.

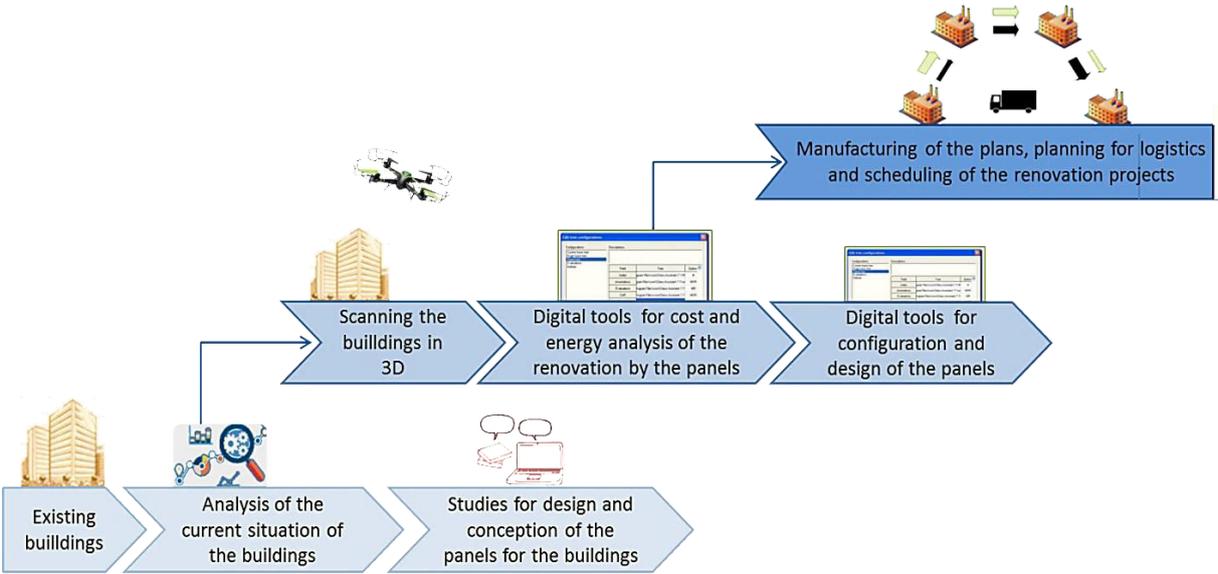


Figure 12- Executive process of thermal building renovation in the context of the CRIBA project.

1.4.1 Scope and coverage

Having seen the practices that have been determined in order to renovate buildings in the context of the CRIBA projects, the research works that will ensure their technical and scientific feasibility include the following topics:

- *Design of appropriate insulating panels with efficiency of 25Kwh/m²/year made up of wood/ steel and the insulating materials for undertaking the treatment of the facades and roofs with architectural enhancement of the buildings:* For this purpose, a study has been carried out in the RAPSODEE research center of IMT Mines Albi-Carmaux. The research work provides guidelines to design the panels that on the one hand are adapted to the specification of the different buildings (such as the strength of the building to support the weight of the panels, the current energy efficiency of the buildings, etc.) and on the other hand to meet the CRIBA objectives in obtaining an energy efficiency of 25Kwh/m²/year.
- *Propose a procedure to industrialize the process of thermal renovation of buildings:* the research work corresponding to this purpose has been set up in the framework of a PhD project involving collaboration between the Industrial Engineering department of IMT Mines Albi-Carmaux and SYRTHA company, through the work of (Falcon et al., 2013). From a practical perspective, the thesis aims to define a procedure to renovate the buildings in an industrialized way. From a technical point of view, it attempts to provide a procedural decision-making tool to ensure quality in performing the thermal renovation projects.
- *Develop a computer based application to create the 2D model for the configuration of the panels:* in keeping with this aim, a PhD study has been conducted in the Industrial Engineering department of IMT Mines Albi-Carmaux. Its purpose is to provide a tool that helps architects with their decision-making processes in the configuration and positioning of the panels. Based on the driving factors such as configuration costs and aesthetics aspects, a set of solutions have been produced and are available through the use of a web-based support system. The application provides the possibility for the decision makers to choose the most appropriate solution. For further information on the application and its solving procedure, we refer the readers to (Barco et al., 2015) and (Barco et al., 2016).
- *Provide a decision aiding tool to plan the thermal renovation projects under the just-in-time procurement of resources by the corresponding supply-chain network:* This part forms the purpose of the current research work. Relying on the primary study in line with this objective presented in (Gholizadeh-Tayyar et al., 2014), a comprehensive planning framework, as introduced generally in this section, is developed. Subsequently a web-based application is provided to support the modeling framework. Three main components of the application are *i.* data queries: to provide infrastructures that allow data entry related to the planning of a set of projects with its supply network, *ii.* model creation and execution interfaces, implemented to define functionalities that allow the application to utilize and exploit the decision making model for planning of the different cases envisaged, and *iii.* reporting and graphics, to enable the decision support system to extract and present the results from the solution of the model, as shown in Figure 13.

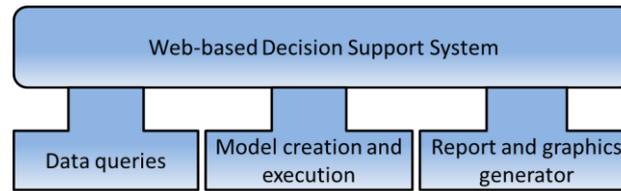


Figure 13- Building blocks of the decision-support system provided for the modeling framework presented in Figure 7.

A typical instance of the potential actors that may be involved in the CRIBA project network is depicted in Figure 14. In general, five sorts of stakeholders can be recognized including suppliers of raw materials, manufacturing centers, project worksites, recycling centers and organizational management. In the figure, two types of manufacturers have been featured: the manufacturing centers for carpentries and the manufacturing centers for panels. These two centers were chosen as examples due to the importance of their products. Panels and carpentries are customized by the project architects with regard to their covering materials and their aesthetics aspects. As a result, there is a high variability in their manufacturing. Since these products are critical, their manufacturing centers are highlighted and their production and supply operations are considered for planning purposes. Other products such as fasteners or metal supports are standard and non-customized products which could be available at the project worksites without any restrictions. However, for the critical products, negotiations on reserving sufficient capacity for producing and supplying them to the destinations of use will play a major role in project management at the worksites.

In this project supply chain network, as with conventional supply chain networks, the suppliers provide the required raw materials to the manufacturing centers. The carpentries are produced and transported to the panel-manufacturing centers to be embedded in the panels. Production of these products requires appropriate lead-time. Similarly, there is a transportation lead-time to ship the different items to their destination of use. As depicted in the figure, after installing the panels, all the waste generated at the worksites is shipped to the recycling centers. All the process of supplying the resources to the worksites, carrying out the building renovation projects and management of the waste is coordinated under the supervision of a managerial enterprise. The planning model based on the restrictive factors in the supply chain and the intrinsic limiting factors of scheduling for the projects for comprehensive planning and management of the system is presented in Chapter 4.

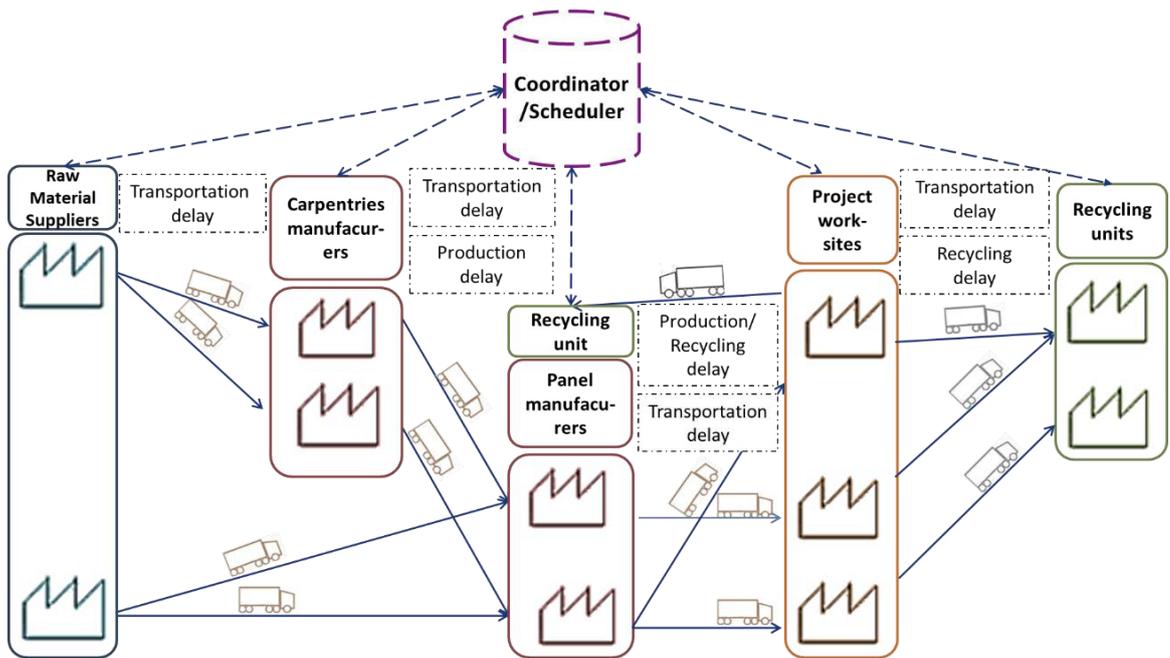


Figure 14- An illustration of the structural network of thermal renovation projects, with multiple project worksites linked to a typical supply chain network.

1.4.2 Research positioning in the CRIBA context

Considering the planning horizons from a company level perspective, decision making for system management can be analyzed in three levels: strategic, tactical and operational (Anthony, 1965) (Bilgen and Ozkarahan, 2004):

- *Strategic level:* strategic decisions are made at the highest level of management. They mainly concern long term policies lasting for several years. Decisions made by managers at this level influence all decisions at lower levels. Examples of strategic decisions may be the initial selection of the projects, the design of the supply chain, the selection of new technologies or locating new facilities.
- *Tactical level:* Decisions at the tactical level are associated with mid-term planning. The planning horizon mainly depends on the tasks the organization needs to perform. Commonly, it can vary from one month up to one year. Decisions at this level concern planning the procurement of required materials, planning for inventories, planning for production, distribution of the products as well as ranking the projects in the portfolio in terms of their length or complexity .
- *Operational level:* at the operational planning level, decision making concerns very short-term decisions ranging from a few hours to a couple of weeks. The most detailed and precise

instructions for execution of managerial tasks are specified at this level. Control and planning for required materials and short-term transportation policies are examples of decision-making at the operational level.

Figure 15 summarizes different decisions corresponding to each level of management of the projects subject to material procurement issues. In terms of the hierarchical levels, decision-making for the lower levels is impacted by the decisions made in the upper levels. On the other hand, in the two upper vertical levels a mutual influence exists between the decisions made regarding management of the projects and management for procurement of the resources.

Typically, at the strategic level, decisions on selection of the suppliers and design of the supply chain network mutually depend on the projects that have been selected. That is to say, the design of the supply chain for procuring the materials is inevitably associated with the selection of the projects and vice versa.

A similar concept is envisioned for making decisions at the tactical level of planning. At this level, decisions regarding management of the multiple projects have been influenced by their scheduling. Conversely, scheduling for the projects has been incorporated with planning of the supply chain network, wherein the design of the supply network by selection of the suppliers results from decision making at the strategic level. The planning issues discussed in Section 1.3 involve the tactical level of decision making for management of the projects, integrated with material procurement issues. Depending on the size of the projects (number of activities and number of resources), the execution of thermal renovation projects will last for different periods of time. A small size project encompassing a single building could be performed at a horizon of less than one month while a project including five buildings may last over six months.

Subsequently, operational decisions in such systems deal with planning of the shop-floor for the manufacturing centers of the supply chain network and execution and control of the activities in the project worksites.

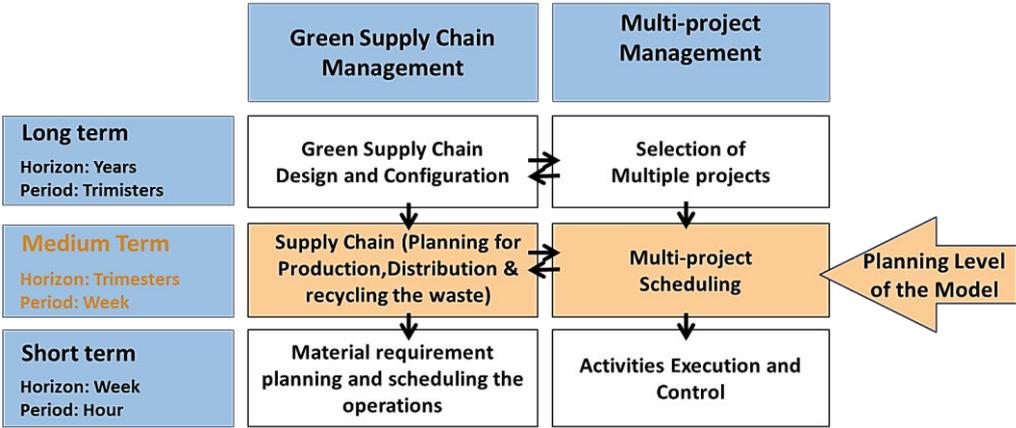


Figure 15- Levels of decision-making in planning for projects integrated with a supply chain representing the positioning of the study throughout the levels.

1.5 Chapter conclusion and discussion

In this chapter, the overall context of the research relating to the first question of the study (**Q.1**) is described. In this regard, three contextual parts of planning for the projects including the structuring, scheduling of the resources and scheduling of the activities have been presented. By addressing the elements of these three parts, the primary perimeter of the work has been determined. Furthermore, the framework of a model has been developed by evaluation of requirements for planning of so-called pull-type project scheduling. The proposal for the modeling framework is introduced on the basis of simultaneous planning of the projects and the supply chain network which procures the resources for the project worksites. In line with current developments in green issues, the model has been designed to incorporate the collection and recycling of waste generated at the project worksites.

The CRIBA project has been introduced and its scope and objectives have been described. The last part of the chapter is dedicated to positioning the research work within the CRIBA project.

“Wisdom must be intuitive reason combined with scientific knowledge.”
Aristotle

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2.1 Chapter introduction

Having presented the context and problematic of the work in the Chapter 1, the current chapter reviews the literature in the field of project scheduling. The objective of the chapter is to (1) understand the *specifications* of the different project scheduling models, (2) review the *complexity issues* in optimization of the constrained project scheduling problems and (3) study the *methodologies* that are used for *solving* the constrained project scheduling problems. To this end, the chapter starts with a brief introduction to the primary research conducted on project scheduling and describes the research objectives related to these studies. It then describes the constrained project scheduling problems in Section 2.3. The models in this area are classified into two main classes: resource constrained project scheduling problems and time constrained problems. Sections 2.3.1 and 2.3.2 review these problems and outline the mathematical representation of the chosen models. Complexity issues for optimizing the constrained project scheduling problems and different criteria for scheduling single and multiple projects are reviewed in Sections 2.4 and 2.5. Thereafter, Section 2.7 and Section 2.8 describe the solving methodologies that are exclusively developed to tackle, respectively, resource constrained and time constrained models. Although these methods are problem-dependent, they provide building blocks for the improved methods outlined in Section 2.8.

2.2 Preliminary studies on project scheduling: unconstrained problems

Early studies on scheduling for projects consisted in planning for so-called unconstrained project scheduling problems. The motivation of these studies was simply to determine the start date for activities of the projects solely subject to precedence relations, wherein the required resources for performing the projects were fully on hand in an unlimited quantity. Although this case is not very practical and not adapted to real-world situations due to restricted availability of resources, project planning under unconstrained resources has been studied widely for more than thirty years. Since its development by DuPont Corporation during the 1950's, the Critical Path Method (CPM) has been used as a tool for dealing with unconstrained project scheduling problems throughout the works of (Ahuja 1976) (Wiest and Levy 1977) (Halpin and Woodhead 1984) (Antill and Woodhead 1982).

2.2.1 Critical Path Method (CPM)

The main objective of this method is to define “the shortest possible completion time” for the project whilst not violating “the precedence constraints” imposed by the project network. The application of the algorithm is dedicated to cases where the activities possess a deterministic processing time omitting minimum/maximum time lags, finish-to-start acyclic precedence relations and with a single mode of execution. Without loss of generality, two dummy activities, which correspond to the beginning and ending activities of the project with zero processing time and zero

requirements for the resources, are added to the activity list of the project. In order to deal with the precedence constraints in the representative network, activities are supposed to be numerated by use of a topological ordering that determines if activity i is the predecessor of activity j , then $i < j$. In more complex projects with complicated activity relations, the numerating procedure provided by (Shtub et al., 1994) includes guidelines for labeling the activities. Using the critical path method, the earliest start and finish time (respectively denoted by ES_j and EF_j) for all the activities are defined within a forward pass. Having supposed $ES_1 = EF_1 = 0$ and denoted d_j as the processing time of activity j , then:

$$ES_j = \max \{EF_i \mid i \text{ belongs to the predecessors of } j\} \quad \text{for } j=2, \dots, n \quad 2-1$$

$$EF_j = ES_j + d_j \quad \text{for } j=2, \dots, n \quad 2-2$$

Subsequently, the latest starting and finishing time are computed for all the activities by a backward pass beginning with $ES_n = EF_n$

$$EF_j = \min \{LS_h \mid h \text{ belongs to the successors of } j\} \quad \text{for } j=n-1, \dots, 1 \quad 2-3$$

$$LS_j = LF_j - d_j \quad \text{for } j=n-1, \dots, 1 \quad 2-4$$

The calculation of these values in the CPM leads the managers to determining a sequence of activities which is called the critical path. The critical path is an important concept in planning and management of the project due to its impact on the entire project. Indeed, if the activities which lie on the critical path are delayed, the planned completion time for the project will be delayed as a result. In CPM, the term “float” is used to determine a flexible spare time existing within the activities. Two major types of float are introduced: total float and free float. The total float is the spare time which is on hand when all preceding activities ensue at the earliest possible time and all succeeding activities occur at the latest possible time. Free float is time available when all preceding activities again occur at the earliest possible time, but where the succeeding activities also take place at the earliest possible time.

Besides calculating the completion time of the project by applying the forward-backward procedure, a linear programming model is formulated with the same intention (Elmaghraby and Kamuruowski, 1992) (Carruthers and Battersby, 1966). By denoting S_j and $Pred_j$ respectively as the starting time of job j and the predecessors of activity j , the mathematical formulation of the problem is presented as follows:

$$\text{Minimize } Z = S_n \quad 2-5$$

s.t.

$$S_i + d_i \leq S_j \quad \text{for } j=2, \dots, n \text{ and all } i \in Pred_j \quad 2-6$$

$$S_1 = 0 \quad 2-7$$

In this formulation, the objective function (equation 2-5) minimizes the total completion time of the project. Constraint 2-6 satisfies the precedence relations and equation 2-7 sets the start of the project to the beginning of the planning horizon. It is worth noting that the values of S_j may not exactly correspond to the earliest starting times calculated by the forward-backward pass. Therefore, in order to get the same values, a penalty term ($\varepsilon \cdot \sum_{j=2}^n S_j$) needs to be added into the objective function.

Because it is simple and efficient, the forward-backward pass has been extensively used for calculation of the earliest and latest start times as well as for critical path analysis. The optimization formulation can be useful when the number of the constraints increases by growth in the number of activities in large size projects. Furthermore, the method is well suited to project scheduling problems with time lags and more generalized activity networks, i.e. either acyclic or cyclic networks. Several extensions of CPM have been introduced in the literature. (Zhan, 1992) addresses a critical path method with non-working days. (Chen et al., 1997) deals with problems where the activities are supposed to be executed through predefined time windows. (Chen et al., 2015) develops a new algorithm which combines a heuristic based on the differential evaluation algorithm and the critical-path method to enhance the CPM algorithm in exploring and exploiting the global optimal solution more efficiently.

Although different uses of CPM have emerged in project planning, the method suffers from drawbacks owing to unsatisfactory responses in the cases of scheduling for projects with limited availability of resources, budget, etc. The requirement to resolve this issue was behind the introduction of so-called “Constrained project scheduling” and their solving procedures.

2.3 Constrained project scheduling

Project scheduling problems with restricting aspects clearly represent “more realistic cases” and have thus drawn the attention of many researchers and managers. In contrast to the un-constrained project scheduling models, the constrained approach assumes that the projects are bounded in terms of some driving factors, which would affect the allocation of resources and, consequently, project schedules. These restricting factors can be investigated from two angles, involving time and resource aspects. Depending on the factors involved, two major kinds of the problem can be envisaged and discussed. They include so-called “Resource Constrained Project Scheduling Problems” and “Time Constrained Problems”. Sections 2.3.1 and 2.3.2 provide details about both of these models and cite their corresponding literature.

2.3.1 Resource Constrained Project Scheduling Problem (RCPSP)

Since the early 1970s, a growing interest has been seen in modeling and scheduling of projects with limited availability of resources in multiple areas and the associated RCPSP problem has drawn the

attention of numerous researchers and managers. The basic RCPSP concept is described as a problem of scheduling a project with a given set of activities which are inter-related by finish-to-start precedence relations. No pre-emption of activities is allowed in the standard form of the problem, which means that once an activity starts being performed, it is executed consecutively until fully accomplished. The trigger of each activity is subject to the limited availability of the resources required as well as the precedence constraints between the predecessor and successor activities. In its basic form, a set of renewable resources is considered to be used for processing the activities. In every time period, resource availability is a constant number, b_r denoting the available amount of resource r . Over a time period, the total demand for the ongoing activities for a resource r , $\sum_j v_{rj}$, must not exceed the total available amount. At any time instant t , if the set of candidate activities that qualify to be triggered requires more than b_r units for any r , then some activities will have to be postponed in order to satisfy the resource constraints.

The main goal of the RCPSP is to determine a non-pre-emptive schedule of activities so that the precedence relationship between the activities and the resource constraints is not violated and the duration for accomplishing the project is minimized. Figure 16 depicts a typical Activity-On-Node (AON) network of a project. According to the characteristics of the model and its distinctive aspects, a possible feasible solution for scheduling the events and an optimal solution of the problem is presented in Figure 17.

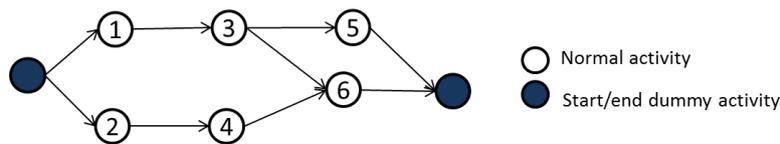


Figure 16- AON precedence presentation for a typical example.

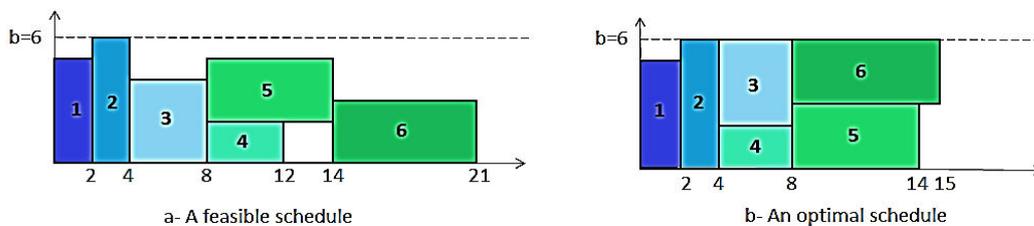


Figure 17- Feasible and optimal solutions for a typical RCPSP.

2.3.1.1 Mathematical representation

One of the pioneer mathematical representations of RCPSP was formulated by (Pritsker et al., 1969). In the model, the solutions are determined by 0-1 variables X_{jt} , where, X_{jt} holds the value of 1 if activity j is finished at the end of period t , and 0 otherwise.

$$\text{Minimize } Z = \sum_{t=EF_n}^{LF_n} t X_{nt} \quad 2-8$$

s.t.

$$\sum_{t=EF_j}^{LF_j} X_{jt} = 1 \quad \text{for } j \in J \quad 2-9$$

$$\sum_{t=EF_j}^{LF_j} (t-d_j) X_{jt} - \sum_{t=EF_i}^{LF_i} X_{it} \geq 0 \quad \text{for } j \in J, i \in \text{Pred}_j \quad 2-10$$

$$\sum_{j \in E(t)} v_{rj} \sum_{q=\max(t, EF_j)}^{\min(t+d_j-1, LF_j)} X_{jq} \leq b_r \quad \text{for } r \in R, t \in T \quad 2-11$$

$$X_{jt} \in \{0,1\} \quad \text{for } j \in J, t \in [EF_j, LF_j] \quad 2-12$$

The objective function in the model (equation 2-8) seeks to minimize the completion time of the project. Constraint 2-9 guarantees that exactly one finishing time is assigned to each activity. Constraint 2-10 ensures that no job can be started before all its predecessors have been accomplished. Therefore, it guarantees the satisfaction of the precedence relationship between the activities. Constraint 2-11 indicates that the resource constraints should be guaranteed over each of the time periods for all types of resources. In this context, the total resource demand of the activities processed in period t , $j \in E(t)$, must be determined. An activity j is executed in a period, if it is accomplished at the end of the period $t, \dots, t+d_j-1$. However, the finishing time of the activity must hold a value within the time interval $[EF_j, LF_j]$.

The formulation 2-8-2-12 necessitates the definition of up to $J.T$ binary variables and includes up to $J+|A|+R.T$ constraints, where A is the set of arcs. In the other words, because it includes at most $n.(n-1)/2$ arcs, the model possesses $O(J^2+R.T)$ constraints. Relying on the notation given by (Brucker et al., 1999), the basic model of the RCPSP is presented in the form of $\text{PSm}|\text{prec}|C_{\max}$. With this notation, the first field is defined to distinguish the resource environment. “PSm” indicates m type of renewable resources limited in their availability quantity. The second field determines the activity characteristics. In this context, “prec” indicates that precedence constraints exist between the activities. The last field relates to the objective function. The notation “ C_{\max} ” is used to present the objective for minimizing the makespan of the project.

2.3.1.2 Instances of the problem

In the literature, the modeling concepts for resource constrained project scheduling problems have been extensively studied. This could be because of the large body of real-life cases which are motivated by the same intentions as those of RCPSPs. Some of these applications include the following examples:

2.3.1.2.1 Scheduling for construction projects

As construction projects involve numerous activities with various types of resources in limited available quantities, managing and planning such projects is made more complex when the number of the activities increases and more resources are required. Understandably, therefore, the application of resource constrained project scheduling methods has been of considerable interest to construction managers and researchers. In scheduling Architecture, Engineering and Construction (AEC) projects, the use of RCPSP models adapted to different running conditions allows managers to track projects with objectives on minimizing the time and cost or maximizing performance quality. Examples of research in this context can be seen in (El-Ray et al., 2005) (Senouci and Al-Derham, 2008) (Long and Ohsato, 2009) (Faghihi et al., 2014) (El-Abbasy et al., 2016).

The research in (El-Ray et al., 2005) is designed to transform the traditional two-dimensional time-cost trade-off analysis to an advanced three-dimensional time-cost-quality trade-off analysis. A multiple-objective genetic algorithm (the principals of the genetic algorithm are described in Section 2.9.3.1) was developed to provide the capability of quantifying and considering quality in construction optimization. (Senouci and Al-Derham, 2008) develop a robust multi objective optimization model that allows construction planners to generate and evaluate optimal or sub-optimal construction scheduling plans in which both the project time and cost are minimized. The application of an algorithm based on the genetic algorithm is used in order to determine the pareto solutions of the model. (Long and Ohsato, 2009) present a method for simultaneously optimizing the project completion time and cost. The solution method is based on the genetic algorithm approach in that it considers different attributes of activities (such as activities which allow or do not allow for interruptions), and different relationships between direct costs and durations for activities (such as linear, nonlinear, continuous, or discrete relationships), to design a procedure to provide a satisfactory schedule. In (Faghihi et al., 2014), the authors demonstrate a novel approach of retrieving enough information from the buildings in order to determine the construction sequencing for the project elements. (El-Abbasy et al., 2016) aims to help contractors define schedules that are the result of trade-offs between different projects objectives, namely: duration of multiple projects, total cost, financing cost, maximum required credit, profit, resource fluctuations and peak demand. The principles of the genetic algorithm are used in order to build up the resolution procedure.

2.3.1.2.2 Production and operation scheduling problems

Another application of resources constrained project scheduling problems is dedicated to the scheduling of operations viewed in the context of the Job Shop Scheduling Problems (JSSP). The problem is described by a set of activities which is to be performed on a set of machines with varying processing times. Each job possesses a technological sequence of machines to be operated. The data contains the routing of each activity through each machine and the processing time of

operating the activities on the machines. The main aim of the problem is to define a schedule which minimizes the total makespan (Baker, 1997).

Additionally, the application of the method can be found in the scheduling of manufacturing processes in industries with sensitive operations. Scheduling for multi-stage batch operations, wherein an interruption within a process can damage the value of previous operations, has warranted great attention from managers and academicians. Referring to (Dixit and Yadav, 2010), examples of this type of process can be viewed in manufacturing of semiconductors where production of a wafer requires a set of predefined operations in which a failure in realizing the operation may lead to a calamity. Examples of the research works on this topic are (Mönch et al., 2011) and (Yugma et al., 2012).

2.3.1.3 Variant extensions

Different extensions of the resource constrained project scheduling problems are reviewed in Subsections 2.3.1.3.1 - 2.3.1.3.3. They involve multi-skill scheduling problems, time-lag problems and generalized resources. The outcome of the review within this section results in drawing the framework of the project scheduling model as well as showing opportunities for developing the mathematical model.

2.3.1.3.1 Multi-skill scheduling problems

In multi-skill project scheduling problems, the renewable resources of the project are “multi-skilled”. This is often the case where the resources are mainly labor and human, for instance technicians who are performing maintenance activities. In these problems, each activity may require several skills. For each skill, the workload necessary for performing the activities is known *a priori*. Commonly, a resource has been contributed with at most one skill to one activity at every time. Every resource allotted to an activity during its processing time remains assigned until the activity has been accomplished. Furthermore, the resources allocated to each activity stay together for the duration of the activity. The objective of the basic model is to find a solution that minimizes the makespan of the project subject to resource and precedence constraints. To the best of our knowledge, the research on this topic consists of only a small number of works and contributions in the literature. In the work of Firat and Hurkens, (Firat and Hurkens, 2011), the authors present a mixed integer mathematical model that is proposed to assign the human resources to activities with multi-level skill requirements. (Heimerl and Kolisch, 2009) consider a multi-skill project scheduling model where the objective is to minimize labor costs. In this work, the authors present a mixed integer linear programming model with a tight LP-bound. The performance of the model (gap between the optimal solution and computational results) has been assessed through the application of model to several IT projects. The work demonstrates the benefit of the mixed integer linear programming model compared to simple heuristics models in practice.

2.3.1.3.2 Time lag problems

In the classic model of resource constrained project scheduling problems, an activity has to be finished before any of its successors starts. This assumption can be extended by a minimal time lag, lag_{ij}^{FS} . The lags in the scheduling provide the possibility to determine either that the predecessor and successor activities can be overlapped, or that spare time might be spent between the predecessor and successor activity. The employment of minimal time lag are seen in the works of (Demeulemeester and Herroelen, 1996) (Chassiakos and Sakellariopoulos, 2005) and (Vanhoucke, 2006). Similar to the minimal time lags, maximal time lags between the completion time of activity i and start time of its successor activity j are introduced to follow the intention in which the activity j may not start later than a given period after the completion time of activity i . It is worth noting that that maximal time lag problem may lead to infeasible models and/or cyclic project networks.

2.3.1.3.3 Generalized resources

Besides the renewable and non-renewable resources, other kinds of resources have been introduced and studied in the literature. They can be termed as generalized resources. These resources are indeed extensions for the common type of renewable and non-renewable resources that are brought into study for particular interests. For instance, synchronizing resources are introduced as the resources that can ensure a simultaneous start of a set of activities (Schwindt and Trautmann, 2003). Doubly constrained resources are resources that can be either used as a renewable or non-renewable resource from the view point of their depletion after usage. For further detailed information in this context and more extensions, we refer the readers to the following surveys: (Kolisch and Padman, 2001) and (Węglarz et al., 2011).

2.3.2 Time Constrained Problems

Taking the “time factor” into consideration, time constrained problems generally refer to scheduling problems in which a “strict” deadline is imposed for completion of the projects. In these problems, the imposed deadline is too tight to be met using the renewable resources that are initially provided. Therefore, the model assumes that the capacity of the renewable resources can be temporarily “extended” by renting supplementary quantities. In general, the time-constrained models can be classified into three types: Resource Leveling Problems (RLP), Resource Investment Problems (RIP) and Time Constrained Project Scheduling Problems (TCPSP). Having supposed the possibility of adding the supplementary resources as a common assumption for the aforesaid models, the difference between the models emerges from the objectives they seek to achieve.

2.3.2.1 Resource Leveling Problem (RLP)

Resource Leveling Problems aim to determine a schedule that minimizes the fluctuations in patterns of resource usage (Antil and Woodhead, 1982) (Harris, 1990). The problem follows the hypothesis that more steady usage leads to significantly lower costs. In order to present the objective function mathematically, the demand for each of the renewable resources must be determined. Taking the formulation of the RCPSP given in section 2.3.1 into account, the constraint 2-11 has to be modified and transformed into equation 2-13. In the formulation, b_{rt} is instead a variable of a fixed parameter:

$$\sum_{j \in E(t)} v_{rj} \sum_{q=t}^{t+d_j-1} X_{jq} = b_{rt} \quad \text{for } r \in R, t \in T \quad 2-13$$

Constraint 2-13 guarantees that the resources demanded for executing the activities will be on hand in the required quantity. In addition, the objective function of the model has also to be modified. In this context, formulation 2-14 presents the objective function of the model. Herein, w_r denotes a weight connected with resource type r .

$$\text{Minimize } z = \sum_{r=1}^R w_r \sum_{t=1}^T b_{rt}^2 \quad 2-14$$

2.3.2.2 Resource Investment Problem (RIP)

The resource-investment problem can be obtained from the resource leveling problems. It addresses the scheduling problems which are given with a deadline. The problem makes a decision about the quantity of resources that need to be provided in order to carry out the project. Considering c_r as the expected cost for supplying a single unit of renewable resource type r , the objective function of the RLPs can be transformed into equation 2-15. In this context, it should be noted that the optimization model is subject to constraints 2-9 to 2-12.

$$\text{Minimize } z = \sum_{r=1}^R c_r b_r \quad 2-15$$

2.3.2.3 Time Constrained Project Scheduling Problem (TCPSP)

TCPSP attempts to define a schedule in such a way that the project is not only completed on time but also that the total cost of adding the supplementary renewable resources is minimized (Dekro and Herbert, 1989) (Guldmond et al., 2008) (Hurink, J.L., et al., 2011). Relying on the formulation presented in Section 2.3.1 for the RCPSP, the objective function and constraint 2-11 have to be modified in order to present the TCPSP mathematically. In this context, equation 2-16 attempts to minimize the total cost of adding the resources wherein Add_{rt} presents the additional units of resource type r provided in period t . Subsequently, constraint 2-17 states that the total demand for

the resources should not exceed the initial availability of the resources plus the quantity that may be added.

$$\text{Minimize } z = \sum_{r=1}^R c_r \sum_{t=1}^T \text{Add}_{rt} \quad 2-16$$

$$\sum_{j \in E(t)} v_{rj} \sum_{q=t}^{t+d_j-1} X_{jq} \leq b_r + \text{Add}_{rt} \quad 2-17$$

2.4 Complexity issues in constrained project-scheduling problems

In any discussion of the complexity of the optimization problems, computation time and storage space required for solving the problems are major concerns. The NP-hard class includes problems for which no polynomial time algorithm has been deployed in order to define “an optimal solution”. In this context, the problems wherein at least a “feasible” solution can be found in polynomial time are termed as NP-hard in the ordinary/simple sense. In contrast to these “simple” NP-hard problems, NP-hard in the strong sense of the term defines problems for which no feasible solution can be determined in a polynomial time (Ausiello et al., 2012).

Resource constrained project scheduling problems can be reduced to a known job shop scheduling problem (JSSP). Since the JSSP is NP-hard, the RCPSP and consequently the RCMPSP as well as the GRCMPSP are NP-hard too, (Blazewicz et al., 1983) and (Elmaghraby and Kamburowski, 1992). According to (Neumann et al., 2002), the TCPSP problems are considered to be NP-hard as well. Nevertheless, these problems are not NP-hard in the strong sense of the term, since a feasible solution can be obtained by computing the topological order of the activities in polynomial time. For RCPSPs, according to (Herroelen, 2005), once projects become larger, i.e. involving more than 60 activities from Kolisch and Sprecher’s PSPLIB, presented in (Kolisch and Sprecher, 1997), the branch-and-bound algorithms become computationally intractable.

2.5 Optimization criteria in project scheduling

Considering the state of the art in project scheduling, the optimization criteria in scheduling for projects fall into six main groups, discussed in (Kolisch and Padman, 2001) (Hartmann and Briskorn, 2010) and (Gholizadeh-Tayyar et al., 2014):

- *Time-based objectives*, wherein objectives such as completion time, earliness, tardiness and lateness are supposed to be minimized (Essafi et al., 2008) (Lamothe et al., 2012) (Arabameri and Salmasi, 2013) (Baker, 2014).
- *Quality-based objectives*, which attempt to maximize the quality of the project. The primary optimization model in this regard has been presented in (Icmeli-Tukel and Rom, 1997).

- *Cost-based objectives*, in which the objective function minimizes the total cost of projects, including execution costs, materials costs, inventory holding costs or costs related to the tardiness or earliness of the project. Some recent studies in this area are reviewed below: (Ranjbar et al., 2012) represents an optimal solution procedure for minimizing total weighted tardiness penalty costs in resource constrained project scheduling problems. In (Rodrigues and Yamashita, 2010) the authors consider resource availability cost in their problem and they propose an exact algorithm to report the results. Their algorithm includes a hybrid method where an initial feasible solution is found heuristically and then branching concepts are applied to find the results. (Dodin and Elimam, 2001) pursues RCPSP with minimization of material costs, inventory costs and activity-crashing costs. In the context of the work, activity-crashing costs are the costs of shortening the duration of an activity by increasing the required materials. Besides, the authors consider a bonus for early project completion time or a penalty coefficient for delay in project completion.
- *Net present value objectives* are used when certain cash flows come into the project according to predefined milestones. Net present value maximization reflects the time value of money in project scheduling problems. Some models and solution methods for these problems are reviewed by (Demeulemeester and Herroelen, 2002) (“Wiley,” 2008.) and (Wiesemann et al., 2010).
- *Number of late jobs*, wherein the objective is to minimize the total numbers of the late jobs, (Dauzère-Pérès, 1995) and (Sevaux and Dauzère-Pérès, 2003).
- *Multiple objectives*: in these problems multiple objectives are chosen for optimization, where they are in conflict with the unitary dimensions. Examples of these studies can be seen in (Al-Fawzan and Haouari, 2005) (Abbasi et al., 2006) (Tavana et al., 2014) (Shahsavari et al., 2015) and (Tabrizi and Ghaderi, 2016).

2.6 Single project scheduling vs. multi project scheduling

The resource constrained multi project scheduling problem (RCMPSP) is an extension of the RCPSP and consists of concurrent scheduling of two or more projects with a common pool of renewable resources, while attempting to satisfy some performance criteria. (Payne, 1995) states that 90 % of projects are carried out in a multi-project environment. (Lova and Tormos, 2001) made a survey in the construction, textile, IT and public administration sectors about the executive environment of the projects. The survey showed that 84 % of correspondents said they work in a multiple projects environment. The same survey results reveal that project scheduling software packages are not a practical tool for planning multiple projects and that they should be adapted to this need.

In the formulation of the RCMPSP presented by (Lova and Tormos, 2001), a project portfolio encompasses $h=1, \dots, H$ projects that are targeted for scheduling with a limited portfolio of renewable resources. Each project is composed of $g=1, \dots, H_g$ activities. The activities can only be started once all the predecessors are entirely accomplished. Each activity j of project b requires v_{hjr} units of resource type r at every time point of its non-pre-emptive duration d_{hj} . The availability of each resource r at each time point is b_r . The purpose of the model is to schedule the activities in the projects so as to satisfying the resource and precedence constraints in such a way that the performance measurement related to a time criterion is minimized. In the formulation X_{hjt} is 1 if an activity j of project b starts at time t and 0 otherwise.

$$\text{Minimize } f \text{ (time)} \tag{2-18}$$

S.T.

$$\sum_{t=1} X_{hjt}=1 \quad \text{for } j \in J, h \in H \tag{2-19}$$

$$\sum_{t=1} t(X_{hqt}-X_{hjt}) \geq d_{hj} \quad h \in H, (j,q) \in \text{Pred}_h \tag{2-20}$$

$$\sum_{h=1}^H \sum_{j=1}^{J_h} \sum_{t=t-d_{hj}+1}^t v_{rj} X_{hjt} \leq b_r \quad \text{for } r \in R, t \in T \tag{2-21}$$

$$X_{hjt} \in \{0,1\} \quad \text{for } j \in J, h \in H, t \in T \tag{2-22}$$

The objective function 2-18 minimizes the “mean project delay” that is calculated by $\sum_{h=1}^H \sum_{t=1}^t (t X_{h,j_h+1,t} - CP_h) / H$, where CP_h is the resource-unconstrained critical path length of the project b . Constraint 2-19 and 2-20 guarantee the precedence relations between the activities in the projects and assure that the activities will be executed in a non-pre-emptive way. Constraint 2-21 sets the resource constraints. Finally, the type of the variable is represented by constraint 2-22.

Classic optimization methods have been used in the literature to solve multiple projects scheduling problems. Nevertheless, an increase in the number of activities as well as the number of projects, resource types or processing modes of the activities in multi-mode multi-project scheduling problems will result in the problem becoming more “complex” (Tseng 2004). To avoid intractability in solving large cases by traditional approaches, several heuristics and metaheuristics are used. (Kumanan et al., 2006) provides a heuristic-based procedure for scheduling multi-projects. The performance of the generated schedules is measured against project completion time.

(Lova and Tormos, 2001) analyze the use of priority rules (seen in Section 2.7.2.1) to solve multi project resource constrained project scheduling problems. The authors study the effect of the two components of priority rule-based heuristics (schedule generation and priority rule) by two performance measurements. The paper concludes that the parallel generation scheme gives better performance in multiple projects. Furthermore, it states that the use of parallel priority rules (e.g.

MINSLK) leads to good results. Several studies have used artificial intelligent techniques, such as evolutionary algorithms, to generate schedules and resource-allocation results. (Kim et al., 2005) proposes a combined genetic algorithm (described in Section 2.9.3.1) to optimize the schedule of multiple projects in order to minimize the total project time and the total tardiness penalty on completion of the projects. (Singh, 2014) develops a hybrid algorithm to integrate the project priorities with the project schedule. The objective of the model is to minimize the project makespan and penalty cost when some projects hold higher priority. The schedule is generated by use of a hybrid algorithm based on priority rules and the Analytic Hierarchy Process (AHP) approach. The proposed method was validated by a case study under various scenarios. In (Yassine et al., 2007) a genetic algorithm is hybridized with a local search strategy to minimize the overall duration or makespan of the resource constrained multi project scheduling problem. (Geiger, 2017) presents a local search approach for the solution of a multi mode, resource constrained multi project scheduling problem. Their procedure was tested on the instances of the MISTA 2013 Challenge and MMLIB-datasets. The results show the approach described in the article is ranked second.

2.7 Problem-dependent resolution approaches: resource constrained problems

To summarize the literature, we classify solving methodologies to tackle the constrained project scheduling problems under two headings: i. *Problem-dependent* and ii. *Problem-independent approaches*. Problem-dependent approaches are procedures that attempt to take the full advantage of the particularities and specifications of the model when constructing feasible or optimal solutions. Algorithms used in these methods are completely applicable to a certain given type of problem. *Lower-bound approaches* and *heuristics* fall into this category. On the other hand, problem-independent methods imply procedures that could be used for various problems, regardless of the problem category and its specifications.

Sub-sections in section 2.7 discusses the different problem-dependent approaches used for resource-constrained project scheduling problems. The lower bound approaches are classified into two main groups, including *constructive lower bounds* and *destructive lower bounds*. The constructive lower bounds are also grouped in four headings: *the critical path bound*, *the capacity path bound*, *bin packing bounds* and *constraint relaxation-based bounds*. Heuristics methods, in this context, include *priority rule-based approaches* and *adaptive heuristics*.

The problem-dependent resolution methods for time-constrained problems are discussed in section 2.8 under two main titles, including *lower bound approaches* and *heuristics*. Besides, section 2.9 outlines the problem-independent resolution approaches. *Exact procedures* and *metaheuristics* are examples of these methods.

2.7.1 Lower bound approaches

In order theory, the lower bound of a subset S of some partially ordered set (K, \leq) is an element of K which is less than or equal to every element of S . In scheduling research, a lower bound is commonly known as a value which is less than or equal to an optimal value. The purpose behind developing these approaches is threefold: *i.* the lower bounds provide values for problems in which the optimal value is absent. *ii.* the computed value for the lower bound presents a measurement for judging the performance of algorithms producing semi-optimal/near-optimal solutions. In keeping with this purpose, if the gap between the lower bound and the computed value is “tight”, the calculation effort of the algorithm can be justified. And, *iii.* the lower bounds can be used to precede a solution approach, e.g. the Branch and Bound algorithm.

Methods for computing the lower bounds in resource constrained project scheduling problems can generally fall under two classes: Constructive methods and Destructive methods. Figure 18 summarizes the functionality charter of these approaches. The main concept of each of the methods is outlined in the following:

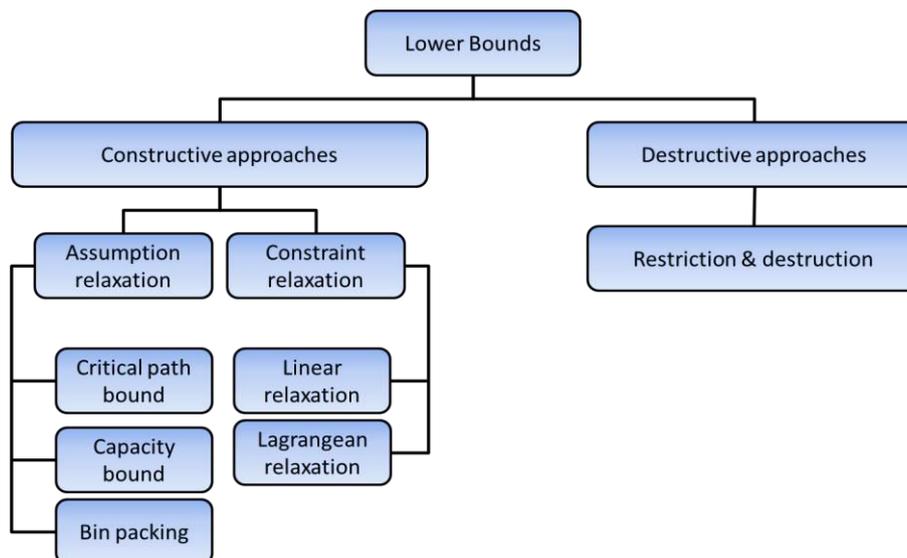


Figure 18- Classification of the lower bounds for solving RCPSPs by their working mechanism.

2.7.1.1 Constructive lower bounds

Constructive lower bounds are calculated by relaxing some driving assumptions of the primary model. This relaxation significantly reduces the complexity of the model and consequently the resolution effort. Nonetheless, for some cases it may not result in bounds that are “tight” enough.

2.7.1.1.1 The critical path bound

The critical path bound relaxes the capacity restrictions. The bound is obtained by computing the critical path. The Forward-backward path method (described in Section 2.2.1) is applied on the project network to compute the value of the bound. The algorithm completes in $O(n^2)$ time.

2.7.1.1.2 The capacity bound

The algorithm discards the availability of all resources except one. The bound is calculated in $O(R \cdot n)$ time. Regarding formula 2-23, the total requirement of the resource is divided by its availability and then rounded up to the next large integer value.

$$LB_{\text{Capacity}} = \left\{ \left\lceil \frac{\sum_{j=1}^n v_{rj} \cdot d_j}{b_r} \right\rceil \mid r=1, \dots, R \right\} \quad 2-23$$

2.7.1.1.3 Bin packing bounds

In this algorithm, the precedence constraints are omitted, as are all capacity constraints but one, for resource type r . For every resource at a given time, the activities are sorted according to a non-increasing order of the resource requirement, v_{rj} . Two sorts of set denoting $Q_1(r)$ and Q_2 are established. The set $Q_1(r)$ contains the activities whose requirement for the resources exceeds one half of the capacity, ($v_{rj} > b_r/2$). The value of SL_1 , denoting the length of the resulting schedule, can be taken as an initial lower bound for the project. This bound may be improved by the second set $Q_2(r)$. The set $Q_2(r)$ contains all the activities with $v_{rj} \in (b_r/3, b_r/2]$. Since over every time point, the availability of the resources is constrained by a constant value, at most one activity from $Q_2(r)$ can be executed in parallel with each activity $i \in Q_1(r)$. In order to determine which activities can be performed simultaneously, the activities from $Q_2(r)$ are examined according to an inverse sorting order. All activities are scheduled as early as possible, respecting the resource constraints. With g_1 and g_2 referring to the latest finishing time of the two latest activities in the schedules, the lower bound can be computed as shown in formula 2-24.

$$LB_{\text{Bin Packing}} = \max \left\{ SL_1, \left\lceil \frac{g_1 + g_2}{2} \right\rceil \right\} \quad 2-24$$

Application of this algorithm can be seen in (Moriyama et al., 1983) and (Van Houdenhoven et al., 2007).

2.7.1.1.4 Constraint relaxation-based bounds

As presented in Section 2.3.1.1, the binary variables X_{jt} , defining whether an activity j finished at time t , are generally used to formulate resource constrained project scheduling problems. By relaxing the restrictions in 0-1 programming of the problems, linear programming (LP) relaxation has been shown to present a new approach for computing the lower bounds. One of the earlier studies, (Christofides et al., 1987) modifies the variable types from binary to bounded positive real variables. For this purpose, the constraints $X_{jt} \in \{0,1\}$ are replaced by $X_{jt} \geq 0$ and $X_{jt} \leq 1$ constraints. In addition, the authors introduce cutting planes in order to strengthen the bounding procedure. (Carlier and Néron, 2000) proposes a lower bound based on linear programming methods. Relying on a new linear programming formulation, the authors demonstrate how resource requirements can be satisfied simultaneously for a given resource capacity.

Besides linear programming relaxation, Lagrangian Relaxation (LR) is also used to produce the lower bounds. With LR, a set of constraints are removed from the original model. However, they are included in the objective function, making the resulting model easier to solve. To achieve this, the weighted slacks of the removed constraints are added to the objective function. The challenge in applying the algorithm is to determine a set of the accorded weights, which are also known as the Lagrangian multipliers. (Geoffrion, 1974) (Christofides et al., 1987) and (Domschke, 1997) present the application of the algorithm in defining the lower bounds for RCPSPs. (Möhring et al., 2003) examines the procedure proposed by (Christofides et al., 1987) and improves it by integration of a minimum cut problem. (Kimms, 2001) proposes resource constrained project scheduling through maximizing the net present value of capital (cash). The paper contributes to tight upper bounds on the basis of a Lagrangian relaxation of the resource constraints. The author uses this approach as a basis for a heuristic and shows that the heuristic as well as the cash flow weight heuristic proposed by (Baroum and Patterson, 1996) results in tight bounds for the optimum value.

2.7.1.2 Destructive lower bounds

Destructive lower bounds, introduced by (Klein and Scholl, 1999), bound a resource constrained project scheduling model by determining a maximal objective function, value D . Subsequently, the destructive procedure attempts to contradict the feasibility of the reduced model. In case of success, the value of D (as well as $D+1$) can be presented as the lower bound. (Brucker and Knust, 2003) defines a destructive lower bound for the multi-mode resource constrained project scheduling problem with minimal and maximal time lags. Two methods are used for calculation of the lower bound. The first uses constraint propagation techniques, while the second is based on a linear programming formulation which is solved by a column generation procedure.

(Akker et al., 2006) presents a solution framework to find a feasible schedule that minimizes the objective function of minimax type on a set of parallel, identical machines, under the constraints of release dates, deadlines, and/or generalized precedence constraints. The authors develop a bounding procedure by applying the column-generation approach to linear-programming

relaxation. In the following work, (Akker et al., 2007), the authors adapt the procedure to the problem of minimizing maximum lateness on a set of identical, parallel machines. (Haouari et al., 2012) presents new and effective lower bounds for the RCPSPs. The bounds are calculated using the formulations found in concepts of energetic reasoning. Computational evaluation of the formulation resulting from several enhanced new feasibility tests proves that the new formulation outperforms the classic energetic-reasoning- based lower bound.

2.7.2 Heuristics

Since “time” and “resource” constrained project scheduling models belong to the class of NP-hard problems, the complexity of the problems sets limitations on employing exacte solving procedures discussed in Section 2.9.1. The model instances can be solved by exact methods only for small projects with a limited number of activities, resources and/or processing modes. However, effective solutions obtained during a reasonable effort can be obtained by employing heuristic as well as meta-heuristics approaches. While reducing the computational effort, these methods are likely to result in optimal or near-optimal solutions. This part discusses various heuristics used for solving the RCPSPs. In general, heuristic-based approaches can fall into two categories: Priority rule based approaches and Adaptive heuristics.

2.7.2.1 Priority rule based approaches

Priority rule based heuristics are stepwise procedures, where a schedule is built up by selecting a subset of legible activities through the steps, assigning a start time until all the activities are scheduled. In this context, the activities are ranked using “priority rules”. Motives for using and improving these methods can be justified for the following reasons:

- Heuristics are usually adapted to the problem. Using the problem specificities (such as precedence information on the activities or execution time windows for a scheduling problem), they are capable of providing a solution in a reasonable search time where the optimal solution is not available.
- The output of a priority rule based heuristic can be used as a starting point for other solution approaches.
- Heuristic methods are widely used by developers to provide software environments for project management and scheduling purposes (Klein, 1999).

Priority rule based heuristics rely on two main concepts, the Scheduling Generation Scheme (SGS) and Priority Rules (PR):

- **The SGS** determines a stepwise process to build up a feasible schedule of activities. It uses priority rules to rank activities for scheduling. Two scheduling schemes are introduced in

the literature, the Serial Scheduling Generation Scheme (SSGS) and the Parallel Scheduling Generation Scheme (PSGS):

The SSGS was first proposed by (Kelley, 1963). It is an activity-oriented approach which constructs the schedule in “exactly n ” iterations, where n is the number of activities. Two disjoint activity lists are defined to arrange and schedule the activities: the list of activities already *scheduled* and the list of *eligible* activities for scheduling, members of which are those activities whose predecessors belong to the set of activities already scheduled. In each iteration of the algorithm, one single activity is chosen by a priority rule from the eligible list and then scheduled at the earliest feasible time point. Through every iteration, when an activity is chosen from the eligible list and scheduled, the residual availability of the resources is modified and the earliest start time for the activities from the eligible list is updated.

On the other hand, the Parallel Scheduling Generation Scheme (PSGS) is a time-oriented scheme. The approach is proposed by (Kelley, 1963) and later developed by (Brooks, 1982). In this procedure, the schedule is built up in “at most n ” iterations. In every iteration, a set of activities, which could be empty, is scheduled. A time point t_n is associated with an iteration n . If $m \leq n$, then, $t_m \leq t_n$. Three adjoin lists including *eligible*, *complete* and *in-process* are defined. Regarding the time point t_n , the list of scheduled activities from the serial scheme is partitioned into two subsets: scheduled activities which are accomplished up to the time point make up the members of the *complete* list and those which are not accomplished are in the *in-process* list. The *eligible* list includes all the activities which are not scheduled and are available for scheduling without violating the precedence and resource constraints. The schedule time within the iteration is the earliest finish time of the activities scheduled during all earlier stages. Within the procedure, the new schedule time is determined and activities with a finish time equal to the new schedule time are removed from the *in-process* set and added into the *complete* set. That may place a set of activities into the *eligible* set. Subsequently, one activity from the eligible set is selected by employing a priority rule and scheduled to start at the current schedule time taking into account the availability of the resources. Thereupon, this activity is deleted from the eligible list and added into the *in-process* list. The procedure continues until the eligible set becomes empty.

- **Priority rules** sort a set of eligible activities in the scheduling process. To this end, a priority value (or an index) is calculated for every activity. Depending on the rule type, one activity with a lower or upper value is selected for scheduling. In case of equality, an additional rule can be applied to decide the order of scheduling. Every rule results in different schedules. Summarized by Table 1 from (Kurtulus and Davis, 1982), some of the best-known priority rules are the Shortest Processing Time (SPT), Latest Finish Time (LFT), Minimum Total Slack (MINSLK), Most Total Successor (MTS) and Greater Resource Demand (GRD). For multiple projects, some of the more successful heuristics introduced in the literature are the Shortest Activity from Shortest Project (SASP), Maximum Total Work Content

(MAXTWK), Maximum Total Work Content-earliest Latest Start Time (TWK-LST) and First Come First Serve (FCFS).

Table 1- A set of well-known heuristics and their working mechanism.

Heuristic		Initialism/ Acronym	Working mechanism
Shortest Processing Time		SPT	Give preference to activities with smaller processing time.
Latest Finish Time		LFT	Give preference to activities with smaller late finish time.
Minimum Slack	Total	MINSLK	Give preference to activities with smaller total slack.
Most Successor	Total	MTS	Give preference to activities which have more total successors.
Greater Demand	Resource	GRD	Give preference to activities with greatest resource demand.
Shortest from Project	Activity Shortest	SASP	Having determined the shortest project by use of CPM, give preference to shortest activity from the shortest project.
Minimum Case Slack	Worst	MINWCS	$\text{Min}(LS_j - \text{Max}[E(j,i) (i, j) \in AP_t])$, where $E(j,i)$ is the earliest time to schedule activity i if activity j is started at time t , and AP_t is the set of all feasible pairs of eligible, un-started activities at time t .
Maximum Work Content	Total	MAXTWK	Give priority to activities with maximum total work content, $\text{Max}(\sum_{k=1}^K \sum_{j \in AS_a} d_{ja} r_{jak} + d_{ja} \sum_{k=1}^K r_{jak})$, with AS_a : set of activities already scheduled in project a , d_{ja} : duration of activity j in project a , r_{jak} demand of activity j of project a to resource k .
Maximum Total Work Content-earliest Latest Start Time		TWK-LST	First prioritize projects by MAXTWK and then the activities within the project by $\text{Min}(LS_{ja})$, where LS_{ja} is latest start time activity j from project a .
First Come First Serve		FCFS	$\text{Min}(ES_{ja})$, where ES_{ja} is the earliest start time of activity j from project a .

In general, priority rule based algorithms have been categorized in the single-path method and multi-pass method.

2.7.2.1.1 Single pass method

The single pass method constructs only one single schedule on the basis of one single Scheduling Generation Scheme and Priority Rule. (Panwalkar and Iskander, 1977) presents a summary of over

100 priority rules. Their work provides a classification of the schemes and affords a list of the existing heuristics in the different research works. (Lova and Tormos, 2001) studies the effect of the schedule generation schemes (including both serial and parallel schemes) and priority rules (containing MINLFT, MINSLK, MAXTWK, SASP and FCFS) in scheduling for multi project and single project cases. The study concludes that the performance of the parallel schedule generation scheme is superior in cases of scheduling for multi project scheduling problems. (Lova et al., 2006) deal with a typical multi-mode resource constrained project scheduling model. Taking a well-known set of project instances into account, the performance of the priority rule based heuristics presented within the work are evaluated against the best ones published in the literature and the results are summarized for the different chosen test problems. (Browning and Yassine, 2010) addresses a resource constrained multi project scheduling problem with two lateness objectives, project lateness and portfolio lateness. The paper provides a comprehensive analysis of 20 priority rules on 12,320 test problems. From an individual project manager's perspective, TWK-LST performs well under high network complexity, while SASP performs well under low complexity. From a portfolio manager's Perspective, MINWCS performs well regardless of complexity.

2.7.2.1.2 Multi pass method

In contrast to the singlepass methods, the multi-pass method, also known as X-pass method, constructs more than one single schedule. Indeed, this solution approach extends the single-pass method by performing several passes. The basic idea of such methods originates from the integration of scheduling generation schemes with various priority rules. The approaches in this context may be classified into three methods: multi priorityrule methods, forward-backward scheduling methods and sampling methods.

2.7.2.1.2.1 Multi priority rule methods

Multi priority rule methods use scheduling generation schemes several times with a different priority rule being employed each time. The best solution is finally chosen amongst the multiple solutions. Various studies including (Boctor, 1990) (Özdamar and Ulusoy, 1994) (Kolisch and Hartmann, 1999) have been conducted to solve the RCPSP by use of multi priority rule techniques. (Fündeling and Trautmann, 2010) presents a resource constrained project scheduling problem that is formulated on the basis of a concept called "work content". The work content implies resource-time units, for instance person-days. The problem aims to define a feasible resource usage for each activity so that the project duration is minimized. To this end, a multi priority rule scheduling method is developed by the authors. The numerical results illustrate that the method is an encouraging procedure for solving project instances. These procedures show promise in providing a better solution quality compared to a set of algorithms from the literature. (Almeida et al., 2016) studied a parallel heuristic for the multi skill resource constrained project scheduling problem. The authors define two concepts called the resource weight and the activity grouping, which are used

to construct a new heuristic framework. Several single- and multi priority rules are considered to compare the performance of the heuristics. The evaluation shows that the developed heuristic is able to find high-quality solutions within a very small CPU time with a gap of less than 2.65%. For larger instances, the heuristic is able to obtain feasible solutions quickly. (Hasan et al., 2008) considers a Job Shop Scheduling Problem. The objective of the model is to minimize the makespan of the project subject to satisfying the constraints. A number of priority rules such as partial reordering, gap reduction and restricted swapping are developed to improve the performance of a solution approach which is mainly based on the genetic algorithm.

2.7.2.1.2.2 Forward-Backward scheduling methods

Forward-backward scheduling methods use a SGS to schedule a project by turning from forward and backward scheduling passes. The method was proposed in the work of (Li and Willis, 1992) and subsequently used in (Özdamar and Ulusoy, 1994). In the basic presentation of the Forward-Backward method, activities are started as early as possible in the forward loading technique while they are started as late as possible through scheduling in the backward technique. (Lova et al., 2000) extends the procedure of (Li and Willis, 1992) to deal with scheduling for multi-project problems. The algorithm is based on the concepts of the “forward and backward free slack of the activities”. The backward pass is employed on a feasible schedule. With the “forward free slack”, activities are shifted to the latest feasible position. Then, they are rescheduled in decreasing order of their scheduled finish times. The forward pass is applied to the feasible schedule resulting from the backward pass and the activities are shifted left to the earliest feasible position in their “backward free slack”. The iterative backward-forward procedure shows encouraging solutions in scheduling multi-projects, minimizing the mean project delay as well as minimizing the multi-project duration. (Chtourou and Haouari, 2008) designed a forward-backward procedure to tackle a RCPSP for minimum project duration and for maximum quality-robustness. The work addresses the development of a simple priority rule-based algorithm. It possesses two stages. The first stage solves the RCPSP for minimizing the makespan by using a priority rule based heuristic called an enhanced multi-pass random-biased serial schedule generation scheme. Using the makespan resulting from the first stage, the problem is then solved in a similar way for maximizing the schedule robustness. Twelve alternative robustness-predictive indicators are employed to select the best schedule in the problem.

2.7.2.1.2.3 Sampling methods

Referring to the literature, the main concept of this approach relies on the use of Random Sampling methods wherein a probability of being chosen has been associated with each activity. The sampling methods form a set of feasible schedules by use of associated random numbers and they appoint the best schedule obtained.

The common characteristic of the multi priority rule methods and forward-backward scheduling methods is that they attain the same final schedule even if they are run several times (Tormos and Lova, 2001). The difference between random sampling methods and forward-backward scheduling approaches is that a different schedule can result from each pass using sampling methods wherein the best schedule is selected as the final result.

Several studies have been conducted to solve resources-constrained project-scheduling problems by applying sampling methods (Kolisch, 1996) and (Tormos and Lova, 2001). According to (Tormos and Lova, 2001), the most powerful random-sampling method is the Parameterized Regret-Based Biased Random Sampling (RBRS) method that chooses the activities according to a procedure which generates random numbers. In (Tormos and Lova, 2001), the authors develop a robust technique for resource constrained project scheduling problems. The algorithm presents a combination of multi-pass random-sampling methods with backward–forward scheduling. Both serial and parallel scheduling generation schemes are undertaken in the solving approach. The authors conclude that the combination of sampling methods and backward–forward scheduling can be taken into consideration as a promising approach to develop further heuristic-based resolution methods. Also, they indicate that the procedure can easily be integrated into commercial project-management software such as Microsoft Project, CA-SuperProject or Time Line.

2.7.2.2 Adaptive heuristics

In the literature, a set of procedures is used for constructing feasible solutions in resource constrained project scheduling problems. The methods can be described separately, since they do not completely belong to a specific group of the aforementioned algorithms. Terming the methods as “Adaptive heuristics” in the course of this study, the truncated branch and bound approach as one of the corresponding algorithms is brought into focus:

2.7.2.2.1 Truncated branch and bound approach

Instead of exhaustively searching the solution tree through the procedure of Branch and Bound (viewed in Section 2.9.1.2), the truncated branch and bound approach evaluates the capacity of each node to find the best solution. The algorithm then constructs the schedules from the most promising node. Therefore, by following only one single path, it partially explores the search space. To the best of our knowledge, these methods are used in only a few research works in the literature. Applications of this approach can be found in (Franck et al., 2001) and (Klaus and Jürgen, 2002).

2.8 Problem-dependent resolution approaches: time constrained problems

This section discusses the solution procedures that are specifically adapted to time constrained problems. Since the specification of a time constrained problem is mainly different from that of a resource constrained problem, the procedures viewed in Section 2.7 cannot be completely suitable for this category and would need to be adapted to the problem. Although imposed deadlines and the addition of supplementary resources often occur in real-world projects, to the best of our knowledge, the corresponding models, in the context of time constrained problems, have not been extensively studied by researchers as dedicated solution methodologies (termed as problem-dependent solving approaches in the course of this report) and there are only a scattering of studies in the literature. Having been confirmed by (Guldemon et al., 2008) and (Verbeeck et al., 2016), as relevant to time constrained project scheduling problems (TCPSPs), these methods suffer from the shortage of research in the literature into developing the models and solving methods. Nevertheless, the motivation in studying so-called problem-independent approaches, including meta-heuristic approaches and Zero-One programming models on RLP and RIP have been extensively described in the literature by researchers. Similarly to resource constrained project scheduling problems, problem-dependent solution approaches are categorized into two headings: Lower bound and Heuristic.

2.8.1 Lower bound approaches

(Drexel and Kimms, 2001) presented the pioneer work in computing the lower bounds for resource investment problems. As mentioned by the authors, up to the work date, only exact algorithms were used in order to tackle the RIPs. The research presents two algorithms. The first one is based on Lagrangian relaxation with sub-gradient optimization. Given a set of Lagrangian multipliers, the resulting sub-problem can be solved in polynomial time by use of the procedure. The second algorithm uses column generation techniques. The computational results shows that, compared to Lagrangian relaxation, column generation solves the instances more slowly, but it results in tight enough bounds.

2.8.2 Heuristics

(Neumann and Zimmermann, 1999) presents a polynomial multi-priority rule-based heuristic for different types of resource leveling problems with minimum and maximum time lags between project activities. The algorithm can be suitable for time constrained project scheduling problems as well. (Guldemon et al., 2008) proposes a two-stage heuristic for an extension of the TCPSP. In the first stage, the algorithm constructs partial schedules. Then, in the second stage, an ILP formulation is used to change the partial schedule into a feasible solution.

The first heuristic procedure for a resource leveling problem was proposed by (Burgess and Kilebrew, 1962). The procedure is a single pass algorithm using a single mode of representation and a single priority rule. It attempts to determine the start time based on a concept which is termed as minimum squares. The proposed procedure readjusts the start time of each activity and decreases the variability of the resource use. In the first stage, it constructs the start time of the activities by their positioning at the earliest start time. Then, the activities are selected based on a priority rule, which is considered to be the earliest finishing time rule. Latter, the best time point for starting the activities is determined by the minimum squares. The start date holds a value which minimizes the total sum of the squares of the resource consumption for each time period. (Leachman, 1983) studied resource leveling problems in order to develop a heuristic procedure. The work provides an algorithm which is based on the activities' demand rate for resources. It seeks to minimize the resource capacity costs in an iterative procedure in order to satisfy the planned deadlines. (Neumann and Zimmermann, 1999) presents adapted priority rule based algorithms to solve a typical resource leveling problem with maximizing net present value subject to general temporal constraints given by minimum and maximum time lags between activities. (Harris, 1990) presents a new heuristic for resource leveling problems using the critical path method. The minimum moment of the resource histogram is considered to compute the level of resources. The procedure allots project activities to specific days so that the final resource histogram approaches a rectangle shape and its moment approaches a minimum value. In the work, incremental moments have been introduced by use of each activity's resource rate with penalties to recognize network interactions. Each activity is scheduled in a way that the sum of the incremental moments holds a minimum value. In a following work, (Hiyassat, 2000) modifies Harris' procedure by using the value of the activity's free float and its resource rate in the selection criteria.

2.9 Problem-independent resolution approaches

Regardless of the type of constrained project scheduling model, a set of approaches and their solution procedures can be applied for solving both time constrained and resource constrained project scheduling problems. It is worth noting that since the modeling framework of the current study inherits the specifics of both resource-constrained project scheduling problems and time constrained project scheduling problems, problem-independent resolution methods could come to be of interest for the application in the course of this work. The approaches in this context can be classified into two main groups including exact procedures and meta-heuristics:

2.9.1 Exact procedures

This section presents the exact procedures that are used in solving constrained project scheduling problems. The most widely-used methods can be classified into three approaches: Zero-One programming, Dynamic programming and Branch and Bound procedures.

In the current study, a Zero-One formulation is employed to model the problem. Through Exact procedures, a Branch-and-Bound algorithm using the CPLEX solver is employed for primary resolution of the model.

2.9.1.1 Zero-One programming

Besides the mathematical formulation that is presented in Section 2.3.1.1 for resource constrained project scheduling problems, other models have been proposed and developed in the literature for different orientations of interest. (Haït and Artigues, 2011) presents an alternative for modeling project-scheduling problems with a continuous scale of time. The formulation focuses on the relative positions of tasks and time periods. The proposed modeling framework improves the computation time significantly. (Koné et al., 2011) proposes new mixed integer linear programming formulations for the RCPSP based on the concept of events with constant availability of the required resources: the Start/End formulation and the On/Off formulation. Since the variables used for modeling the problem are not a function of the time horizon, the formulations present the advantage of involving fewer variables. The authors compare the linear relaxations of these new formulations with the existing ones in the literature. The results prove that On/Off formulation outperforms all other MILP formulations and obtains results close to those of a specialized method. (Kopanos et al., 2014) gives details of some of the existing mathematical formulations of resource constrained project scheduling problems in the literature. The models are reviewed and presented in terms of discrete and continuous time scales. In the paper, the authors propose two binary integer programming discrete time models and two precedence based mixed integer programming models with continuous time formulations. The discrete-time models are formulated on the basis of binary variables that describe the processing state of every activity between two consecutive time points. On the other hand, the continuous time models are based on the concept of overlapping of activities, and the definition of a “number of newly introduced sets”. A computational evaluation is carried out by use of four comparison factors: Feasible (%): percentage of instances that gave an integer solution (i.e., optimal, suboptimal, or non-proven optimal) in a limited resolution time, Good (%): the percentage of instances that gave a good integer solution (i.e., optimal, or suboptimal with a gap $< 3\%$ from the optimal solution) through a given resolution time. Optimal (%) is the percentage of proven optimal solutions found in a given resolution time. Gap (%): the average gap between the integer non-proven optimal solutions and the optimal solution. This evaluation shows the relative success of the different models, those models developed by the authors and those from the literature.

(Easa, 1989) presents an integer linear optimization model of resource leveling with single resource type. The model minimizes the absolute deviations between the resource requirements and a uniform resource level, between consecutive resource requirements, or between the resource requirements and desirable non-uniform resource levels. (Son and Mattila, 2004) presents a linear-program binary model for leveling resources in situations where the activities can be split. (Rieck et al., 2012) proposes a new mixed-integer linear model formulation for the classic resource-leveling

problem which solves the small and medium-size problem efficiently by use of the standard solver CPLEX.

2.9.1.2 Branch and Bound procedures

The basic rationale of a Branch and Bound (B&B) algorithm is to build a search tree with nodes and branches that explores the solution space of the problem to find the optimal solution. In the simplest form, the branches can be defined as scheduling decisions on which activities need to be delayed, and the bounds are the precedence and resource constraints (Bartusch et al., 1988) (De Reyck and Herroelen, 1998). Figure 19 depicts a typical example of the search tree in a Branch and Bound algorithm. As shown in the figure, the root of the tree relates to the first activity that can be scheduled. The second level of the tree encompasses the set of activities that can be scheduled after scheduling the first activity, and so forth. Every sequence from the root to the leaf of the tree represents a feasible schedule. The searching process in Branch -and -Bound traverses the tree until the best solution is found. Regarding the number of activities, it is obvious that when this value increases in large projects, the tree grows quickly. For problems with multi-mode execution of the activities, each execution mode adds another layer into the structure of the research tree and this increases the computation effort of the algorithm. These procedures are the main dissolution procedures in optimization software, like as CPLEX Studio, LINGO, GAMS and so forth, to solve to optimality the linear integer programming model with a given level of gap.

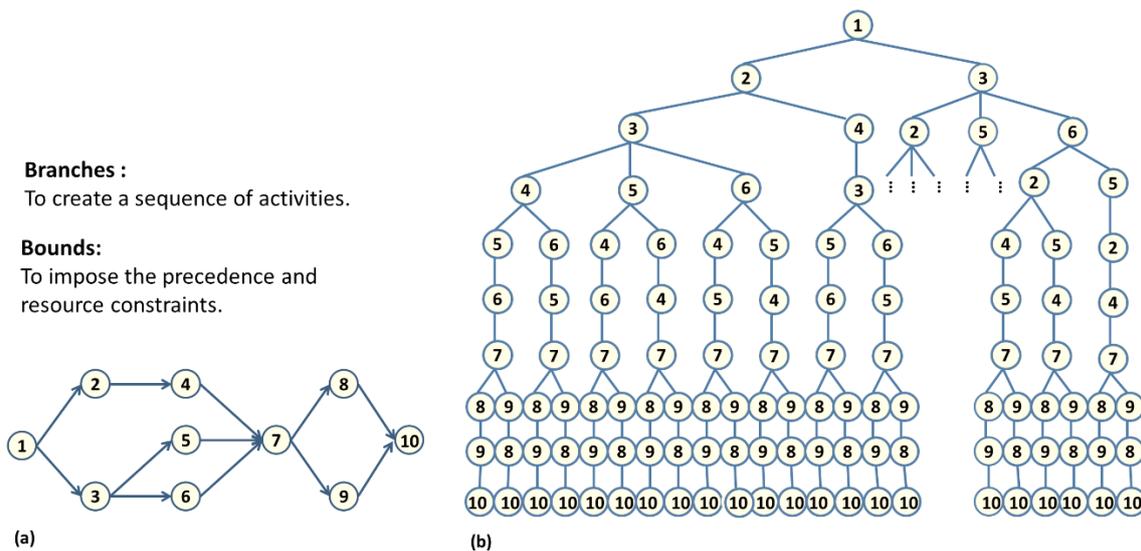


Figure 19- (a): AON representation of a project plan. (b): Search tree of a Branch and Bound procedure for generating feasible solutions.

A Branch and Bound algorithm developed by (Patterson et al., 1990) creates a set of nodes in the solution tree that stands for certain partial schedules. The partial solutions possess the important particularity that they are always feasible from the viewpoint of satisfying the resource and precedence constraints. The algorithm adds a new eligible activity to a partial schedule by a “Branching” procedure. As the number of feasible combinations of the eligible activities increases, the algorithm creates as many new partial schedules. Various exact approaches based on implicit enumeration with Branch and Bound have been presented in the literature: (Christofides et al., 1987) (Brucker et al., 1998) (Dorndorf et al., 2000). An effective Branch and Bound algorithm developed by (Demeulemeester and Herroelen, 1992) for RCPSPs outperforms all the other exact methods in the literature. The algorithm is based on a depth-first solution strategy in which the nodes represent resources and precedence feasible partial schedules. The branching scheme emanates from a parent node and corresponds to exhaustive and minimal combinations of activities. A time-oriented Branch and Bound algorithm for the RCPSP explores the set of schedules by enumerating possible activity start times (Dorndorf et al., 2000). (Bellenguez-Morineau and Néron, 2007) proposes a Branch and Bound procedure for solving a multi-skill project scheduling problem. (Heilmann, 2003) presents a Branch and Bound algorithm for a typical resource constrained project scheduling problem where multiple modes are available for executing activities. Besides, minimum and maximum time lags between the different activities are also given. The results of the experimental performance analysis are quite encouraging. However, the authors indicate that for larger problem instances, with a higher number of activities and modes of processing, the computation of an optimal solution does not seem to be reachable in reasonable time. Hence, for such instances, they suggest applying a heuristic based solution approach. (Gather et al., 2010) presents a new enumeration scheme based on Branch and Bound approaches to solve resource-leveling problems to optimality for small (10 activities) and medium (20 activities) instances.

2.9.1.3 Dynamic programming

Dynamic programming is an algorithmic paradigm which is used to decompose a problem into different sub-problems and tackle the decomposed problems one by one. The solutions from each sub-problem are combined into a complete solution in order to determine the final solution of the main problem. A procedure built up by Carruthers and Battersby, (Carruthers and Battersby, 1966), was the first work to apply dynamic programming for solving resource constrained project scheduling problems. Its objective is to find the expected maximum path length by reinterpreting the original problem as finding the maximum path length of the final activity of the network using the symmetry of the problem. The approach constitutes an advance in critical path methods, but it cannot handle practical networks. (Bandelloni et al., 1994) used dynamic programming to solve a resource leveling problem to optimality. (Baptiste et al., 2008) assume the JJSP with earliness and tardiness penalties. The authors offer two Lagrangian relaxations of the problem. The first one is based on the relaxation of precedence constraints while the second one intends to relax machine-availability constraints. Two adjoin algorithms are introduced to solve the corresponding dual

problems. The first procedure employs Branch and Bound, whereas the second is based on a simple dynamic programming algorithm. In both cases, the relaxations provide lower bounds.

2.9.2 Metaheuristics

Metaheuristics are used to cope with complexity in the solution of NP-hard problems. The main purpose of using these approaches is to find optimal or near optimal solutions within a reasonable computational effort. The difference between heuristics and metaheuristics can be stated from four points of view: 1- heuristics are totally “problem-dependent” algorithms whereas metaheuristics are “problem-independent” procedures. 2- In the main, heuristics are “constructive” procedures. They start from an initial state and follow a set of operations in order to obtain a solution. However, metaheuristics are “improver” methods. They begin with an initial feasible solution, which can result from a heuristic, and transform it into another solution by iteratively executing a set of procedures. While attempting to improve the obtained results, the quality of the solution does not get worse in every run of the metaheuristics and at the very least it remains the same. 3- Heuristics are greedy approaches and therefore they usually get stuck in local optima. Metaheuristics, however, are not completely greedy procedures. As such, by allowing an intermediate deterioration of the objective function, the algorithms provide the possibility to avoid getting stuck in the local optima. And finally, 4- metaheuristics can be applied on the different multi objective problems in order to find Pareto solutions. Despite the potential advantages of metaheuristics, they have one major drawback, in that these techniques require a fine-tuning of their intrinsic parameters that is not easy to perform in a thorough manner.

Six common design questions concern all iterative metaheuristics: 1- Representation and generation of initial solutions, 2- Objective (fitness) function 3- Search operators, 4- Constraint handling, 5- Stop criteria 6- Parameter tuning (Coello Coello, 2002) (Blum and Roli, 2003) (Salcedo-Sanz, 2009) (Siva Sathya and Kuppuswami, 2011) (Kaveh, 2016).

- 1- *Representation and generation of initial solutions:* since a solution (or a set of solutions) is supposed to be modified and optimized during the search process by use of the metaheuristics, encoding (representation) of any given solution plays a major role in the efficiency and effectiveness of any types of these algorithms, and the “representation” needs to be relevant to the target problem.. Generally, direct and indirect representations can be distinguished when establishing a solution. Using a direct representation, solutions are represented in their appropriate search space and no mapping (decoding) step is required to transform a representation into a real solution. In contrast to direct representation, an indirect representation requires an explicit mapping. With this sort of the representation, a tentative solution to the problem is presented as standard data structures (for instance string of binaries, integers, etc) and then a procedure is used to transform these solutions into a corresponding solution in the feasible research space. Indirect encoding is widely used in optimization problems and deals with many of the constraints in a scheduling problem. Referring to (Rothlauf, 2006), indirect representation makes it possible to use standard

search operators. Furthermore, employing indirect representation facilitate resolution by reducing the difficulty of the problem.

Figure 20 depicts some classic encodings for a set of optimization problems. They include permutation, binary, continuous and discrete encoding.

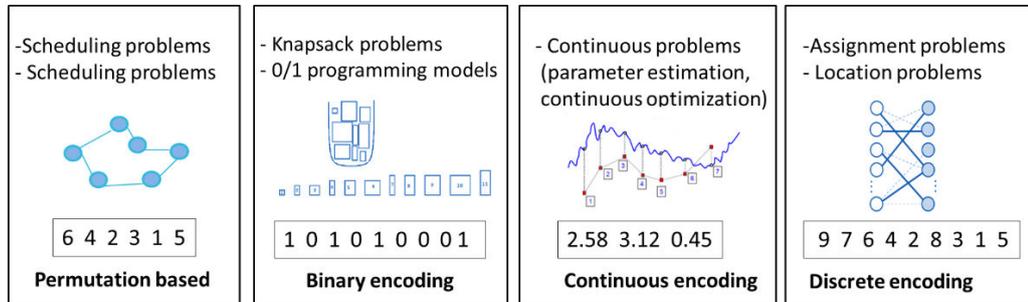


Figure 20- Permutation, binary and real encoding represented for some optimization problems, adapted from (Talbi, 2009).

Besides classic encodings, non-classic representations such as “Random key encoding” have also been used to tackle optimization problems. When using the “key representation”, each object is assigned a random value that is generated uniformly from [0, 1). The decoding procedure sorts the objects in an ascending order. Then, each element of the representation is decoded by its rank in the sequence. Probable ties can be broken arbitrarily. Figure 21 schematizes the encoding based on these random-key procedures. This encoding type can be useful for many sequencing problems that are viewed as permutation problems, including scheduling and routing problems. In the scheduling problems, an Activity List is an array that is obtained by applying the random key representation on a permutation of numbers.

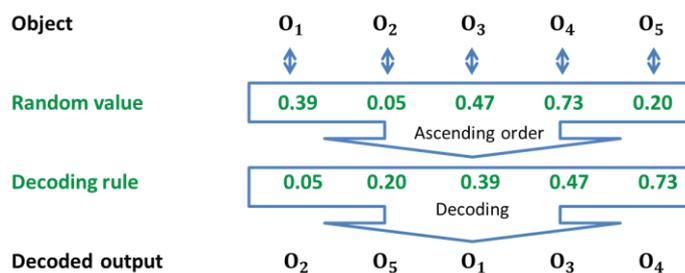


Figure 21– Encoding in the random key-based representation.

Depending on the metaheuristic used (either population-based or single solution based algorithms), one or more solutions need to be initialized in order to begin the search

process. If some problems specific information about the high quality solution(s) is on hand, an initial solution can be built up by use of this knowledge. In cases of deficiency or lack of good solutions, the initial solution has to be created, either randomly, or by sequential diversification or heuristic initializations. When using the population-based algorithms, a diversity of solutions must be engendered in the population in order to ensure an effective application of the metaheuristic.

- 2- *Objective (fitness) function*: the objective function, also known as the fitness function or evaluation function, assigns a fitness value to each solution. It guides the procedure towards good solutions. Indeed, the fitness function states the quality of a solution with regard to the assumed goal. In many cases, especially for continuous linear and nonlinear optimization problems, the evaluation function corresponds to the objective function (Talbi, 2009). However, sometimes it is modified to improve the efficiency of the procedure or to involve additional characteristics of a corresponding solution. For other problems that do not belong to linear or nonlinear optimization problems, the definition of an appropriate fitness function is a challenging task. For instance, with satisfiability problems (in which the aim is to find an assignment that satisfies a given Boolean formula), the objective function must be transformed into other terms to provide a better convergence for the algorithm.

Figure 22 schematizes the concept of the fitness value associated to a solution obtained from a decoding process.

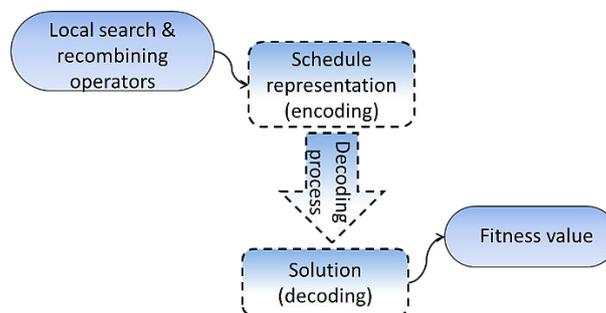


Figure 22- Fitness value of a solution from a decoding process, from (Talbi, 2009).

- 3- *Search operators*: metaheuristics search strategies generally rely on two main concepts: exploration and exploitation (Rothlauf, 2006). In exploration, the algorithm searches for new areas and new solutions, whereas exploitation focuses on promising regions in the search space. In metaheuristics, the search operators can be grouped as local-search and recombining operators. A local-search operator moves from a given solution to a neighbor solution in the space of candidate solutions. The concept of neighborhood implies similarity between the solutions. In contrast to local search, recombination operators require at least two solutions to build up more than one new solution.

- 4- *Constraint handling*: dealing with constraints in constrained optimization problems is another important point to consider for the efficient design of metaheuristics. Generally, the constraint-handling methods act on the representation of the solution or the objective function. Various approaches in this context can be classified as reject strategies, repairing strategies, penalty methods and decoding strategies. Other constraint-handling approaches, which do not rely on the representation of the solution or the objective function, such as multi-objective optimization and co-evolutionary models, are also used.

Reject strategies: this approach keeps only feasible solutions and rejects all infeasible ones. This sort of strategy is credible if the portion of infeasible solutions in the research space is small. In some optimization problems where the search space is discontinuous, the procedure does not result in good solutions. This is because of the fact that the algorithm strictly rules out exploring any infeasible boundaries (Luke, 2015).

Repairing strategies: this strategy uses some operations and heuristics to transform an infeasible solution into a feasible one. The strategy is a promising procedure for cases where the search operators used in the optimization procedure may result in infeasible solutions, (Krawiec, 2014).

Penalty methods: The penalizing strategy is the most popular approach for dealing with constraints in the optimization process by use of metaheuristics. Within this strategy, a constrained problem transforms to unconstrained one by use of a fining term which is added to the object function to penalize infeasible solutions (Richardson et al., 1989). Various alternatives can be used to determine penalties (Kuri-Morales and Gutiérrez-García, 2002). They generally involve “additive forms” and “multiplicative forms”. One method of using the “additive form” is described as follows:

Having considered a typical minimization problem given below, the additive method can be stated as follows:

$$\text{Min } f(x)$$

s.t.

$$g(x) \leq g_0$$

$$\text{Objective function} = \begin{cases} f(X'), & \text{if } X' \text{ is feasible} \\ f(X') + p(X'), & \text{otherwise} \end{cases}$$

Where $p(X')$ is the cost of the constraint violation. If no violation exists, $p(X')$ will be zero and positive otherwise.

The additive penalty function can be calculated by use the relation 2-25:

$$\sum_{e=1} k_e G_e \quad 2-25$$

Where G_e is function of the constraints and k_e are penalty parameters, see 2-26:

$$G_e = \max \left(0, \left(\frac{g_e(X')}{g_0} \right)^\beta - 1 \right) \quad 2-26$$

In formulation 2-26, β holds a positive value that can be estimated by the algorithm designer.

Another common way is to use “multiplicative form”, as shown below:

$$\text{Objective function} = \begin{cases} f(X'), & \text{if } X' \text{ is feasible} \\ f(X') p(X'), & \text{otherwise} \end{cases}$$

When dealing with minimization problems, if no violation occurs, $p(X')$ is one and otherwise it holds a value more than one.

In classic optimization, exterior penalty functions relying on an additive form are also used, with the calculation based on equation 2-25. The main reason for this is the fact that there is no need to start with a feasible solution.

Decoding strategies: a decoding procedure can be defined as a function $R \rightarrow S$ in which a feasible solution $s \in S$ is related to a representation $r \in R$. In this approach, indirect encoding is used in the representation and the decoding process is applied to transform the representation to the solution. The decoding function should have the following properties (Michalewicz, 1997) and (Talbi, 2009):

- For each representation $r \in R$, a feasible solution $s \in S$ exists.
 - For each feasible solution $s \in S$, a representation $r \in R$ exists.
 - The decoder reduces the computational complexity.
 - The representation space must have the locality property in the sense that distance between solutions in R must be positively correlated with the distance between feasible solutions in S .
- 5- *Stop criteria:* the search process using the metaheuristic is stopped when a given condition is satisfied. Commonly, the algorithm terminates when either a maximum number of iterations has been reached or a satisfactory fitness level has been obtained or if a given computational time has elapsed.
- 6- *Parameter tuning (setting):* each metaheuristic possesses a given set of parameters that must be initialized. A proper initial parameter setting has an important impact on the solution procedure for pursuing the exploitation and exploration objectives of the algorithm in

searching the solution space, and subsequently, it has a significant influence on the quality of the obtained results. However, there is no general optimal initialization available for the parameters of the metaheuristics and they should be calibrated within the application of the algorithm to the problem.

In traditional approaches, the parameters of the algorithms are tuned one at a time and their values are defined empirically. In these approaches, interactions between parameters is not taken into consideration, so there is no guarantee that the algorithm will find the optimal setting. In order to cope with this problem, experimental design is a focus of investigation (Fiğlalı et al., 2009). One of the promising approaches in this context is known as Design of Experiments, or DOE. DOE is used as a powerful tool to allow multiple inputs (factors) to be manipulated simultaneously. It considers the concurrent impact of these factors on a desired output (response). Therefore, by manipulating the multiple factors at the same time, it can undertake important interactions that may otherwise be missed in the defining of optimal outputs.

When using DOE concepts, all possible combinations of the factors (known as full factorial experimentation), or, only a portion of the possible combinations (fractional factorial experimentation) can be investigated. The application of these methods in optimization of metaheuristics can be seen in (Lucas et al., 2006) (Kramer et al., 2007) (Zoraghi et al., 2012) and (Tabrizi and Ghaderi, 2016).

2.9.3 Most widely-used metaheuristics for project scheduling

With a view to finding the most successful metaheuristics used for tackling constrained project scheduling problems, 259 research works conducted from 2000 to 2016 on “constrained project scheduling problems” have been reviewed, in Web of knowledge, ScienceDirect and SpringerLink data bases.

Figure 23 summarizes the results of the review. The five most widely-applied algorithms are the Genetic Algorithm, Particle Swarm Optimization, Ant Colony Optimization, Tabu Search and Simulated Annealing. Note that the meta-heuristics for solving the multi-objective problems are included in the class of each one’s basic search procedure. For example the NSGA-II algorithm, in order to solve multi-objective scheduling problems, is incorporated in the GA class. The following Sections 2.9.3.1-2.9.3.5 look at the processing mechanism of these algorithms.

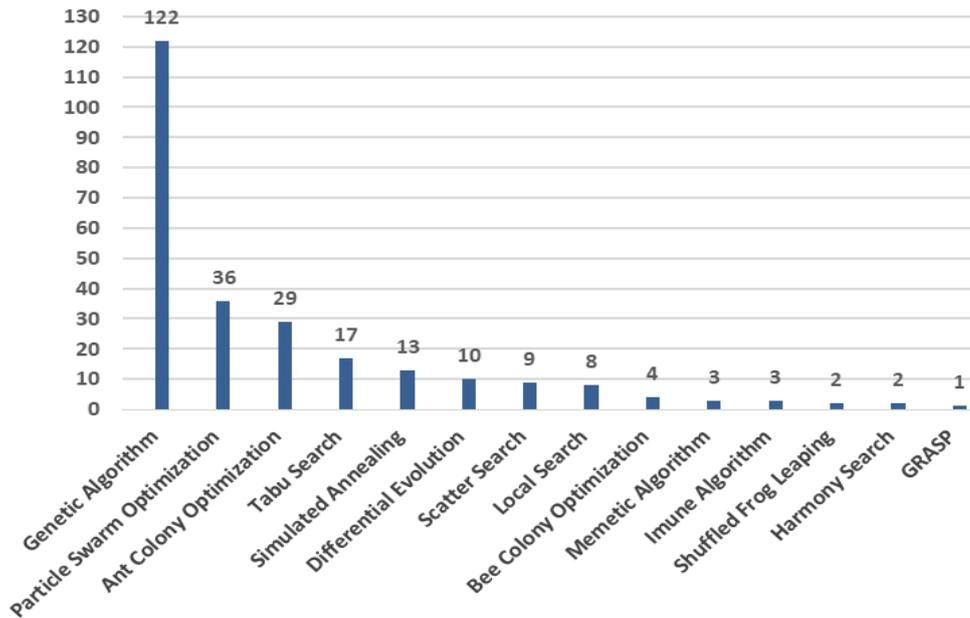


Figure 23- Research results on different metaheuristic-based search algorithms used for solving constrained project-scheduling problems from 2000 to 2016.

2.9.3.1 Genetic Algorithm (GA)

Genetic algorithm (GA) is a metaheuristic that derives its behavior from Darwin's theory of natural selection. It was first proposed by J.Holland in the 1970s, (Holland, 1975) and applied by De Jong, (De Jong, 1975) and Goldberg, (Goldberg, 1989) for solving complex optimization problems. Unlike the single solution based optimization metaheuristics, such as simulated annealing, seen in Section 2.9.3.5, it maintains a population of solutions. The size of the population can be denoted as the *PopSize*. The first step in the use of any GA is to provide a representation for the solutions, or population members. Generally, the representation is made in the form of a string, also known as a chromosome, see Figure 24. Each allele of the chromosome is referred to as a gene. Both binary and non-binary representations have been favored by many genetic algorithm designers (Bean, 1994). Like all population-based metaheuristics, the deployment of a GA starts with initializing a population of chromosomes. The individuals of the population are evaluated by their fitness and elitism. Afterward, they are submitted to specific operators to reproduce new individuals. The aim of this reproduction is to give more chance to the search procedure to find better solutions regarding the fitness function value. The next generation is formed by three operators of elitism, cross-over and mutation. In elitism, a number of best individuals in terms of fitness function value survive, and are transferred directly to the next generation. In addition, the variation operators including crossover and mutation are used to exploit and explore the solutions in the search space. For that purpose, each of the cross-over and mutation operators is implemented by appropriate rates that are known as the *Cross-over Rate* and *Mutation Rate*. Generally, when using the cross-over operator, two individuals of the population, called parents, are selected

to reproduce two new solutions, called offspring. Various types of crossovers have been proposed in the GA literature. The most popular ones are one-point, two -point and three-point cross-overs. Figure 25 illustrates the operation of a two-point crossover over two parents. The mutation operator is applied on a gene of an individual to alter its value, in order to create a new individual, as shown in Figure 26. The search procedure continues until one of the *stop criteria* mentioned in Section 2.9.2 has been met. The working process of the genetic algorithms is illustrated in Figure 27.

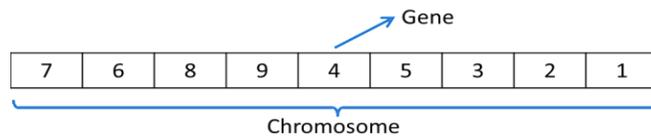


Figure 24- Presentation of a chromosome and a gene for a permutation-based representation.

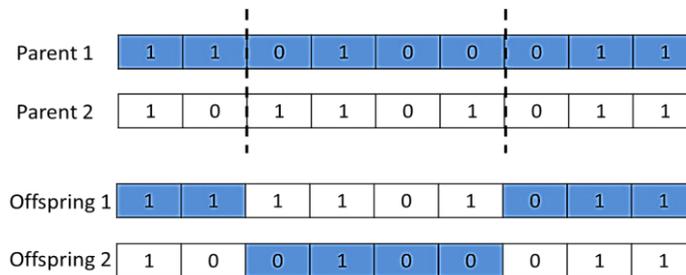


Figure 25- Two-point cross-over operated on two binary represented parents.

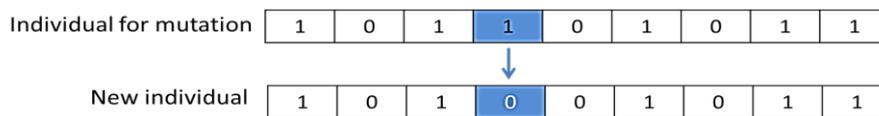


Figure 26- Representation of an operating procedure of mutation in a genetic algorithm.

The advantage of the genetic algorithm is in its intrinsically parallel search, due to it being a population-based search approach and its strong ability to explore and exploit the solution space. Nevertheless, like other metaheuristic-based approaches, it requires fine-tuning of the parameters, including the crossover rate, mutation rate, size of the population and the stop criteria (such as the number of iterations) in order to avoid getting stuck in local optima. Therefore, the performance is directly dependent on the values of these design variables (Talbi, 2009).

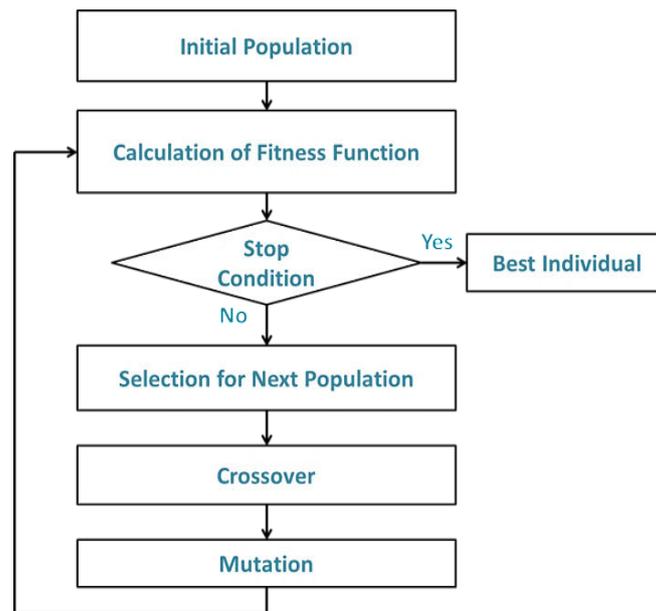


Figure 27- Genetic algorithm flowchart, adapted from (Renner and Ekárt, 2003).

Several studies have been conducted to solve the RCPSP using a genetic algorithm, presented in (Hartmann, 1998) (Kohlmorgen et al., 1999) (Alcaraz and Maroto, 2001) (Hartmann, 2002) (Valls et al., 2004) (Valls et al., 2005) (Najafi and Niaki, 2006) (Shadrokh and Kianfar, 2007) (Gonçalves et al., 2008) (Zhang and Wong, 2015) and (Maghsoudlou et al., 2016).

A permutation based genetic algorithm proposed by (Hartmann, 1998) makes use of activity-list representation and serial schedule generation scheme. It outperforms a set of heuristics and algorithms that are presented in (Sampson and Weiss, 1993) (Leon and Balakrishnan, 1995) (Özdamar and Ulusoy, 1996) (Kolisch, 1996) and (Cho and Kim, 1997). In addition the algorithm results in better performance compared to the simulated annealing algorithm of (Bouleimen and Lecocq, 2003). A genetic algorithm proposed by Alcaraz and Maroto, (Alcaraz and Maroto, 2001), consists in the generalization of the activity list of (Hartmann, 1998). The research uses the serial SGS and includes the representation scheme which involves an additional gene to present whether the activity list is scheduled in a forward or backward direction. From extensive computational experiments on the basis of instances of PSPLIB, (Kolisch and Sprecher, 1997), the procedure shows a good performance. The study involves two different levels of crossover and mutation probabilities, 0.5, 0.8 and 0.05, 0.01, respectively.

An extended self-adapting genetic algorithm (SAGA) designed by (Hartmann, 2002) is developed on the basis of the previous genetic algorithm (Hartmann 1998). SAGA has several new aspects: an extended representation of an individual that involves an additional gene which decides the decoding procedure, adapted crossover and mutation operators, and a new method for computing an initial population. Although the quality of solutions is increased, a computational effort is required.

(Toklu, 2002) develops a GA that is applied directly on schedules using a vector of start times. In the study, the author introduces a penalty function in order to repair infeasible offspring schedules that the genetic operators may produce.

(Valls et al., 2005) proposes an extended activity list based genetic algorithm by integrating the forward-backward improvement of (Valls et al., 2003). A peak crossover operator is introduced and developed with the aim of inheriting those parts of the parents' activity lists which correspond to peaks in resource usage. (Gonçalves et al., 2008) studies a GA for the resource constrained multi-project scheduling problem. The chromosomes in the algorithm are represented on the basis of random keys. The initialization of the procedure relies on a heuristic that generates parameterized active schedules based on priorities, delay times, and release dates. (Montoya-Torres et al., 2010) proposes a genetic algorithm to solve the problem in which the chromosome representation is based on the features of object-oriented programming.

(Zhang and Wong, 2015) studies a process planning for a job shop planning problem as a generalization of resource constrained project scheduling problems. The work develops a genetic algorithm named object-coding GA. In the proposed algorithm the operation sequences are used directly as chromosomes. The search operators, crossover and mutation, are customized to cope with the new genetic representation. (Kaiafa and Chassiakos, 2015) studied a multi-objective resource constrained project scheduling problem. The problem aims to minimize the total cost that is associated with (a) resource over-allocation, (b) project deadline exceedance, and (c) day-by-day resource fluctuations. The authors develop a genetic algorithm. They evaluate the performance of the algorithm on several test problems and they compare the results with the output of Microsoft Project. The evaluation shows that the procedure can provide adequately- balanced solutions.

(Najafi and Niaki, 2006) develops a genetic algorithm for solving a resource investment problem where the objective is to maximize the discounted cash flow of the project payments. The use of a heuristic based on the forward and backward approach is made to initialize the population. The research operators (crossover and mutation) are adapted to the proposed representation. (Najafi et al., 2009) develops a previous work of (Najafi and Niaki, 2006) for a resource investment problem with discounted cash flows and maximal/minimal time lags. To improve the efficiency of the proposed GA, its parameters were fine-tuned using response surface methodology by a central composite face-centered design on 45 test problems. In (Shadrokh and Kianfar, 2007), a genetic algorithm is proposed to solve a resource investment problem. The model supposes that the tardiness of the project is permitted with a defined penalty. Each individual includes two parts. The first part uses an activity sequence approach that is presented in the work of (Hartmann, 1998) and the second is a list that verifies the resource capacities to start the activities.

(Maghsoudlou et al., 2016) represents a new multi-skill, multi-mode resource constrained project scheduling problem. The model pursues multiple objectives encompassing: minimization of the makespan of the project, minimization of the total cost of allocating workers to skills, and maximizing total quality of the processing activities. A metaheuristic, namely the multi-objective invasive weeds optimization algorithm (MOIWO) is developed to solve the model. Two other

metaheuristics, called non-dominated sorting genetic algorithm (NSGA-II) and multi-objective particle swarm optimization algorithm (MOPSO) are employed to validate the solutions resulting from the developed MOIWO. The Taguchi method is used to tune the parameters of the model.

2.9.3.2 Particle Swarm Optimization (PSO)

PSO is a population-based method which is inspired from the social behaviour of flocking birds and schooling fish when searching for food. It was developed by Kennedy and Eberhart in the mid-1990s, (Kennedy, Eberhart, 1995). Unlike the genetic algorithm, it does not resample individuals to produce new ones. Instead, the algorithm holds a single static population whose members are tweaked according to new information in the research space. In the initial form of the algorithm, a swarm of particle is moving in different dimensions. Each particle represents a solution of the given optimization model. Every particle possesses a position and a velocity. The search process takes advantage of the particles' intelligence in finding the good solutions. Indeed, each particle adjusts its own position toward a global optimum relying on two main factors that are i . the best position visited by itself and ii . the best position found by the whole swarm. The particle-updating for particle flying (i.e., the search process) can be formulated as:

$$V_i(t) = w(t) V_i(t-1) + c_1 r_1 (X_i^L - X_i(t-1)) + c_2 r_2 (X_i^G - X_i(t-1)) \quad 2-32$$

$$X_i(t) = V_i(t) + X_i(t-1) \quad 2-33$$

Where X_i^G represents the local best of the i^{th} particle after $t-1$ iterations, c_1 and c_2 hold positive constant values, r_1 and r_2 are random values from $(0,1]$, $w(t)$ is an inertia weight employed to control the effect of the previous velocities over the current velocity. Equation 2-32 is utilized to calculate a particle's new velocity. And, formula 2-33 is employed to find the particle's new position.

(Zhang et al., 2006) uses a PSO procedure to resolve resource constrained project scheduling problems with the objective function of minimizing the project makespan. In the study, activity priorities are represented by particles. Thereafter, a parallel scheme is utilized to transform the particle to a feasible schedule subject to the precedence and resource constraints.

(Jarbouli et al., 2008) uses the PSO algorithm to solve a multi-mode resource constrained project scheduling problem. The problem consists of two separate sub-problems, the assignment of modes to the activities and the scheduling of the activities. The PSO procedure deals with the first problem to produce an assignment of modes to activities, which are the particles. Then, a local search optimizes the sequences.

(Joy et al., 2016) develops a PSO algorithm for solving a resource-constrained project-scheduling problem with varying resource levels. The objective is to schedule the activities in a way in which effective utilization of resources is achieved by utilizing varying resource levels. The authors use the serial scheduling scheme to create the schedules of the activities subject to the constraints of the problem.

2.9.3.3 Ant Colony Optimization (ACO)

The fundamental idea of Ant Colony Optimization (ACO) is to imitate the behaviour of ants in the rapid discovery of food. In a real colony of ants, when the ants are searching for food, they leave a chemical trail (known as pheromone) on the path from their colony to the food source. Pheromone is a volatile substance. Its role is to guide the other ants toward a target point where the food is located. The paths that contain larger volumes of the pheromone have a high probability of being visited by the ants. Typically, an ant from the swarm chooses a path wherein a large quantity of pheromone can be smelt. The amount of the pheromone left on the ground decreases over time by evaporation. Moreover, the quantity of pheromone spattered by an ant directly relates to the amount of the food it has found. The ACO algorithm as an optimization technique explicitly imitates these natural phenomena. In the ACO algorithm, every ant builds a candidate solution. The solution is evaluated according to its fitness. The pheromone on each path to the fitted solutions increases. In order to avoid quick convergence of the algorithm through the paths with high value of the pheromone, the algorithm assumes that the pheromone of the path can be decreased as well.

This search algorithm was introduced by (Dorigo et al., 1996) and the algorithm was applied in order to solve the classic traveling salesman problem. The main features of the ant system are the positive feedback that accounts for rapid discovery of good solutions, distributed computation that avoids premature convergence, and the utilization of a constructive greedy heuristic that helps to obtain acceptable solutions in the early stages of the search process.

The first application of the ant colony optimization approach to a resource constrained project scheduling problem is found in the work of (Merkle et al., 2002). The study combines the ACO with various other heuristics found in the computational study of (Hartmann and Kolisch, 2000). In the study, the serial SGS representation is used to construct the schedules. Based on a weighted evaluation of the latest start time priority rule and so-called pheromones that represent the learning effect of previous ants, the eligible activity to be scheduled next is selected. The computational results show that the ACO algorithm performed best on average against several other heuristics, including simulated annealing, tabu search, and different sampling methods.

2.9.3.4 Tabu Search (TS)

The tabu search algorithm was created by Glover in 1986, (Glover, 1986). The basic idea of this research system was also outlined by Hansen at the same time in an approach that is named steepest ascent/mildest ascent (Hansen, 1986). When using the tabu search, the procedure forbids making certain moves. Such forbidden moves constitute a list that is called the tabu list. This list is dynamically updated during the execution of the algorithm. The application of the tabu list gives the algorithm the capacity to discard those neighbors that have been visited previously. In so doing, the search system avoids getting stuck in the probable cycles. Relying on the memory created by the tabu list, the algorithm always accepts the best neighbor that is not tabu.

A tabu search method introduced by (Tormos and Lova, 2003) operates directly on schedules by defining three different moves. This approach requires a repair procedure to change an infeasible schedule into a feasible one in cases where the resulting schedules may be infeasible. A tabu search procedure named RETAPS (Reactive Tabu Search for Project Scheduling) was presented by (Klein, 2000) and tested on the J30 and J60 standard instances (Kolisch and Sprecher, 1997) for a project scheduling problem in which the availability of resources varies over time.

A tabu search approach developed by (Nonobe and Ibaraki, 2002) is a generalized variant of the resource constrained project scheduling problem. In the proposed procedure activity list representation, serial SGS, shift moves, and a specific neighborhood-reduction mechanism were employed. Major features of the model include multi-mode processing and variable availability of renewable and non-renewable resources. A tabu search procedure with an insertion technique devised by (Artigues et al., 2003) iteratively chooses an activity, in which the activity is first removed from the schedule and then reinserted with a network flow-based insertion algorithm. (Mika et al., 2005) uses the tabu search for solving a multi-mode resource constrained project scheduling problem with positive discounted cash flows and different payment models. In (Skowroński et al., 2013) two approaches based on the tabu search are proposed to solve a multi-skill, resource constrained project scheduling problem. The objective of the paper is to research the usability and robustness of proposed approaches in solving different models.

2.9.3.5 Simulated Annealing (SA)

Simulated annealing (SA) was first proposed by Kirkpatrick, Galtt and Vecchi, (Kirkpatrick et al., 1983). The basic concept of the algorithm relies on the principles of statistical mechanics in which the annealing operations require the heating and then gradual cooling of a material to obtain a strong crystalline structure. Within the annealing process, if the initial temperature of the material is not sufficiently high or a fast cooling occurs, immature and unreliable products will be obtained. The SA accordingly simulates this behavior in order to find high-quality solutions for an optimization problem. Basically, it begins with one solution and then moves in a direction that brings improvement and attractive solutions. The fitness function of the problem is similar to the energy state of the cooling system. A solution of the research space is equivalent to a system state. Various possible values of the decision variables give the different molecular positions. During the research process, the SA prefers to move to a new solution if the direction is downhill, that is, going towards a better value of the fitness function. However, in order to avoid getting entrapped in local optima, it allows an occasional uphill move. This movement is made under the influence of a random number generator and a control parameter that is based on the temperature. The algorithm attempts to delay the temperature convergence and escape from local optima. The search and improvement process continues until one of the stop criteria occurs.

Various studies have been carried out to solve the resource constrained project scheduling problems (RCPSP) by applying the simulated annealing approach: (Boctor, 1996) (Bouleimen and

Lecocq, 2003) (Mika et al., 2005) (Chen and Shahandashti, 2009) (Yannibelli and Amandi, 2013a) (Yannibelli and Amandi, 2013b).

(Boctor, 1996) makes use of simulated annealing for solving non-pre-emptive RCPSP problems. The performance of the algorithm is compared with the tabu search algorithm. The procedure developed shows efficiency in resolution of the model. A simulated annealing algorithm presented by (Bouleimen and Lecocq, 2003) covers RCPSP and the multiple mode project scheduling problems (MRCPSP). An activity list representation that is similar to that of (Boctor, 1996) and a serial SGS to schedule activities are utilized for both RCPSPs and MRCPSPs. For RCPSPs, the search is based on an alternated activity. On the other hand, for MRCPSP, it is based on two embedded search loops alternating activity and mode neighborhood exploration. The computational results on the benchmark instances (Kolisch and Sprecher, 1997) show the promising performance of the algorithm, placing it among the most competitive algorithms for RCPSPs. (Mika et al., 2005) develops a simulated annealing algorithm for solving multi-mode resource constrained project scheduling problems with the objective of maximizing the net present value of cash flows. A feasible solution is represented by two n-element lists, wherein n is the number of activities. The first corresponds to the activity list, that is, a procedure for sorting the activities based on their precedence relation. The second relates to the mode assignment. Having obtained a feasible solution from the two lists, the serial SGS is utilized to determine the start time of the activities.

(Chen and Shahandashti, 2009) develops a hybrid genetic-simulated annealing approach for solving a multi-project and multiple resources project scheduling problem. The work introduces the concept of a “system of coding and priority index” to set the priority among all the activities and determine the start time of activities based on the availability of resources.

(Yannibelli and Amandi, 2013a) develops a hybrid simulated annealing and evolutionary algorithm to solve a multi-objective project scheduling problem. The objective of the problem is to minimize the makespan of the project and assign the most effective set of renewable resources. The representation of the solution is based on the work of (Yannibelli and Amandi, 2013b). Using the encoding procedure, also similar to the work of (Mika et al., 2005), the solutions are represented by two lists, the activity list and resource assignment list. The serial schedule generation method is used to generate the start time of the activities.

2.10 Chapter conclusion and discussion

The main objective of this chapter was to provide a state of the art analysis of project scheduling techniques. After a brief introduction to the primary research works on scheduling for unconstrained project scheduling problems, the chapter continues with an overview of the literature in scheduling for constrained project scheduling problems. In this context, two categories of such problems, resource constrained and time constrained problems, are presented and their specific approaches and the different extensions of the problems have been discussed. Specific

methodologies that are dedicated to solving each of the resource constrained and time constrained project scheduling problems have been presented and discussed within the chapter. Next, a category of solution methodologies that are not specific to the type of problem, known as problem independent methods, are described and their resolution mechanisms outlined. Since the project scheduling of the current study inherits the attributes of the resource constrained project scheduling problems and the time-constrained project scheduling problems, the problem-independent resolution methods are of particular interest in the course of this work.

“Study the past if you would define the future.”
Confucius

3. Planning for green supply chain networks: Concepts and key elements

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3.1 Chapter introduction

As discussed in Section 1.3 of Chapter 1, the scheduling of projects with just in time procurement of non-renewable resources is associated with the planning of the supply chain network that supplies the required non-renewable resources to the project worksites. At the same time, the goal of developing environmentally responsible decision making tools has led the study to consider greening factors in the modeling framework. The current chapter reviews the main concepts of *green supply chain networks* in Section 3.2. In Section 3.2.1 it discusses the *key elements that are necessary in the planning of the green supply chain* by closed networks. And finally, it reviews the literature on *material ordering issues in scheduling for the projects* in Section 3.3 and concludes by positioning the study and its contributions in Section 3.4.

3.2 Introduction to Green Supply Chain Management (GSCM)

A “supply chain” implies a network of organizations that are incorporated, through upstream and downstream interconnections in different processes and activities to produce value in the form of products or services and deliver them to the ultimate users (Christopher, 1999). Basic concepts of “supply chain management” (SCM) can be traced back to systems integration research done in the 1960s, seen in (Bucklin et al., 1966). However, it first appeared in the literature in the 1980s with the work of (Keith and Webber, 1982) (Houlihan, 1985) and (Thomas C. Jones and Daniel W. Riley, 1985). The Council of Supply Chain Management Professionals describes “Supply Chain Management” (SCM) as follows, seen in (Vitasek, 2010):

“Supply chain management encompasses the planning and management of all activities involved in sourcing, procurement, conversion, and all logistics management activities. Importantly, it also includes the coordination and collaboration with channel partners, which can be suppliers, intermediaries, third-party service providers, and customers. In essence, supply chain management integrates supply and demand management within and across companies. Supply chain management is an integrating function with primary responsibility for linking major business functions and business processes within and across companies into a cohesive and high-performing business model. It includes all the logistics management noted above, as well as manufacturing operations, and it drives coordination of processes and activities with and across marketing, sales, product design, finance and information technology.”

Conventional SCM decision-making practices focus only on economic and financial criteria. However, with increasing public attention on environmental issues and greater regulatory

requirements, as well as consumers' awareness of the need for the protection of the environment and its natural resources, green and sustainable subjects have become a major competitive factor for firms and also an unavoidable part of decision making, (Benita M. Beamon, 1999). The term "Green Supply Chain Management" has been introduced to add environmental concerns to the decision-making issues of supply chain networks (Dekker et al., 2012). Indeed, it is based on different environmental initiatives that attempt to decrease or eliminate the adverse impact of logistic activities. There are different definitions of GSCM:

(Srivastava, 2007) defines GSCM as "integrating environmental thinking into supply-chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as end-of-life management of the product after its useful life."

(Sarkis et al., 2011) presents green supply chain management as "integrating environmental concerns into the inter-organizational practices of supply chain management including reverse logistics".

Based on a study conducted on the wood processing sector in Spain in 2012, the authors in (Cordero and Poler, 2012) note that the main benefits of green practices are not only from reducing the environmental impacts but also from the diverse gains obtained in the company's image and the opening of new marketing opportunities, in addition to meeting legislative requirements. The GSCM scope ranges widely, from creating general environmental programs to their implementation and control. Generally, it encompasses five major headings including green design, green purchasing, green manufacturing, and green transport as well as waste management and backward logistics:

Green design:

Green design is an important sub-topic of the GSCM. Studies in the literature show that 80% of the costs and the environmental impacts of products relates to their specifications at the design stage in regards to the products' structure, packaging, and market positioning, ("Product Design for Manufacture and Assembly, Third Edition," 2010). The literature emphasizes both environmentally sustainable design and life cycle assessment/analysis (LCA) of the product. (Gungor and Gupta, 1999) comments that life cycle analysis "examines and quantifies the energy and materials used and wasted and it assesses the impact of the product on the environment." Practices on this issue, regardless of the field of the application, look for incorporating environmentally preferable outcomes such as:

- Lower consumption of energy and water throughout the entire lifecycle from manufacturers to the ultimate destinations of use and to disposal.
- Restricting resource consumption through waste-free manufacturing, with priority given to the use of renewable (recyclable) resources, and an emphasis on recycled materials in the production of the products and their packaging.
- Enhancement of quality and durability over price.
- Minimization of the emission of greenhouse gases by the employment of carbon neutralizing activities.
- Reducing or eliminating waste by minimizing consumption, by reusing when possible, and recycling when necessary.

Green purchasing:

Green Purchasing refers to the procurement of items and services that have a less harmful effect on human health and the environment compared to other products or services that serve the same purpose. The items under this condition encompass the raw materials, manufactured products, packaging materials and the products after use. Green purchasing is also known as environmentally responsible purchasing and affirmative procurement. According to (Zsidisin and Siferd, 2001) and (Alberg Mosgaard, 2015) the practices on green purchasing mainly encompass:

- Purchasing environmentally friendly materials which are recyclable, biodegradable and reusable.
- Selecting suppliers who have environmental certifications, such as ISO 14001, etc.
- Making partnerships with suppliers who seek environmental solutions and develop environmentally friendly products.

Green manufacturing:

In the process of green production, the input and output of the production process as well as the resource consumption are considered to be effectuated in an environmentally friendly way. This includes mainly the following aspects:

- Production of products according to their impact on the environment.
- Recovery and remanufacturing of materials or failed components.
- Recycling and reuse of materials or product components after the end of their lifespan.
- Productive and higher levels of processing technologies with the aim of reducing waste and scrap material.
- Preventive and predictive maintenance of equipment in order to provide suitable functioning and increased lifespan.

In (Ferroq et al., 2016), the authors conduct a study that aims to reduce waste in manufacturing processes. The study measures the influence of the different methods (based on lean manufacturing concepts and green management philosophies) and adapts an approach using a design of experiments tool. The analysis of the results gives rise to a hierarchy of progress factors for a waste minimization plan. (Garrone et al., 2016) studies the reduction of waste in food manufacturing centers. The authors consider 10 cases from different food manufacturing companies in Italy. The work contributes to some points that are important in waste minimization of the companies. In general, they include the identification of a clear method that enables the manufacturers to establish an efficient procedure for managing surplus foods and in particular for transporting them to the proper food assistance centers.

Green transport:

This is mainly based on the logistic process. Green transports in general include the evaluation of distribution centers and the consumption of resources and energy for transportation as well as reasonable shipment route planning. Many of the studies on this context in the literature are conducted to decrease the negative effect of transportation by reducing the amount of greenhouse gases emitted from delivery of materials and products (Li et al., 2008) (Elhedhli and Merrick, 2012) (Trappey et al., 2012) (Bazan et al., 2015) (Huang et al., 2016). The subjects related to the selection of transportation modes, seen in (Mallidis et al., 2010) and (Goel, 2010), as well as routing definitions in order to reach a minimum level of greenhouse gas emissions, studied in (Bektaş and Laporte, 2011), are also of interest in the literature in this research area. In (Absi et al., 2013), the authors introduce four types of constraints for limiting the emission of carbon by companies in a lot sizing problem. The constraints include *i.* periodic carbon emission constraints: these are used for the cases in which companies must ensure that the emission of carbon in every time period of the planning horizon does not exceed the maximum permitted level of emissions, *ii.* cumulative carbon emissions: this assumes that the amount of unused carbon emission in a given time period can be used in the following periods so that the cumulative capacities are not exceeded, *iii.* global carbon emission constraints: this guarantees that the unitary carbon emission over the whole horizon cannot be greater than the maximum unitary environmental impact allowed and, *iv.* rolling carbon emission constraints: in contrast to the global carbon emission constraints, these constraints presume that the compensation of the emission can be used only on a rolling period of the planning horizon. The authors demonstrate that the periodic case is solvable in polynomial time, while the cumulative, global and rolling cases are NP-hard.

Waste management and backward logistics:

Waste management refers to the collection, transportation and disposal of solid and liquid waste as well as the treatment of atmospheric emissions prior to their release into the environment with monitoring and regulation. Concepts of waste management are not uniform and they vary among

countries and regions. Traditionally, waste management operations for solid and liquid garbage involve “reducing”, “reusing”, and “recycling”. (Jayal et al., 2010) argues for a need to move from a 3R to a 6R concept, including “reduce”, “reuse”, “recover”, “redesign”, “remanufacture” and “recycle”. (Scur and Barbosa, 2017) summarizes the 6Rs as follows:

““Reduce” refers to the reduced use of resources in pre-manufacturing stages, reduced use of energy and materials during manufacturing and the reduction of waste during the use stage. “Reuse” refers to the reuse of a product or its components after its first life cycle. “Recycle” involves the process of converting material that would otherwise be considered waste into new materials or products. “Recover” is related to the process of collecting products at the end use destinations and disassembling, sorting and cleaning the products for use in subsequent product life cycles. “Redesign” simplifies the post-use processes. “Remanufacture” involves the re-processing of used products for restoration to their original state or a like-new form through the reuse of as many parts as possible without loss of functionality.”

3.2.1 Closed-Loop Supply Chain: Key elements for tactical level planning

The closed-loop supply chain includes the backward flows related to the take-back of products and waste from the customers to the recycling centers as well as the forward flows of the supply chain which are used for shipping the required materials and products from the suppliers toward the customers and end-use destinations (Kumar et al., 2009). Figure 28 details a typical supply chain network for closed loop environments. As shown in the diagram, the recovery and recycling of the waste and used products can be done in the individual recycling centers as well as in the recycling lines of the manufacturers of the products.

Combining the forward and backward flows comprises issues related to different decision-making practices in different corresponding time horizons ranging from operational to strategic, (as seen in Section 1.4.2). At the tactical level of planning, which is also the planning level in the current study, the decision-making practices in a closed-loop supply chain can be divided into two main headings:

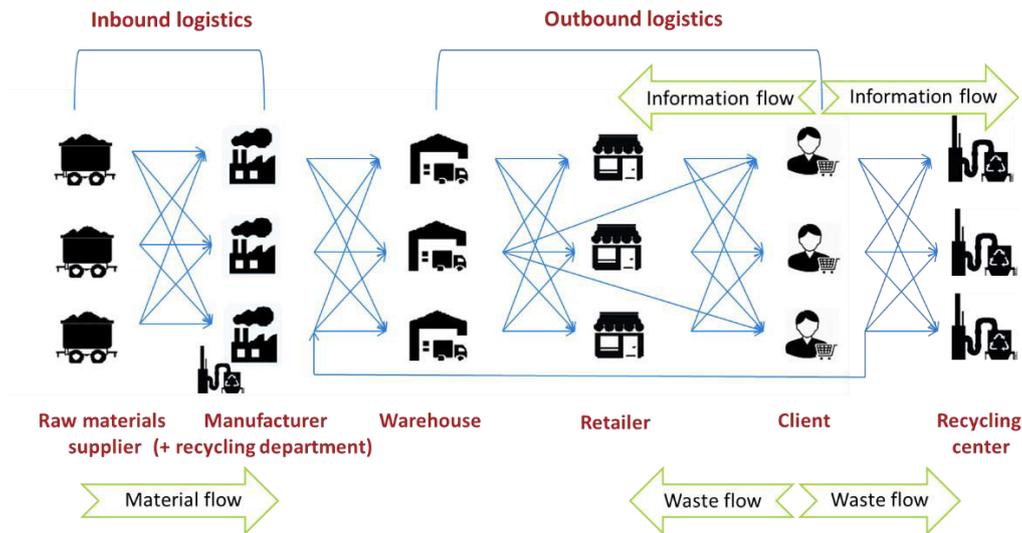


Figure 28- Structure of the forward-backward supply chain network, adapted from (Kumar et al., 2009).

3.2.1.1 Planning for forward supply chain

In general, this includes the planning for procuring raw materials, the production of the products and their distribution.

3.2.1.1.1 Procurement planning

According to (Sun et al., 2010) “material procurement” is the process of obtaining raw materials from potential suppliers. It is considered a capital-intensive decision. In general, planning for the procurement of materials and components determines what to buy from which source(s), how much and when, in order to be able to respond to the customers’ demands at the right time in the right quantity and at a predetermined quality level. To assure optimal input into the production system at all time periods of the planning horizon, the managers need to manage the levels of inventory for the raw materials and intermediate products they receive from the different suppliers under different supply conditions in terms of time and cost. In order to achieve this purpose, a two-level decision-making tool is usually constructed with different decision epochs (Bengtsson and Nonås, 2010): At the upper planning level, external suppliers are chosen and the order amounts for the selected suppliers are commonly decided on a monthly or weekly basis; at the lower scheduling level, more detailed operational schedules for unloading shipped orders are decided on a faster time scale; for instance, daily. Thus, one planning period is the overall decision horizon of the scheduling level, and the detailed schedule in each planning period is required for executing the plan under the various operational constraints and supplier availabilities.

In (Shin and Lee, 2016) a general inventory control problem for supplying raw materials from multiple suppliers to the manufacturers at the tactical level is studied. The planning problem is considered to be a Markov decision process in order to incorporate the uncertainty in supply and demand. The planning problem was integrated with a MILP model at the scheduling level and solved by the dynamic programming methods. (Arnold et al., 2009) presents a deterministic optimal control approach optimizing the procurement and inventory policy of an enterprise that is processing a raw material while the purchasing price, holding cost, and demand rate fluctuate over time. (Hnaïen et al., 2009) uses genetic algorithm approaches in order to optimize decision making in a two-level assembly system with random lead times for minimizing the tardiness cost for late delivery of the finished products as well as minimizing the holding cost of the semi-finished products in the layers of the supply chain.

(Wong et al., 2016) aims to provide insight into the driving factors for green procurement of resources in construction projects and attempts to suggest recommendations for the effective adoption of green procurement in construction projects. For this purpose, the authors take the results of the analysis from surveys and interviews with experts. They indicate that advanced construction methods have to be employed to stimulate the construction process into respecting environmental considerations. Furthermore, the deployment of a fully functioning green material market may help to promote the approaches of green procurement. In addition, the active engagement of suppliers with the aim of providing performance details of construction materials is recommended as well.

3.2.1.1.2 Production planning

Production planning (also known as lot sizing) pertains to the manufacturing of products in a company or industry and planning for producing the ordered modules as well as the management of the inventory levels of the necessary materials and the fabricated products (Wei et al., 2017). This utilizes the allocation of the resources and materials as well as the production capacities in order to carry out the manufacturing and subsequently reduce costs for the customers. Production planning problems have been modeled and solved as optimization problems since the early 1950s, and an extensive literature and reviews have been developed. In this context, (Missbauer and Uzsoy, 2011) focuses on models that support decisions on production quantities and order releases over time. The study highlights related issues on determining planned lead times. (Li et al., 2007) uses a genetic algorithm for solving a capacitated production planning problem with dynamic lot sizing. (Gen and Syarif, 2005) addresses a production and distribution problem in which the objective is to minimize the production, inventory and transportation costs of the supply chain network so that the total demand of the customers of the products is satisfied. Furthermore, the model deals with the availability of resources. Indeed, production in each period is constrained by the availability of resources. Typical resources include labor, material handling equipment and transportation modes. In order to solve the instances of the proposed model, the paper develops a solution methodology based on the genetic algorithm.

(Mula et al., 2014) studies a multi-tier supply chain network problem in which the objective of the model is to reduce the bullwhip effect in the supply network and decrease inventory and cycle times. With this aim in view, the authors develop an optimization linear programming model. In order to tackle more complex problems, they suggest the use of metaheuristic-based algorithms. (Trochu et al., 2015) develops a study of the problem of production planning along with environmental considerations. The study proposes an integer linear programming model corresponding to the tactical level of the supply chain. The proposed model allows the use of clean production technologies to produce one product family based on two types of bills of materials, standard and green. Since compensation regulations fine companies for the excessive weight of products, a green bill of material is used to demonstrate the impact of these regulations using a case study from Quebec.

There are generally different accepted production environments currently used in various companies and firms. The main difference between the manufacturing environments is how customer demand is fulfilled through existing inventory stocks and customer waiting periods. These strategies can be categorized into four main approaches:

- **Make-To-Stock (MTS):** In MTS environments, customer orders are filled from existing products in stock. The method requires a precise forecast of demand in order to define how much stock should be produced. The downfall of this strategy is production due to unreal forecasting of demand. However, it can be effective when the products are standardized and frequently demanded in the market. With this strategy, an important challenge is to define a proper replenishment policy for stocking the finished products and raw materials (Carr and Duenyas, 2000) (Rajagopalan, 2002).
- **Make-To-Order (MTO):** The Make-To-Order strategy, also known as Build-To-Order (BTO) is a demand driven approach where a product is built once a customer order has been received and confirmed. Manufacturing to customer demand implies a trigger of the pull-type supply chain operations. The method is considered suitable for highly configured and customized products with high stocking costs. The final product in MTO is often a combination of standard and customized items that satisfy the customer's specific requirements. Having long transportation lead time as well as long production lead time due to highly engineered production operations, the customers are expected to wait in order to receive their unique feature products (Rajagopalan, 2002) (Gupta and Benjaafar, 2004).
- **Assemble-To-Order (ATO):** In ATO environments, products are assembled from components or modules that are required in customer orders. This strategy is a hybrid of MTO (pull-type production) and MTS (push-type production). The components use a forecast and the MTS policy, while the finished product is driven by customer orders in the MTO approach. With this strategy, the key components are produced and stocked in anticipation of customer orders. Then, the assembly of the final product is accomplished upon receipt of the customer order. The policy is suitable for products that are more highly customized in comparison to the standard products in MTS. Nevertheless, the modules for

assembly of the components are not entirely known *a priori* (Harris and Pinder, 1995) (Song and Zipkin, 2003) (Benjaafar and ElHafsi, 2006).

- Engineer-To-Order (ETO): Engineer-to-order is generally more complex compared to the MTS, MTO and ATO environments. In ETO, customer specifications for the final product require special engineering design, indicative customization, and/or specific materials. The policy also tends to entail smaller lot sizes. ETO products are expensive and the slowest in terms of production and design time. In addition, the raw materials and some of the major components used in the products are often difficult to source or to design and manufacture. In order to deal with the due dates required by the customers of ETO products, high manufacturing flexibility is required on the shop floors (Gosling and Naim, 2009).

Part of the challenge for the suppliers of a supply chain network is in the identification of a point that defines which products and materials have to be forecast-driven and which should be order-driven. Such a point is known as the “customer decoupling point”. Figure 29 shows the mechanism of the above-stated strategies regarding the position of the decoupling points.

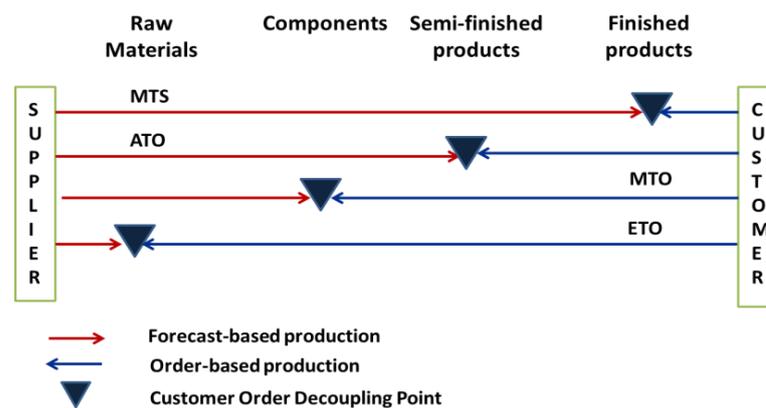


Figure 29- Customer order decoupling points in MTS, ATO, MTO and ETO production environments, from (Higgins et al., 1996).

3.2.1.1.3 Distribution planning

The planning and management of distribution include the determination of optimal quantities of the products that are supposed to be delivered to the customers to provide them with the right quantity of demand at the right place and at the right time using the proper modes of transportation. In the planning and management of distribution practices, the transportation lead time and the transportation capacity of the supply chain actors play a crucial role in achieving the most efficient

delivery (Akkerman et al., 2010). In general, the production and distribution issues of supply chain network planning are simultaneously optimized in the literature. (Meisel et al., 2013) presents a model, solution methods and a case study for the integrated planning of production and intermodal transportation in supply chain networks. The model jointly decides on production setups to indicate whether a product is set up at a potential production site or not, as well as on the management of inventory at the production sites, the output quantities and the reservation of the capacity of road and rail transportation means in a multi-period. The paper proposes exact and heuristic based algorithms to tackle the model and provides the results by applying them to a case study from a company in the chemical industry. (Azadian et al., 2015) studies an integrated problem of production and logistics planning for a MTO contract manufacturer looking to minimize the total cost of fulfilling its contract. On the production side, the authors consider a production planning problem where orders hold release dates, sequence dependent setup times and delivery due dates with nonlinear tardiness penalties. The logistics problem involves a variety of pre-determined shipping options with different lead times and costs. The formulation of the model is presented by the use of mixed integer programming approaches. Since the problem is considered to be in the NP-hard class of optimization problems, they propose a heuristic for solving the problem. (Pal et al., 2011) addresses the problem of integrated procurement, production and shipment planning for a supply chain in order to minimize the total cost of the system including total transportation costs, total inventory holding costs, total set-up costs for the value-addition process, and the total ordering cost of the retail centers over the planning horizon. The problem is constrained to establish the lead times at three echelons, maintain demand-supply balance equations and keep inventory within the maximum holding capacities. Particle swarm optimization and artificial bee colony optimization algorithms are used for solving the given model. (Fallah-Jamshidi et al., 2011) uses a genetic algorithm-based procedure in order to find optimal order release dates of the components in a two-level supply chain with random lead times. (Fahimnia et al., 2012) develops a mixed integer non-linear formulation to support the decisions for production, transportation, warehousing and inventory management of the required products in the supply chain network. The constraints of the model mainly pertain to the limited capacity of the suppliers of raw materials, the constrained production capacity of manufacturers and the limited capacity for stocking the work-in-process items in the buffer as well as the warehouses. The authors use the genetic algorithm in order to solve the model.

3.2.1.2 Planning for backward supply chain

The term backward logistics, according to (Fleischmann et al., 2001) (Badurdeen et al., 2009) and (Agrawal et al., 2015), is for all operations that:

- Collect products after the end of their lifespan and ship them to the manufacturing centers or recycling departments for remanufacturing, recovery and recycling.
- Return and/or replace defective products that are out of specification, malfunctioning or damaged in transportation.

- Characterize and classify the garbage and its disposal in accredited and authorized companies or individual recycling centers.

Studies on planning for backward flows in supply chains mainly regard the practices on the collection and transportation of waste and/or used products from the customers to the proper recycling centers. The decision making at the tactical level for backward logistics encompasses determining the optimum quantity of the waste/used products to be transported to each of the existing recycling centers while minimizing the total cost and/or total environmental impacts of the system (Aksen et al., 2009). (Kannan et al., 2010) aims to develop a multi-echelon, multi-period, multi-product closed-loop supply chain network model that determines the raw material level, production level, inventory-distribution level, disposal level, and recycling level at the different facilities of the supply chain while minimizing the total supply chain costs. The authors develop a resolution methodology based on the genetic algorithm to solve the mixed integer linear programming models. In the work, the computational results obtained through the GA are compared with those obtained by GAMS optimization software to validate the performance of the resolution algorithm.

3.3 Planning for ordering materials in project scheduling: review and bridging the gap

This section seeks to describe the state of the art on the scheduling of projects with a focus on planning for the procurement of non-renewable resources. In this context, various key words of the research area and their combinations are explored in the literature. The most important terms, involving “supply chain planning”, “environmentally responsible project scheduling”, “optimization”, “resource constrained project scheduling problems”, “multi project scheduling”, “resource investment problems”, “material ordering”, “production planning” and “ordering resources in project scheduling”, are reviewed through different databases including the Web of Knowledge, ScienceDirect, SpringerLink and Google Scholar. Table 2 summarizes all the existing research from the primary work in the 1980s up to the latest ones in 2016. A more detailed description of the problems, including model assumptions and solution methodologies, are given below:

(Aquilano and Smith, 1980) introduces the integrated problem of scheduling the project with ordering the material. In the work, the authors state the necessity of capturing the order lead time of the materials in the scheduling of the activities as well as the records of the amount of storable materials at the project worksites and they outline a set of algorithms that are developed to deal with the model. In the given solution technique, the schedules are initially designed by use of the CPM algorithm subjected only to the precedence relation between the activities. Subsequently, additional procedures are implemented to consider the restrictions on material ordering. The problem in the study is determined for situations where no limitations exist in the available amount of resources.

In a following study, Smith-Daniels and Aquilano extend the former work to adapt it more closely to real world circumstances, (Smith-Daniels and Aquilano, 1984). The authors therefore impose a limit on the maximum availability of renewable resources and deal with scheduling for both renewable and non-renewable resources. The work presents a heuristic based on the least-slack rule that extends the applicability of the model to large projects.

Relying on the previously mentioned works, (Smith-Daniels and Smith-Daniels, 1987a) develops an optimization mixed integer programming model wherein the net present value of the money is the criterion of performance of the project to be maximized. The scheduling model in the study is due at a maximum completion time. The major benefit of the model is in investigating the effects of capital and material costs and attempting to optimize the monetary objectives for a project.

Subsequently, (Smith-Daniels and Smith-Daniels, 1987b) develops a mixed integer 0-1 programming model for scheduling projects with material ordering issues. The model assumes lead time for receiving the materials at the project worksite and imposes a due date for the completion time of the project. The objective of scheduling is defined in minimizing the total cost of system execution. Using a heuristic based on the Wagner-Whitin lot-sizing algorithm, (Wagner and Whitin, 1958), they show that an optimal solution might be defined by decomposing the problem into a derivation of the project schedules and the subsequent material lot sizes.

In the following work, (Dodin and Elimam, 2001) extends the work of (Smith-Daniels et al., 1987b) to incorporate variability into the duration of the activities while they attempt to minimize the total execution cost of the projects.

(Sajadieh and Shadrokh, 2009) considers the discount for various ranges of ordering the materials. The model proposes the schedules for processing the activities as well as the proper processing time for every activity in order to minimize the total cost of performing the projects. The authors use a genetic algorithm to solve the model.

(Zoraghi et al., 2012) proposes a mixed integer programming model to handle materials in the scheduling of a project with regard to the project completion deadline. They apply a meta-heuristic based on a genetic algorithm and simulated annealing to solve the mathematical model. In addition, the Taguchi method is employed to tune the parameters of the proposed algorithm. In order to evaluate the performance of the algorithm, the authors compare the results of the algorithm with the results of the test problems which are solved by LINGO software.

(Fu, 2014) considers a multi mode project scheduling problem integrated with the handling of materials. In the model, the availability of renewable resources is bounded. However, this implies no limit in capacity for supplying non-renewable resources to the project worksite. Furthermore, the model considers a due date for accomplishing the project. The goal of the model is to minimize the total cost of the system which is comprised of renewable resource costs, material costs, ordering costs, inventory holding costs, backorder costs and delay penalties or rewards for early completion. An adapted genetic algorithm is used to solve the model.

(Zoraghi et al., 2014) extends their previous work, (Zoraghi et al., 2012), by considering order lead time and scheduling for renewable resource constraints in terms of availability. They employ two hybridized metaheuristic algorithms based on a genetic algorithm and simulated annealing to solve the integrated problem. In addition, statistical methods are employed to calibrate the parameters of both algorithms.

(Tabrizi and Ghaderi, 2015) develops the study of (Sajadieh and Shadrokh, 2009) to include the limited capacity for stocking material at the worksite of the project. They use the GAMS 22.1 solver to solve the instances of the model.

In (Tabrizi and Ghaderi, 2016), which is the subsequent work of (Tabrizi and Ghaderi, 2015), the authors consider the uncertainty in the duration of the activities as well as the execution costs and they develop a robust model which seeks to minimize the total cost of executing the activities and to maximize the robustness of the produced schedules. NSGA-II and a modified version of the multi-objective differential evolution algorithm have been used as solution approaches in the model. In this context, the parameters of the algorithm are tuned by the Taguchi method and the application of the algorithm is verified by comparing the results obtained from the algorithm and those obtained from the ϵ -constraint method.

Table 2 -Classification of the literature in project scheduling integrated with ordering issues from 1980 to 2016.

Reference	Assumptions					Constraints				Objective(s)			Solution Approach				
	Year	Structure Single/multi project	Time factor		Resource factor		Others	Precedence	Limited renewable resources	Limited non-renewable resources	Others	Makespan minimization	Cost minimization	Others	Heuristic	Metaheuristic	Exact
Earliest/latest start			Order lead-time	Due-date	Renewable	Non-renewable											
Aquilano and Smith	1980	✓	✓	✓	✓	✓	Time window for resource acquisition	✓			✓			✓			
Smith-Daniels and Aquilano	1984	✓	✓	✓	✓	✓	Time window for resource acquisition	✓	✓		✓			✓			
Smith-Daniels and Smith-Daniels	1987	✓	✓	✓	✓	✓	Discount	✓					Max. net present	✓			
Smith-Daniels et al.	1987	✓	✓	✓	✓	✓		✓				✓		✓			
Dodin and Elham	2001	✓	✓	✓	✓	✓	Bounded activity	✓				✓		✓			
Sajadieh and Shadrokh	2009	✓	✓	✓	✓	✓	Discount, bounded duration of activities	✓		✓		✓		✓			✓ GA-SA

Table 2- Classification of the literature in project scheduling integrated with ordering issues from 1980 to 2016.

Reference		Assumptions					Constraints				Objective(s)			Solution Approach					
Author(s)	Year	Structure	Time factor			Resource factor		Others	Precedence	Limited renewable resources	Limited non-renewable R.	Others	Makespan minimization	Cost minimization	Others	Heuristic	Metaheuristic	Exact	
			Earliest/latest start	Order lead-time	Due-date	Renewable	Non-renewable												
Zoraghi et al.	2012	✓	✓	✓	✓	✓		✓					✓				GA-SA	✓	
Fu	2014	✓	✓	✓	✓	✓	Multi-mode	✓	✓				✓				Harmony Search	✓	
Tabrizi and Ghaderi	2015	✓	✓	✓	✓	✓	Bounded activity duration, Discount	✓		✓	Limited stock		✓					✓	
Zoraghi et al.	2015	✓	✓	✓	✓	✓		✓	✓				✓				GA-SA	✓	
Tabrizi and Ghaderi	2016	✓	✓	✓	✓	✓	Discount, Uncertain activity duration and execution cost	✓	✓	✓			✓					NSGAI-DE	✓

In referring to Table 2, one could conclude that the research work on this topic forms a small part of the literature and that there is still a need for developing models adapted to practical situations, especially on our research topic on planning for multiple projects accorded to Just-in-Time procurement of non-renewable resources.

On the basis of the rationales given in Sections 1.3 and 1.4.2, the main idea for dealing with this challenge is to integrate the planning of the supply chain network into the scheduling of a typical multiple project scheduling problem. Since the modeling framework includes the management of waste produced at the project worksites, by planning for the backward flows, the network of the model involves both the forward and backward flows; namely, a closed-loop supply-chain network.

From the point of view of the solution methodologies, since the methods presented in Section 2.8 are generally applicable to different problems regardless of their type (either resource constrained project scheduling or time constrained project scheduling, as well as supply chain planning problems), the methods classified as the “problem -ndependent resolution approaches” are mainly of interest for solving the proposed optimization model in the course of this study. In this context, Branch and Bound and metaheuristic procedures are undertaken. The Branch and Bound procedure of CPLEX solver version 12.6.1 is used for the primary resolution of the model and its analyses of the results. Then, in order to tackle the untraceability of the model in large size problems, the application of a proper metaheuristic is targeted. According to the statistics presented in Section 2.9.3 on the application of the different metaheuristic-based algorithms, the genetic algorithm (GA) is chosen to be studied in our constrained project scheduling problems linked to the planning of a closed-loop supply chain, due to its significant dominance and success in the literature applications. The motivation for such an application originates from its strengths in exploring and exploiting the research space, the use of probabilistic transition rules and not deterministic ones, as well as its inherent characteristic of searching multiple solutions in every run of the algorithm that reduces the probability of getting stuck in local optima. Thus, the intention of this study on applying a proper metaheuristic-based search procedure focuses on the GA. The modeling framework with its assumptions and the application of the GA to the model brings novelties into constrained project scheduling problems.

3.4 Chapter conclusion and discussion

The objective of this chapter is to review the main concepts of the literature in planning for green supply chain networks and to study the issues for ordering materials in constrained project scheduling problems. To this end, the chapter starts with an informative introduction to the green supply chain in Section 3.2 and then discusses the main issues in planning for closed-loop supply chain networks in Section 3.2.1. Then it reviews the literature on ordering materials for project scheduling problems. Combining the results of the literature review and the requirements of the industry creates the possibility of designing the framework of the model.

The modeling framework in this study develops a multiple projects scheduling model which inherits some specifications of time constrained problems (imposed deadlines) and resource constrained project-scheduling problems (limited availability of renewable resources and the limited adding of new capacities to these resources), (*Contribution 1*). In order to plan the receipt of non-renewable resources in the worksites under Just-in-Time circumstances, the planning of a supply chain network, which is responsible for the procurement of non-renewable resources, is integrated into the project scheduling framework, (*Contribution 2*). Furthermore, in order to adapt the model to sustainable and green decision-making factors, the waste produced at the project worksites is collected and recycled, (*Contribution 3*). In this context, the model aims to define a plan for the transportation of waste from the worksites and its recycling in the appropriate recycling centers. Regarding solution methodologies, the resolution of the model is done by employing the branch and bound procedure of an optimization solver. In addition, a genetic algorithm is used to tackle the resolution of large-size problems, (*Contribution 4*).

“Method is much, technique is much, but inspiration is even more.”
Benjamin Cardozo

4. Mathematical model and resolution

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4.1 Chapter introduction

This chapter focuses on the contributions of the research stemming from the bibliography study in the previous chapters 2 and 3 and the requirements of real-world cases for scheduling constrained multi project problems. Two main objectives pursued within the chapter encompass:

- The presentation and application of the mathematical model: In this context, Section 4.2 describes the main *characteristics of the proposed optimization model* in detail. Specific *assumptions* of the problem are outlined in Section 4.2.1. Relying on the *notations* presented in Section 4.2.2, Section 4.2.3 represents the *mathematical formulation* of the problem. The application of the model is studied on a *use case* related to the CRIBA project. The *results* of the application and the *analysis* are provided in Section 4.2.5 and Section 4.2.5.1.
- The implementation of a metaheuristic-based search procedure: Concerning the last contribution of the dissertation, this chapter also studies the application of a metaheuristic-based algorithm on the proposed optimization model. The main purpose of this application is to determine a *search procedure* that tackles the intractability of the problem in the resolution of large-size instances. To this end, Section 4.3.1- Section 4.3.3 present the principals of the method used. The presentation of the solutions and the methods for handling the constraints as well as the scheme that has been used for *tuning* the driving parameters of the algorithm are discussed in this context. On the basis of the results obtained from the calibration of the parameters from Section 4.3.3, several experiments have been conducted to show the *performance* of the algorithm. The results of the experiments are summarized in Section 4.3.4.

4.2 Problem definition

The main intention of the problem is to provide an optimization-based decision-making tool for scheduling multiple projects at a tactical level of planning subject to the just-in-time supply of required consumable resources to the project worksites. The mathematical objective of the model is to determine a solution that minimizes the total cost of executing the system.

The model considers a set of projects to be scheduled in parallel while they are sharing a common pool of renewable resources (the attributes of the resource constrained projectscheduling problem). However, the possibility remains for extending the available capacity of these resources by renting a limited supplementary quantity (seen in the attributes of the time constrained project scheduling problem). Among the renewable resources, a set of these has high use cost, e.g. cranes. Therefore, a point of interest in the model is to shorten the time interval in which these resources are maintained at the project worksites.

Each project encompasses a set of activities. Every activity of the project is associated with certain parameters involving earliest start time, latest start time, processing time, demand for renewable resources, demand for non-renewable resources and the amount of waste generated by executing

the activity. In addition, a due date is assigned to the completion of the activities so that in the case of exceeding the due date, an extra cost will be imposed on the system as a penalty cost.

The supply chain network of the system generally encompasses four types of the stakeholders. It includes the suppliers of the raw materials, the manufacturing centers or the manufacturing centers with waste recycling departments, the project worksites and the individual recycling centers. The suppliers provide the raw materials to the proper destinations under their limited transportation capacity. The required intermediate products as well as the final products are produced in the manufacturing centers subject to the limits of their production capacity. To increase reliability in production, the manufacturing centers are flexible so they can increase their production capacity. However, the supplementary capacities in this context are limited by a given value. Two types of stock are considered for the stock of the items. They include the stock of inputs and outputs. The stock of inputs encompasses the holding of items that are received in a unit that will be used in that corresponding unit, e.g. raw material or intermediate products which are received in a manufacturing center in order to be used in producing the final product. The stock of outputs involves the holding of items that have been processed in a unit and can be sent to the next destination of use, e.g. the final products fabricated in a manufacturing center. The waste produced at the worksites is supposed to be shipped to the recycling departments. These departments are located either in a set of individual recycling centers or in the manufacturing centers that have recycling departments. As with the possibility of increasing production capacity, the recycling capacity can be extended as well. However, this supplementary capacity is constrained by a given value.

Figure 30 presents the model framework schematizing the concept of the stocking of input and output items. Other characteristics of the problem are outlined below.

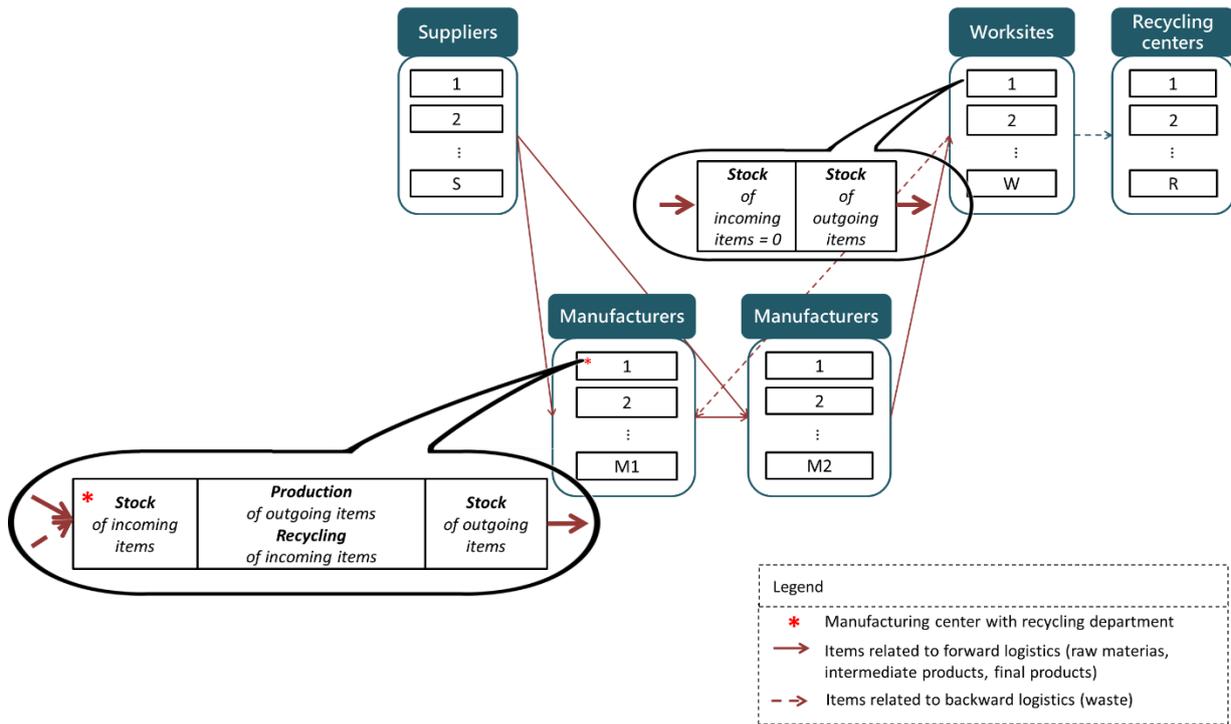


Figure 30- General presentation of the modeling framework schematizing the concept of the stocking of input and output items.

4.2.1 Assumptions

Following the points presented in the previous section, other assumptions of the model include the points below:

- The pre-emption of activities is not allowed; once an activity has started, it cannot be interrupted until it is entirely accomplished.
- The processing time of the activities is a fixed value and known *a priori*.
- Four types of generalized precedence relation are used in the model. In addition, each precedence can be identified as a wait or no-wait precedence.
- The no-wait precedence implies situations in which a sink activity in a precedence relationship should be followed immediately after the process of its source activity while considering the extant time lag to be spent if needed.
- In contrast to the no-wait precedence, the wait precedence excludes the necessity of an immediate process of a successor activity after the processing of its predecessor.
- The calculation for per-period running cost of the project excludes the costs related to the resources that have a high rental/utilization cost.
- The model hybridizes the time constrained project scheduling problem with the resource constrained multiple project scheduling problem by taking the characteristics of the model that allow the possibility of adding supplementary renewable resources while setting a due

date for the activities and giving a limitation in the total availability of the renewable resources.

- The stock of inputs at the project worksites is not allowed.
- The requirements of each activity for each of the renewable and non-renewable resource types as well as the waste generated by the activities are known.
- The time windows for executing the activities (earliest start and latest start time) and the due date are known and estimated by the experts.
- The actors of the supply chain have been selected by the superior decision-making process at the strategic level.
- The capacities of transportation, production and stocking of the materials/products as well as the maximum adding to the capacity in the production/recycling lines are known beforehand.
- The model considers lead times for transportation and the producing/recycling of the items. The value of the lead times is known *a priori*.

4.2.2 Notations

The following notations are used to present the problem mathematically:

Indexes:

i:	index of activities.
t:	index of time periods.
w:	index of project worksites.
m:	index of manufacturing centers.
c:	index of recycling centers.
mc:	index to present a set of units including the recycling and manufacturing centers.
u:	index to show all units of the network, including the project worksites, manufacturing centers, recycling centers, and suppliers of raw materials.
l:	index to present the various lines existing in the manufacturing/recycling centers, including production lines lp and recycling lines lc .
nr:	index of products used at the worksites (non-renewable resources of the projects).
g:	index of waste types generated at the worksites.
pr:	index of network items, including the non-renewable resources required at the project worksites, the waste generated at the worksites, intermediate products and raw materials.
pt	index of items including the intermediate products, the final products of the supply chain network and generated waste.
r	index to present renewable resources used at the worksites.
r'	index to present renewable resources used at the worksites with high rental cost, $r' \in R$.

f (o,d,p):	index to present flows which are to determine the shipment of item p from origin o to destination d , $o \in U$, $d \in U$, $p \in PR$.
in (d,p):	index of pairs which are to show item p received at destination d , $d \in U$, $p \in PR$.
out (o,p):	index of pairs used to determine an item p which is sent from origin o , $o \in U-S$, $p \in PR$.
line (l,mc):	index to relate production/recycling lines l to the corresponding manufacturing/recycling center mc .
pro (l,mc,pt):	index of triplets presenting the production/recycling of item pt in line l at manufacturing/recycling center mc .
b (p, p'):	index of pairs to present the linkage between composing element p and final product p' , $p \in PR$, $p' \in PR$.

Sets:

I:	set of activities.
T:	set of time periods.
W:	set of project worksites
PR:	set of various items of the network, including the non-renewable resources of the projects, the waste generated at the worksites, intermediate products and raw materials.
PT:	set of items including the intermediate products, the final products of the supply chain network and generated waste.
U:	set of all units of the network, including the project worksites, manufacturing centers, recycling centers, and suppliers of the raw materials.
MC:	set of units including the recycling and manufacturing centers.
L:	set of various lines existing in the manufacturing/recycling centers, including production lines lp and recycling lines lc .
NR:	set of non-renewable resources.
R:	set of renewable resources.
Flow(o,d,p):	set of flows which are to determine the shipment of item p from origin o to destination d , $o \in U$, $d \in U$, $p \in PR$.
IN(d,p):	set of pairs which are to show item p received at destination d , $d \in U$, $p \in PR$.
OUT(o,p):	set of pairs used to determine an item p which is sent from origin o , $o \in U-S$, $p \in PR$.
LINE(l,mc):	set of pairs used to determine the relationship of the production/recycling lines l to the corresponding manufacturing/recycling center mc .
I_w :	set of activities that belong to worksite w , ($I_w \subset I$).
SSpre :	start-to-start precedence relation of activity j , denoted by pair (i, j) .
SFpre :	start-to-finish precedence relation of activity j , denoted by pair (i, j) .
FSpre :	finish-to-start precedence relation of activity j , denoted by pair (i, j) .
FFpre :	finish-to-finish precedence relation of activity j , denoted by pair (i, j) .
Nowait _{SSpre} :	1 if activity j of precedence relation SSpre starts immediately after activity i has started, 0 otherwise.
Nowait _{SFpre} :	1 if activity j of precedence relation SFpre finishes immediately after activity i has started, 0 otherwise.
Nowait _{FSpre} :	1 if successor activity j of precedence relation FSpre starts immediately after finishing the predecessor activity i , 0 otherwise.

Nowait_{FFpre} : 1 if successor activity j of precedence relation FFpre finishes immediately after finishing the predecessor activity i , 0 otherwise.
 φ_w : a linkage between i and j to determine beginning activity i and ending activity j of worksite w .
 $\varphi'_{r'w}$: a linkage between i and j where activity i represents the activity of placing high-rental-cost renewable resource r' in worksite w and activity j represents the activity of displacing the high-rental-cost renewable resource r' in worksite w .

Parameters:

ET _{i} : earliest start time of activity i .
 LT _{i} : latest start time of activity i .
 DD _{i} : due date of activity i .
 Du _{i} : duration of activity i .
 Dnr _{i ,nr} : demand of activity i for non-renewable resource nr .
 Dr _{i ,r} : demand of activity i for renewable resource r .
 FS _{ij} : minimum time lag between the end of activity i and the start of activity j .
 SS _{ij} : minimum time lag between the start of activity i and the start of activity j .
 SF _{ij} : minimum time lag between the start of activity i and the end of activity j .
 FF _{ij} : minimum time lag between the end of activity i and the end of activity j .
 Ar _{r} : initial availability of renewable resource r .
 Max _{r} : maximum addable quantity of resource r .
 Pc _{w} : per-period cost of running worksite w .
 Cc _{$r'w$} : cost of using renewable resource r' at worksite w .
 Rc _{r} : rental cost of renewable resource r .
 Penc _{i} : penalty cost for one period of delay in the accomplishment of activity i .
 StinCap _{u} : capacity for stocking the incoming items in unit u .
 StoutCap _{u} : capacity for stocking the outgoing items in unit u except for the suppliers of the raw materials.
 TnCap _{u} : transportation capacity of unit u .
 LAVCap_{line(l ,mc) t} : production/recycling capacity of line l in center mc at time period t .
 MaxAdd_{line(l ,mc)} : maximum capacity that can be added to the initial capacity of line l in center mc .
 Wl _{pt,l} : workload of the process of item pt in line l .
 Tc_{f(o,d,p)} : cost for shipping a unit of item p from origin o to destination d .
 Tl_{f(o,d,p)} : lead time for shipping item p from origin o to destination d .
 Pl_{pro(l ,mc, pt)} : lead-time for production/recycling item pt in line l of manufacturing center mc .
 StinC_{pr} : cost for stocking a unit of used item pr .
 StoutC_{pr} : cost for stocking a unit of produced item pr .
 StCof_{pr} : coefficient which presents the space occupied by a unit of item pr .
 ProdC_{pt} : production/recycling cost of product pt .
 AddCL_{line(l ,mc)} : cost for adding a unit of capacity to line l in center mc .
 V_{b(p,p')} : amount of composing element p in product p' .

Gp_{gi} : amount of type g waste generated by activity i .

4.2.3 Mathematical formulation

Using the above-mentioned notations, the decision variables, constraints and objective functions of the model are defined below. Figure 31 summarizes the decision variables used for modeling schematically.

Decision variables:

- Z_{it} : 1 if activity i starts at time t , 0 otherwise.
- U_{it} : 1 if activity i is processing over time t , 0 otherwise.
- $Ltns_i$: lateness of activity i .
- S_i : start date of activity i .
- $AddR_{rt}$: added quantity of renewable resource r over time period t .
- $TQ_{f(o,d,p),t}$: transported quantity of item p from origin o to destination d at time t , $o \in U$, $d \in U$, $p \in PR$.
- $Stin_{in(d,p),t}$: stock quantity of item p that is received at destination d at time t , $d \in U$, $p \in PR$.
- $Stout_{out(o,p),t}$: stock quantity of item p that is sent from origin o at time t , $o \in U$, $p \in PR$.
- $ProdQ_{pro(l,mc,pt),t}$: produced/recycled quantity of item pt in line l of unit mc at time t .
- $AddL_{line(l,mc),t}$: quantity of added supplementary capacity to line l in unit mc at time t .

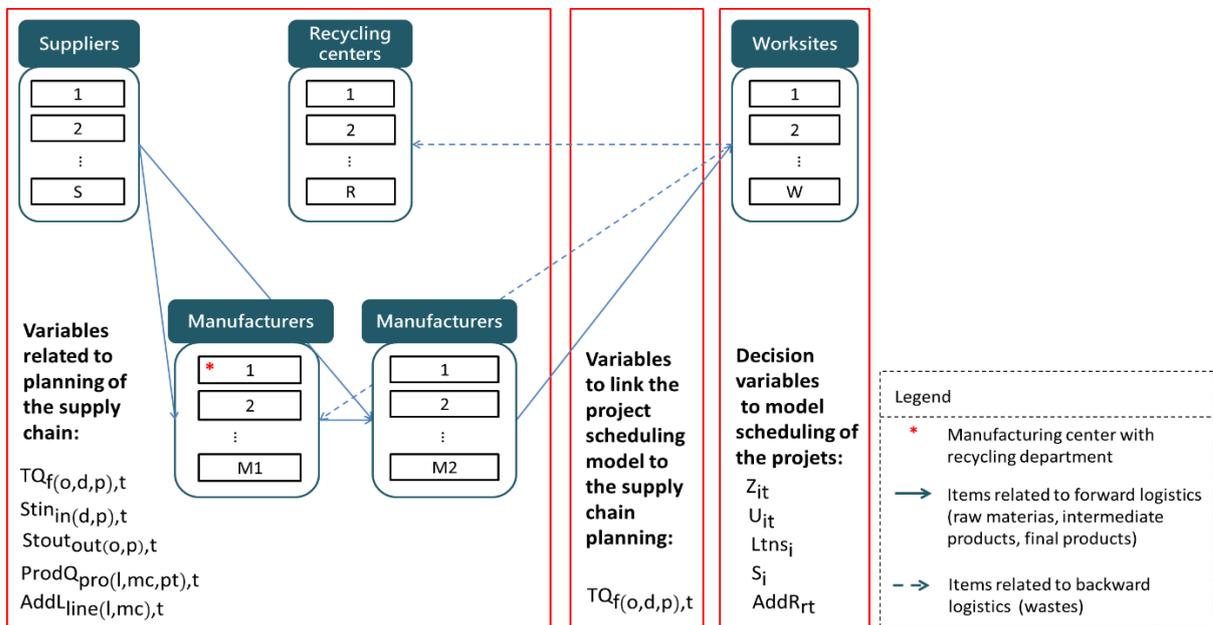


Figure 31- Classifying the decision variables of the mathematical model.

Objective Function

$$\begin{aligned}
 \text{Min OF} = & [\sum_w \sum_{(i,j) \in \varphi_w} (S_j + Du_j - S_i) Pc_w + \sum_w \sum_r \sum_{(i,j) \in \varphi'_{r,w}} (S_j + Du_j - \\
 & S_i) Cc_{r,w} + \sum_i Ltns_i Penc_i \\
 & + \sum_r \sum_t AddR_{rt} Rc_r] + \\
 & [\sum_{f(o,d,p)} \sum_t TQ_{f(o,d,p),t} TC_{f(o,d,p),t} + \sum_{in(d,p)} \sum_t Stin_{in(d,p),t} StinC_p + \\
 & \sum_{out(o,p)} \sum_t Stout_{out(o,p),t} SoutC_p + \sum_{pro(l,mc,pt)} \sum_t ProdQ_{pro(l,mc,pt),t} ProdC_{pt} + \\
 & \sum_{line(l,mc)} \sum_t AddL_{line(l,mc),t} AddCL_{line(l,mc)}] \tag{3-1}
 \end{aligned}$$

The objective, equation 3-1, of the model is to minimize the total cost of the system. It includes two types of costs:

- *Costs of projects*: These costs are mathematically presented by terms included in the first bracket of the objective function. They involve respectively the total cost of running the projects, the cost related to use of renewable resources whose rental cost is high (where the objective is to minimize the duration that these resources will be used at the worksites), the total penalty cost for late completion of the activities and the total cost of adding supplementary renewable resources.
- *Costs of supply chain*, the terms included in the second bracket are associated with supply chain planning costs. They are respectively the total transportation cost of shipping the items, the stock cost of the incoming items into units, the stock cost of the outgoing items from units, the production/recycling cost of products/waste and the cost related to adding new production/recycling capacities in the related lines, discussed in (Gholizadeh-Tayyar et al., 2016b).

Subject To

Project planning constraints :

$$\begin{aligned}
 \sum_{t=ET_i}^{LT_i} Z_{it} &= 1 & \forall i \in I & \tag{3-2} \\
 \sum_{t=ET_i}^{ET_i + Du_i - 1} U_{it} &= Du_i & \forall i \in I & \tag{3-3} \\
 S_j &\geq S_i + Du_i + FS_{ij} & \forall (i, j) \in FSpre, Nowait_{FSpre} = 0 & \tag{3-4} \\
 S_j &\geq S_i + SS_{ij} & \forall (i, j) \in SSpre, Nowait_{SSpre} = 0 & \tag{3-5} \\
 S_j + Du_j &\geq S_i + SF_{ij} & \forall (i, j) \in SFpre, Nowait_{SFpre} = 0 & \tag{3-6} \\
 S_j + Du_j &\geq S_i + Du_i + FF_{ij} & \forall (i, j) \in FFpre, Nowait_{FFpre} = 0 & \tag{3-7} \\
 S_j &= S_i + Du_i + FS_{ij} & \forall (i, j) \in FSpre, Nowait_{FSpre} = 1 & \tag{3-8} \\
 S_j &= S_i + SS_{ij} & \forall (i, j) \in SSpre, Nowait_{SSpre} = 1 & \tag{3-9} \\
 S_j + Du_j &= S_i + SF_{ij} & \forall (i, j) \in SFpre, Nowait_{SFpre} = 1 & \tag{3-10} \\
 S_j + Du_j &= S_i + Du_i + FF_{ij} & \forall (i, j) \in FFpre, Nowait_{FFpre} = 1 & \tag{3-11} \\
 \sum_{k=t}^{t+Du_i} U_{ik} &\geq Du_i Z_{it} & \forall i \in I, t \in \{ET_i, \dots, LT_i\} & \tag{3-12} \\
 S_i &= \sum_{t=ET_i}^{LT_i} t Z_{it} & \forall i \in I & \tag{3-13} \\
 Ltns_i &\geq S_i + Du_i - DD_i & \forall i \in I & \tag{3-14}
 \end{aligned}$$

$$\sum_{i \in I} D_{r_{it}} U_{it} \leq A_{r_t} + \text{Add}R_{r_t} \quad \forall r \in R, \forall t \in T \quad 3-15$$

$$\text{Add}R_{r_t} \leq \text{Max}_r \quad \forall r \in R, \forall t \in T \quad 3-16$$

Constraints that link the project planning problem to the closed-loop supply chain planning problem:

$$\sum_f TQ_{f(o,w,nr), t - \Pi_{f(o,w,nr)}} = \sum_{i \in I_w} Z_{it} D_{nr_{i, nr}} \quad \forall w \in W, nr \in NR, t \in T \quad 3-17$$

$$\begin{aligned} \text{Stin}_{in(m,p), t-1} + \sum_f TQ_{f(o,m,p), t - \Pi_{f(o,m,p)}} = \\ \text{Stin}_{in(m,p), t} + \sum_{b(p,p')} \sum_{\text{pro}} \text{Prod}Q_{\text{pro}(lp, m, p'), t} V_{b(p,p')} \quad \forall in(m,p) \in \text{IN}(d,p), t \in T \end{aligned} \quad 3-18$$

$$\begin{aligned} \text{Stin}_{in(d,g), t-1} + \sum_f TQ_{f(o,d,g), t - \Pi_{f(o,d,g)}} = \\ \text{Stin}_{in(d,g), t} + \sum_{\text{pro}} \text{Prod}Q_{\text{pro}(lc, d, g), t} \quad \forall in(d,g) \in \text{IN}(d,p), t \in T \end{aligned} \quad 3-19$$

$$\begin{aligned} \text{Stout}_{out(m,p), t-1} + \\ \sum_{\text{pro}} \text{Prod}Q_{\text{pro}(lp, m, p), t - \Pi_{\text{pro}(lp, m, p)}} = \\ \sum_f TQ_{f(o,m,p), t} + \text{Stout}_{out(m,p), t} \quad \forall out(m,p) \in \text{OUT}(o,p), t \in T \end{aligned} \quad 3-20$$

$$\begin{aligned} \text{Stout}_{out(w,g), t-1} + \sum_{i \in I_w} Z_{it} G_{p_g, i} = \\ \sum_f TQ_{f(w,d,g), t} + \text{Stout}_{out(w,g), t} \quad \forall out(w,g) \in \text{OUT}(o,p), t \in T \end{aligned} \quad 3-21$$

$$\begin{aligned} \sum_{\text{pro}} \text{Prod}Q_{\text{pro}(l, mc, pt), t} W_{l, pt, l} \leq \\ \text{LAvCap}_{\text{line}(l, mc), t} + \text{Add}I_{\text{line}(l, mc), t} \quad \forall \text{line}(l, mc) \in \text{LINE}(l, mc), t \in T \end{aligned} \quad 3-22$$

$$\text{Add}I_{\text{line}(l, mc), t} \leq \text{MaxAdd}_{\text{line}(l, mc)} \quad \forall \text{line}(l, mc) \in \text{LINE}(l, mc), t \in T \quad 3-23$$

$$\sum_p \text{Stin}_{in(d,p) | d=u, t} \text{StCof}_p \leq \text{StinCap}_u \quad \forall u \in U, t \in T \quad 3-24$$

$$\sum_p \text{Stout}_{out(o,p) | o=u, t} \text{StCof}_p \leq \text{StoutCap}_u \quad \forall u \in U, t \in T \quad 3-25$$

$$TQ_{f(o,d,p) | o=u, t} \leq \text{TnCap}_u \quad \forall u \in U, f(o,d,p) \in F(o,d,p), t \in T \quad 3-26$$

$$\text{Stin}_{in(d,p), t} = 0 \quad \forall in(d,p) \in \text{IN}(d,p), t \in \{0, T\} \quad 3-27$$

$$\text{Stout}_{out(o,p), t} = 0 \quad \forall out(o,p) \in \text{OUT}(o,p), t \in \{0, T\} \quad 3-28$$

Decision variables:

$$0 \leq U_{it} \leq 1 \quad \forall i \in I, t \in T \quad 3-29$$

$$\begin{aligned} \text{Ltns}_i, S_i, R_{rt}, TQ_{f(o,d,p), t}, \text{Stin}_{in(d,p), t}, \text{Stout}_{out(o,p), t}, \\ \text{Add}I_{\text{line}(l, mc), t}, \text{Prod}Q_{\text{pro}(l, mc, pt), t} \geq 0 \quad \forall f(o,d,p) \in F(o,d,p), \\ in(d,p) \in \text{IN}(d,p), \\ out(o,p) \in \text{OUT}(o,p), \\ \text{pro}(l, mc, pt) \in \text{PRO}(l, mc, pt), \\ i \in I, r \in R \end{aligned} \quad 3-30$$

$$Z_{it} \in \{0, 1\} \quad \forall i \in I, t \in T \quad 3-31$$

Constraint 3-2 guarantees that all activities of the projects will be started at a time point from the interval between their earliest start times to their latest start times. Equation 3-3 represents the sum of the periods in which an activity is running from its earliest start to the latest finish time, $ET_i + Du_i$, should be equal to its processing time. Constraints 3-4-3-11 deal with the precedence

constraints between the activities. In this context, constraint 3-4 defines the start time for successor activities subject to the “wait” condition, the finish-to-start relation and the extant time lag in the precedence relation. Similarly, constraints 3-5-3-7 deal with the determination of the start time for the activities subject to the “wait” condition respectively under start-to-start, start-to-finish, and finish-to-finish relations wherein a time lag accorded to the precedence that might be spent. Equation 3-8 considers the activities under a finish-to-start precedence relation with a “no-wait” condition and determines the start time of a successor activity with regards to the time lag in the precedence relationship. Similarly, this purpose is followed in equations 3-9-3-11 for the activities respectively subjected to the start-to-start, start-to-finish, and finish-to-finish precedence relations. Constraints 3-12 and 3-13 link the decision variables Z_{it} , U_{it} and S_i . Constraint 3-14 calculates the lateness that may occur in the completion of the activities. This is defined by the difference between the due date imposed for the accomplishment of an activity and its real completion time. Constraints 3-15 and 3-16 deal with the availability of renewable resources. In this context, constraint 3-15 guarantees that the requirement for renewable resources at every time period must not exceed the initial quantity of the renewable resources plus the supplementary quantity that could be added in. Constraint 3-16 limits the quantity of the added supplementary renewable resources. Taking the transportation lead time into account, equation 3-17 guarantees that at every time period t the total quantity of non-renewable resources that are transported to the worksites satisfies the total demand of the activities, which are going to be started in that time period, for every non-renewable resource m . Constraints 3-18-3-19 deal with the constraints related to the balance of the flow. In this context, constraint 3-18 considers the materials and/or intermediate products received in a production center. Considering the transportation lead time, the equation states that in every time period t , the inventory level of these incoming products that are available from the former period plus the quantity which is going to be received in the production center from their suppliers is equal to the quantity of the raw materials/products that are used for producing the products of the production center plus the quantity of the incoming items that are stocked at the end of time period t at the manufacturing center. Constraint 3-19 applies the same approach for the different waste types that are received in the recycling centers. Equations 3-20 and 3-21 determine the balance of the flow for the items that are going to be delivered from a unit to their end-use destinations, (out-going products). In this context, equation 3-20 regards the production centers. Considering production lead-time, this guarantees that the level of inventory for products that are available from the former period in the corresponding manufacturing center plus the quantity that will be produced is equal to the quantity that will be sent to the next destination of use and the quantity that will be stocked in the unit at the end of the period. Constraint 3-21 employs the same concept to the waste that is transported from the project worksites to the recycling centers. Constraint 3-22 requires that the production/recycling of the products cannot exceed the available production/recycling capacities plus the capacity that could be added. Constraint 3-23 defines a limit on extending the production/recycling capacity. Equations 3-24 and 3-25 respectively deal with the limited capacity for stocking the incoming and outgoing products. Constraint 3-26 considers the limited transportation capacity. Equations 3-27 and 3-28 define the initial and final states of the products in stock, respectively for incoming and outgoing items. And finally, constraints 3-29-3-31 determine the type of decision variables. It is

worth noting that in the model the only binary decision variables are Z_{it} . Indeed, considering constraints 3-12 and 3-3 on one hand and constraint 3-29 on the other hand, U_{it} will always result in 0 or 1.

4.2.4 Instance problem and data setting

The above-mentioned modeling framework has been applied to a case study related to the CRIBA Project. The dimension of the instance problem includes two worksites of the projects that are integrated into a supply chain network. The forward supply chain network includes one supplier of raw materials, two carpentry manufacturing centers and two panel manufacturing centers. The backward supply chain encompasses one individual recycling center and one recycling center located in one of the carpentry manufacturing centers (intermediate products), Figure 32.

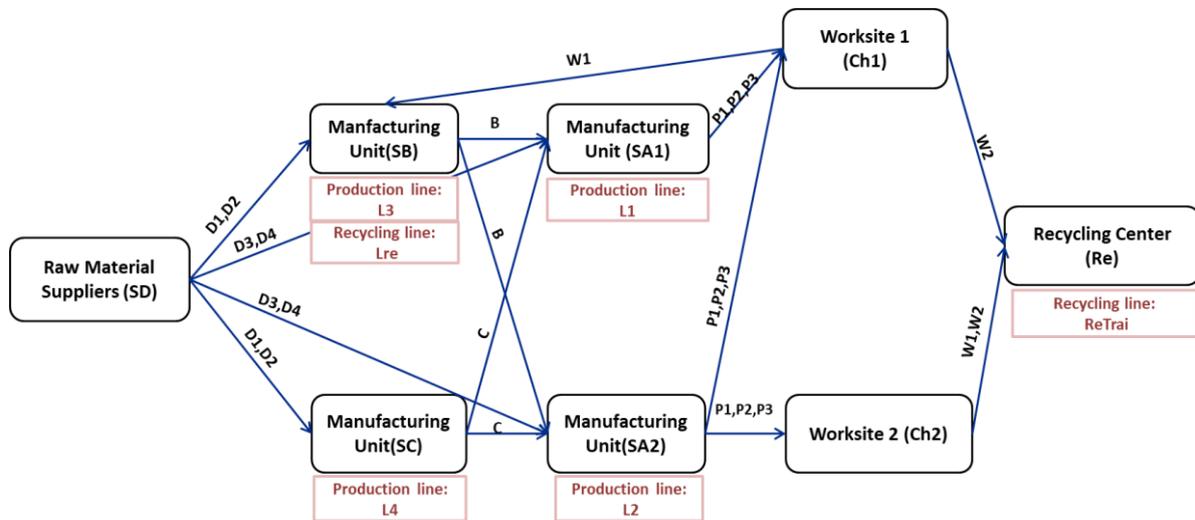


Figure 32- Presentation of a typical problem instance under the CRIBA project.

Table 3 -Activity list of the projects and their data settings.

ID	Activity Description	Worksite	Associated dates (Day)			Penalty cost (Euro)	Renewable resources (unit)			Non-renewable resources (Unit)			Produced wastes (kg)	
			Processing time	Earliest start time	Latest start time		Due-date	workers	Crane	Truck	P1	P2	P3	W1
1	Start	Ch1	0	7	20	13	10	0	2	0	0	0	0	0
2	Crane assembly	Ch1	2	7	21	15	2	2	0	1	1	1	0.4	0.4
3	Preparing for access	Ch1	1	15	21	16	3	2	2	2	1	1	1.4	0.4
4	Building 2. ground floor	Ch1	1	16	18	17	4	2	2	0	1	1	0.4	0.4
5	Building 1. ground floor	Ch1	1	17	25	18	2	2	2	2	1	1	1.6	0.6
6	Building 3. ground floor	Ch1	2	19	27	22	2	2	2	1	1	1	0.8	0.5
7	Building 2. first floor	Ch1	1	8	26	19	4	2	2	0	1	1	0.4	1
8	Building 1. first floor	Ch1	1	9	27	20	2	2	2	0	1	1	0.48	0.48
9	Building 3 first floor	Ch1	1	10	28	24	3	0	0	1	1	1	0.3	1
10	Building 2. second floor	Ch1	2	12	29	24	2	1	1	0	2	2	0.6	0.6
11	Building 1. second floor	Ch1	1	14	27	18	4	2	2	1	3	3	2.28	0.28
12	Crane disassembly	Ch1	1	15	28	21	2	0	0	2	1	1	0.4	0.4
13	Building 1. annex	Ch1	1	7	21	27	1	0	2	2	2	2	2.4	0.4
14	Building 2. finishing	Ch1	1	18	30	25	3	0	2	1	2	2	2.4	0.4
15	Building 1&3. finishing	Ch1	2	22	29	26	2	0	2	0	1	1	0.3	0.6
16	Finish	Ch1	0	24	31	28	10	0	2	0	0	0	0	0
17	Start	Ch2	0	7	20	13	10	0	2	0	0	0	0	0
18	Crane assembly	Ch2	2	7	21	15	2	2	0	1	1	1	0.4	0.4
19	Preparing for access	Ch2	1	15	21	16	3	2	2	2	1	1	1.4	0.4
20	Building 2. ground floor	Ch2	1	16	18	17	4	2	2	0	1	1	0.4	0.4
21	Building 1. ground floor	Ch2	1	17	25	18	2	2	2	2	1	1	1.6	0.6
22	Building 3. ground floor	Ch2	2	19	27	22	2	2	2	1	1	1	0.8	0.5
23	Building 2. first floor	Ch2	1	8	26	19	4	2	2	0	1	1	0.4	1
24	Building 1. first floor	Ch2	1	9	27	20	2	2	2	0	1	1	0.48	0.48
25	Building 3 first floor	Ch2	1	10	28	24	3	0	0	1	1	1	0.3	1
26	Building 2. second floor	Ch2	2	12	29	24	2	1	1	0	2	2	0.6	0.6
27	Building 1. second floor	Ch2	1	14	27	18	4	2	2	1	3	3	2.28	0.28
28	Crane disassembly	Ch2	1	15	28	21	2	0	0	2	1	1	0.4	0.4
29	Building 1. annex	Ch2	1	7	21	27	1	0	2	2	2	2	2.4	0.4
30	Building 2. finishing	Ch2	1	18	30	25	3	0	2	1	2	2	2.4	0.4
31	Building 1&3. finishing	Ch2	2	22	29	26	2	0	2	0	1	1	0.3	0.6
32	Finish	Ch2	0	24	31	28	10	0	2	0	0	0	0	0

The list of the activities to perform in each of the projects and their data settings are presented in Table 3-Table 5. The parameter settings related to the different actors of the supply chain network regarding their stock, production and transportation capacity, the costs related to production, stock, transportation and the adding of supplementary production/recycling capacities as well as the production/recycling lead times and bills of materials (BOM) are outlined in Table 6-Table 12.

Table 4 -Precedence relations between the activities and the associated time lags.

Activity ID	Predecessor activity	Time-lag	Precedence type	No-wait	Activity ID	Time-lag	Precedence type	No-wait
2	1	1	Finish-to-Start	0	18	1	Finish-to-Start	0
3	1	1	Finish-to-Start	0	19	1	Finish-to-Start	0
4	2	1	Finish-to-Start	0	20	1	Finish-to-Start	0
5	2	1	Finish-to-Start	0	21	1	Finish-to-Start	0
5	3	-1	Finish-to-Start	0	21	-1	Finish-to-Start	0
6	3	1	Finish-to-Start	0	22	1	Finish-to-Start	0
7	4	0	Finish-to-Start	1	23	0	Finish-to-Start	1
8	5	0	Finish-to-Start	1	24	0	Finish-to-Start	1
9	6	0	Finish-to-Start	1	25	0	Finish-to-Start	1
10	7	0	Finish-to-Start	1	26	0	Finish-to-Start	1
11	8	0	Finish-to-Start	1	27	0	Finish-to-Start	1
12	10	1	Finish-to-Start	0	28	1	Finish-to-Start	0
12	11	1	Finish-to-Start	0	28	1	Finish-to-Start	0
13	11	1	Finish-to-Start	0	29	1	Finish-to-Start	0
14	10	1	Finish-to-Start	0	30	1	Finish-to-Start	0
15	9	-1	Finish-to-Start	0	31	-1	Finish-to-Start	0
15	13	1	Finish-to-Start	0	31	1	Finish-to-Start	0
16	14	1	Finish-to-Start	0	32	1	Finish-to-Start	0
16	15	1	Finish-to-Start	0	32	1	Finish-to-Start	0

Table 5-Data settings related to use of renewable resources and the execution of the projects.

	Cost/period	Max-add	Availability
Workers	120	25	10
Crane	1200	5	2
Truck	250	15	5

Cost by type	Start activity	End activity	Cost/period
Run	1	16	2500
Run	17	32	2500
Crane use	2	12	1200
Crane use	18	28	1200

Project ID	Max finish date
Ch1	35
Ch2	35

Table 6-Data setting related to the stock capacity of the units for incoming and outgoing items as well as the units' transportation capacity.

Unit	ID	Input stock capacity(m3)	Output stock capacity(m3)	Supply capacity(m3)
Ch1	1	0.05	4	10
Ch2	1	0.05	4	10
SA1	2	10	12	50
SA2	2	11	12	50
SB	2	60	50	100
SC	2	60	50	100
SD	3	50	0	60
Re	4	20	2	10

Table 7 –Production, recycling and stock costs of the different items in the units.

Item	ID	Production/ recycling cost(Euro)	Stock cost(Euro)	Stock coefficient (m3/unit)
P1	1	200	5	1
P2	1	210	8	1
P3	1	300	10	1
B	2	40	3	1
C	2	50	4	1
D1	3	0	3	1
D2	3	0	3	1
D3	3	0	5	1
D4	3	0	5	1
W1	4	1	0.2	1
W2	4	1	0.2	1

Table 8 -Processing workloads and lead times of the different items on their corresponding lines.

Processing line	Item	Workload (Machine-Day)	Production/recycling lead-time (Day)
L1	P1	1	1
L1	P2	1	1
L1	P3	1	1
L2	P3	1	1
L2	P1	1	1
L2	P2	1.2	1
L3	B	1	1
L4	C	1	1
ReTrai	W1	1	1
Lre	W1	1	1
ReTrai	W2	1	1

Table 9 -Available production and recycling capacity in every line.

Available capacity in Line	Time Periods												
	1	2	3	4	...	8	9	10	11	...	33	34	35
L1	50	50	50	50	...	50	50	50	50	...	50	50	50
L2	50	50	50	50	...	50	50	50	50	...	50	50	50
L3	20	20	20	20	...	20	20	20	20	...	20	20	20
L4	20	20	20	20	...	20	20	20	20	...	20	20	20
Lre	4	4	4	4	...	4	4	4	4	...	4	4	4
ReTrai	4	4	4	4	...	4	4	4	4	...	4	4	4

Table 10- Maximum capacity addable to every line with the associated costs.

Line	Type	Site	Maximum add into capacity	Cost of adding capacity
L1	Production	SA1	50	300
L2	Production	SA2	50	240
L3	Production	SB	20	210
L4	Production	SC	20	60
Lre	Recycling	SB	5	60
ReTrai	Recycling	Re	5	60

Table 11 -Transportation of items between units, the cost and lead time associated with each transportation.

	Transportation			Lead-time(Day)	Cost(Euro)
	Origin	Destination	Item		
Flow	SD	SB	D1	2	10
	SD	SB	D2	2	10
	SD	SC	D1	2	10
	SD	SC	D2	2	10
	SB	SA1	B	1	20
	SB	SA2	B	1	10
	SC	SA1	C	1	10
	SC	SA2	C	1	10
	SA1	Ch1	P1	1	20
	SA1	Ch1	P2	1	10
	SA1	Ch1	P3	1	10
	SA2	Ch2	P2	1	20
	SA2	Ch2	P3	1	10
	SA2	Ch2	P1	1	20
	SA2	Ch1	P1	1	20
	SA2	Ch1	P2	1	20
	SA2	Ch1	P3	1	20
	Ch1	SB	W1	1	20
	Ch2	Re	W1	1	20
	Ch1	Re	W2	1	20
	Ch2	Re	W2	1	20
	SD	SA1	D3	2	10
	SD	SA1	D4	2	10
	SD	SA2	D3	2	10
SD	SA2	D4	2	10	

Table 12- Presentation of the Bill of Materials.

	Product	Used element	Quantity (Unit)
BOM	P1	B	2
	P1	C	3
	P2	B	4
	P2	C	5
	P3	B	1
	P3	C	1
	B	D1	2
	B	D2	1
	C	D1	1
	C	D2	3
	P1	D3	2
	P2	D3	1
	P3	D3	1
	P1	D4	2
	P2	D4	1
	P3	D4	1

4.2.5 Experimental results: exact procedure

The instance problem presented in the previous section has been solved by use of CPLEX solver version 12.6.1 implemented in Java version 8 in a notebook Intel® Core i7 CPU, 2.20 GHz

processor and with 8 GB of the memory. The resolution process contains two phases: the *pre-process phase* and the *main phase*. These phases are explained in the following section:

4.2.5.1 Implementation of a pre-processing phase: results and sensitivity analysis

The main idea of the *pre-process phase* is to define a procedure to modify the activities' earliest start times and latest start times, which are initially estimated by the experts, and provide new efficient bounds which can decrease the complexity of the instance problem to solve to optimality. Having considered mixed-integer programming models, since the complexity of the models is related to the number of the binary-decision variables, (Wolsey and Nemhauser, 2014), reducing the computational efforts for the resolution of complex problems can be obtained by decreasing the total number of binary decision variables. In the proposed mathematical model, the total number of the binary variables of the problem is equal to $N = \sum_{i=1}^I (LT_i - ET_i)$. Therefore, an efficient way to decrease N is to tighten the interval $[LT_i, ET_i]$ for every activity. To achieve this, a two-step algorithm based on linear-programming relaxation is proposed, (Gholizadeh-Tayyar et al., 2014). The first step of the procedure modifies the earliest start of the activities by attempting to raise the corresponding value for each activity as much as possible. On the other hand, the results obtained from the first step for ET_i are used to determine a modified LT_i in the second step. Subsequently, within the second step, the algorithm decreases the value of LT_i for each activity, in order to tighten the bound as much as possible. The pseudo-code of the algorithm (Algorithm 1) is presented in the following:

Algorithm1: Pre-processing phase

Step 1:

1. Relax binary variables Z_{it}
2. **for all** i **do**
3. $ET_i \leftarrow ET_i, LT_i \leftarrow T$
4. **end for**
5. **while** no change between two sequential ET_i
6. **for all** i **do**
7. $OF' \leftarrow$ Minimum S_i subject to constraints 3-2 to 3-30
8. $OF' \rightarrow ET_i$
9. **end for**
10. **end while**

Step2:

11. **for all** i **do**
12. $LT_i \leftarrow LT_i, ET_i \leftarrow ET_i$
13. **end for**
14. **while** no change between two sequential LT_i
15. **for all** i **do**
16. $OF'' \leftarrow$ Maximum S_i subject to constraints 3-2 to 3-30
17. $OF'' \rightarrow LT_i$
18. **end for**
19. **end while**

Table 13 summarizes the results obtained from the pre-processing phase:

Table 13 –Performance of the proposed exact procedure obtained by its application on a set of data.

Activity ID	Activity description	Initial Estimated values		Modified values	
		Earliest start time	Latest start time	Earliest start time	Latest start time
1	Start	7	20	7	16
2	Crane assembly	7	21	7	16
3	Preparing for access	15	21	15	17
4	Building 2, ground floor	16	18	16	18
5	Building 1, ground floor	17	25	17	18
6	Building 3, ground floor	19	27	19	26
7	Building 2, first floor	8	26	17	19
8	Building 1, first floor	9	27	18	19
9	Building 3,first floor	10	28	21	28
10	Building2, second floor	12	29	18	20
11	Building1, second floor	14	27	19	20
12	Crane disassembly	15	28	20	28
13	Building1, annex	7	21	20	21
14	Building2, finishing	18	30	20	30
15	Building1&3, finishing	22	29	22	29
16	Finish	24	31	24	31
17	Start	7	20	7	16
18	Crane assembly	7	21	7	16
19	Preparing for access	15	21	15	17
20	Building 2, ground floor	16	18	16	18
21	Building 1, ground floor	17	25	17	18
22	Building 3, ground floor	19	27	19	26
23	Building 2, first floor	8	26	17	19
24	Building 1, first floor	9	27	18	19
25	Building 3,first floor	10	28	21	28
26	Building2, second floor	12	29	18	20
27	Building1, second floor	14	27	19	20
28	Crane disassembly	15	28	20	28
29	Building1, annex	7	21	20	21
30	Building2, finishing	18	30	20	30
31	Building1&3, finishing	22	29	22	29
32	Finish	24	31	24	31

Resolution Time (s)	
Using Initial Estimated Earliest and Latest Start Times	Using Initial Modified Earliest and Latest Start Times
1265	738

The modified earliest starts and latest starts are used to solve the problem in the *main phase*. The results of the instance problem are presented in Figure 33 - Figure 36.

Figure 33 depicts the Gantt chart of the activities. Although both of the projects are identical in terms of the number of the activities, their activity network structure and data settings, different start and finish dates (which are related to the “Start” and “Finish” activities in the activity list)

ensue. Similarly, other equivalent activities in the projects (for instance, Activity 2 from project Ch1 and Activity 18 from project Ch2) have unequal start and finish dates as well. This difference is due to the fact that the optimization procedure attempts to balance the workload for production, transportation and stock throughout the supply chain network. Indeed, based on the different demand that could be generated at the start of the activities, the supply chain aims to postpone or expedite the activities throughout their feasible time windows, $[ET_i, LT_i]$, so that the total workload is adjusted in the different units of the supply chain network. Furthermore, the different start date for the seminal activities of the projects can stem from the assignment of renewable resources to the activities. In this context, regarding the limited quantity available of renewable resources, since renting a supplementary quantity will cost the system, the model attempts to avoid renting as much as possible and to allocate the renewable resources available for the activities while considering the due dates and the probable penalty cost resulting from late completion of the activities. Therefore, taking the existing constraints in performing the activities into account, the model postpones or expedites the activities in their executive time windows.

Figure 34 summarizes the results obtained for adding renewable resources to the projects over different time periods. The time periods from 14 to 22 of the instance problem present significant numbers for employing supplementary resources. This interval involves the execution of a major number of activities demanding renewable resources. Obviously, the graphs related to the adding of these resources as well as the lateness of the corresponding activities, Figure 35, are dense in this time area. In fact, considering the limitations that exist in the system in terms of limited production, stock and transportation capacity of the supply chain network as well as the time windows of executing the activities, the model allocates the renewable resources that are initially available for the projects and it also adds the supplementary capacities of the resources in order to be able to satisfy the planning constraints and find a solution to achieve optimality. On the other hand, the lateness of the activities in this time interval originates from the intention of the model to find a balance between either delaying the activity or adding renewable resources in some cases of executing the activities as well as the precedence constraints under the wait and no-wait types.

Figure 36 depicts the results obtained for the total transportation and production quantity of different items in the supply chain network as well as the values for the supplementary capacities which are added to the different production/recycling lines. Considering the start time of the project activities, the production and transportation operations of the supply chain network are adjusted accordingly. In this context, taking the production and transportation lead times into account, the procurement of the raw materials and the production of the intermediate products as well as the production and procurement of the final products are done before the start time of the projects. Regarding Figure 36 and the data setting of the problem of the transportation and production lead time of the final products (panels) in Table 8 and

Table 11 as well as the start time of the projects, it is clear that for some of the items (such as the panels), a quantity of them are produced in the former time periods and they are stocked in their manufacturing centers.

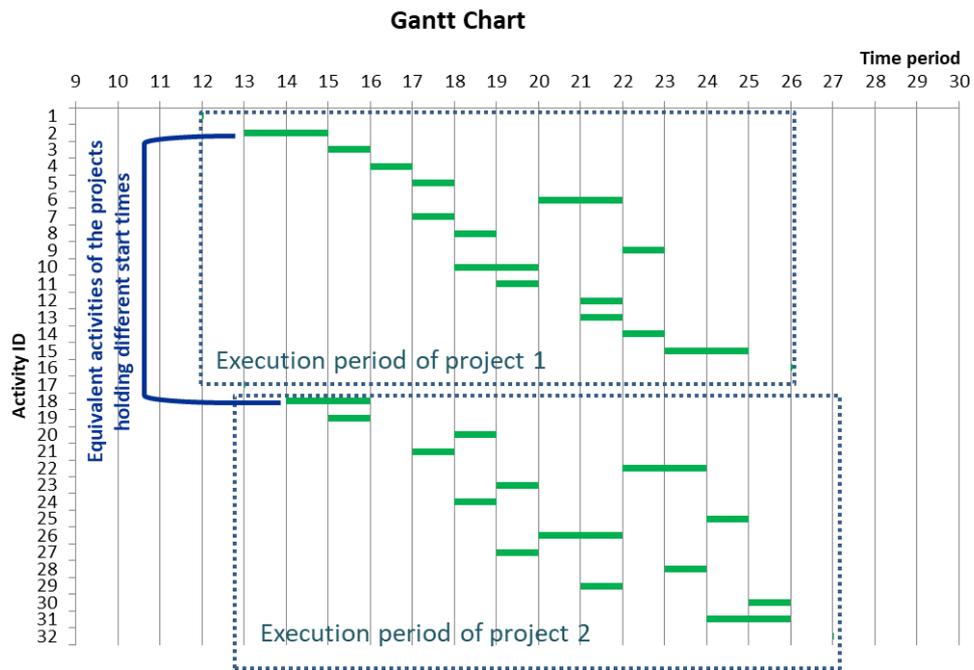


Figure 33- Start and finish dates of the activities.

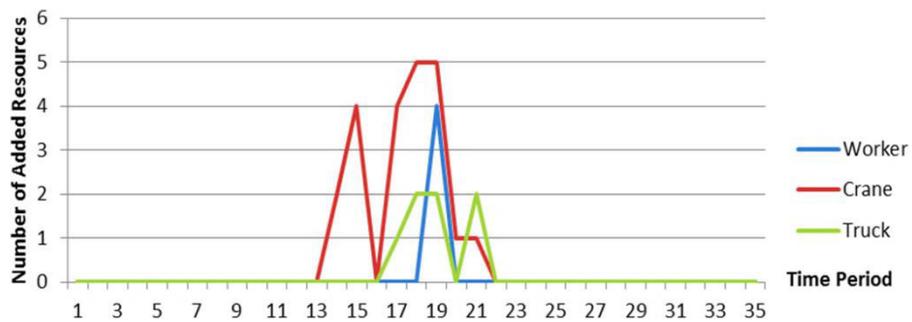


Figure 34- Number of renewable resources added to every time period.

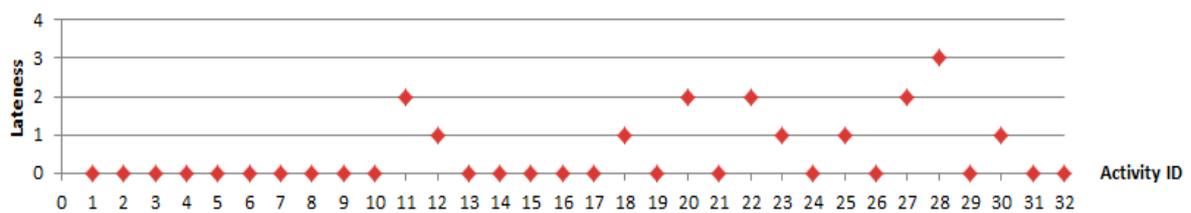


Figure 35- Number of time periods late for the due date for the different activities of the projects.

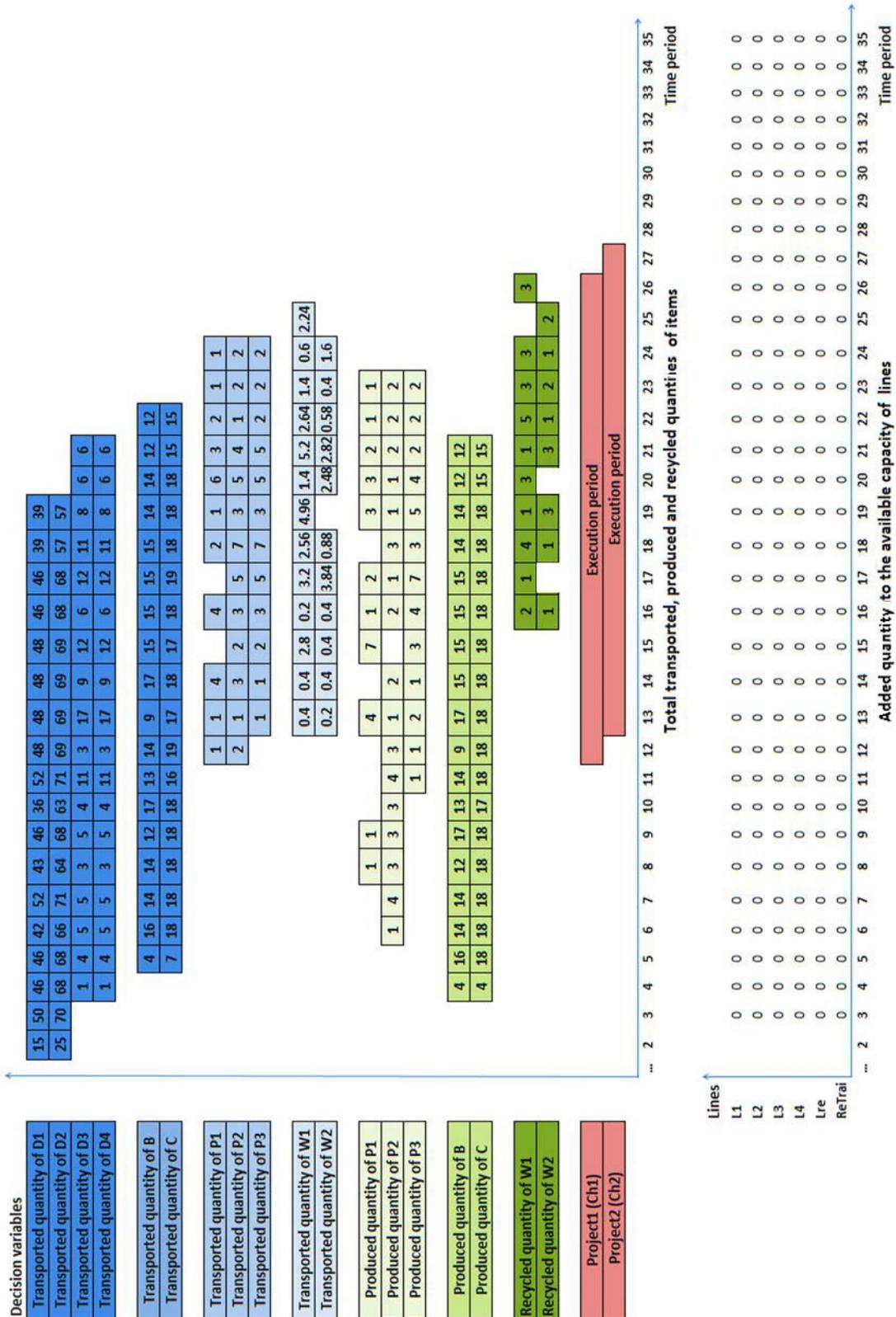


Figure 36- Results for the transported, produced and recycled quantities of every item of the network.

Then, they are gradually allotted to the worksites by the demand generated at the worksites. Similarly, the produced waste is shipped to the recycling centers over different time periods. However, for the most optimum solution, some quantities of waste are stocked at the project worksites (see Figure 36, time period 35 for the transported quantity of waste W1 and W2) and then they are shipped to the proper recycling centers.

However, since the manufacturers of the supply chain networks are selected at the strategic level of planning based on their capacity for production and supply, in the solution of the basic problem, where no risk of losing the production/recycling capacity of the corresponding units is considered, there is no need to add extra production/recycling capacities.

Sensitivity analysis: As an alternative, due to the sensitivity of the optimal solution to the different parameters of the model, the model must be resolved several times with slight variations in the coefficients and parameters of the problem under study, to see its sensitivity to different data before choosing a solution for implementation.

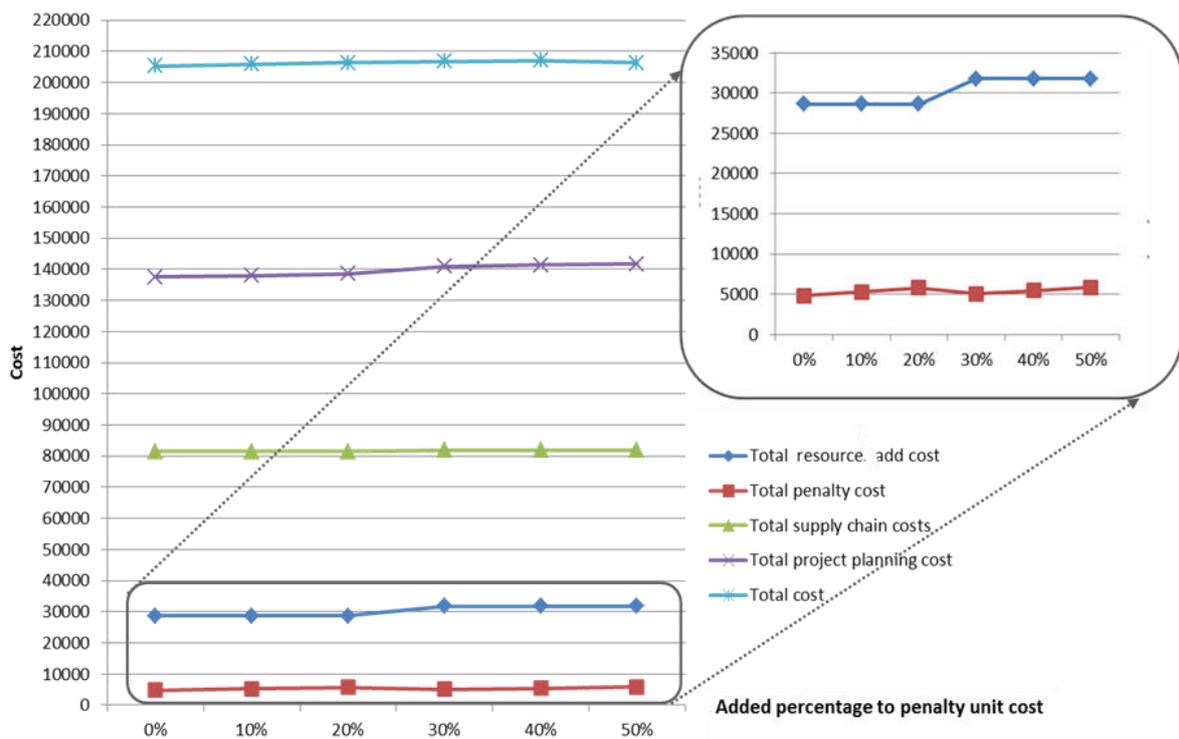


Figure 37- Variation of the total penalty cost and total resource add cost to the variation in unit cost for one period of delay.

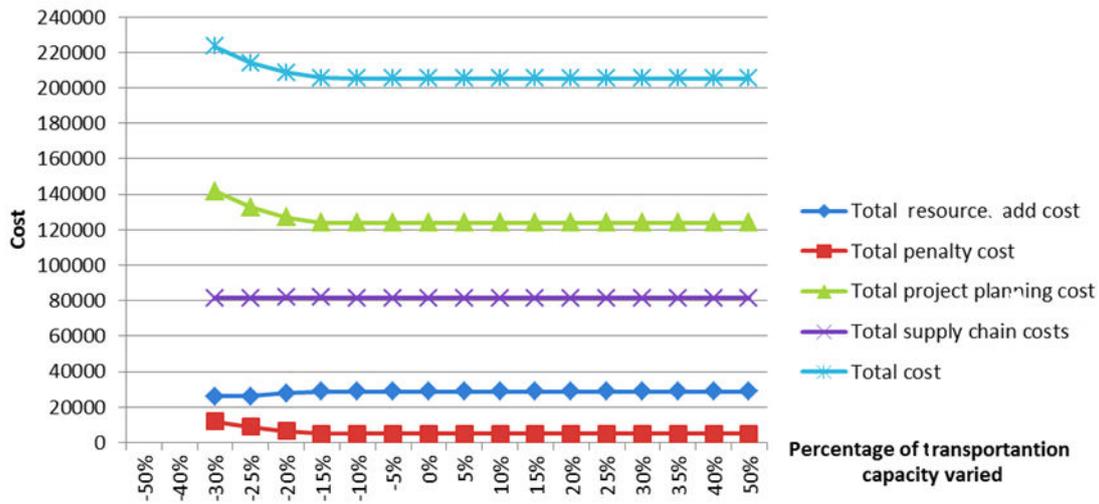


Figure 38- Presentation of the impact of the change in transportation capacity on project planning and supply chain cost.

In keeping with the current instance problem, Figure 37 indicates the variation of the total “penalty cost” and total “resource add cost” to the variation by 50% in the unit cost of the penalty for late completion of the activities. As can be seen from the figure, by increasing the unit “cost of penalty” to 30%, there is an increase in the total cost of adding the renewable resources. Indeed, this matter stems from the fact that the optimization model attempts to employ supplementary resources with the aim of avoiding high penalty costs for late completion of the activities. However, since the behavior of the model depends totally on the characteristics of the activities in the network, in terms of the precedence relations based on wait and no-wait types and also on the limit for the maximum adding of renewable resources, the increase in the unit penalty cost could lead to an increase in the total penalty cost.

Figure 38 depicts the behavior of the model through the change in transportation capacity. As the graph illustrates, reducing the transportation capacity to 40% and 50% less than its initial value does not result in a solution. The reason relates to the matter of the selection of the suppliers and the design of the supply chain network at the higher level of decision making in strategic planning. In fact, in decision making for the design of the supply chain network, the actors of the supply chain have been chosen for their ability to supply the required items. Therefore, having considered this criterion, a large amount of the capacity loss (40-50%) obviously leads the problem to fail in resolution. Decreasing the transportation capacity makes the model start and finish the activities late (the impact of the supply chain as the bottleneck of the system), Table 14. Therefore, in the graph related to the total penalty cost of the model, by decreasing the transportation capacity, the penalty cost for the late completion of the activities and, consequently, the total cost of running the projects increase. However, after the point related to a 15% decrease in transportation cost, the graphs corresponding to the total penalty cost, total resource add cost, total supply chain cost, total project planning cost and, consequently, total cost of the system remain comparatively stable.

Table 14 –Start time, finish time and lateness of the activities at the level of 30%, 20% and 15% in decreases to transportation capacity.

Activity ID	Transport capacity 30% decreased			Transport capacity 20% decreased			Transport capacity 15% decreased		
	Start date	Finish date	Lateness	Start date	Finish date	Lateness	Start date	Finish date	Lateness
	1	13	13	0	13	13	0	12	12
2	14	16	1	14	16	1	13	15	0
3	15	16	0	15	16	0	15	16	0
4	18	19	2	18	19	2	16	17	0
5	17	18	0	17	18	0	17	18	0
6	25	27	5	21	23	1	20	22	0
7	19	20	1	19	20	1	17	18	0
8	18	19	0	18	19	0	18	19	0
9	27	28	4	23	24	0	22	23	0
10	20	22	0	20	22	0	18	20	0
11	19	20	2	19	20	2	19	20	2
12	23	24	3	23	24	3	21	22	1
13	21	22	0	21	22	0	21	22	0
14	28	29	4	24	25	0	22	23	0
15	27	29	3	23	25	0	23	25	0
16	30	30	2	26	26	0	26	26	0
17	12	12	0	12	12	0	13	13	0
18	13	15	0	13	15	0	14	16	1
19	15	16	0	15	16	0	15	16	0
20	16	17	0	16	17	0	18	19	2
21	17	18	0	17	18	0	17	18	0
22	23	25	3	23	25	3	22	24	2
23	17	18	0	17	18	0	19	20	1
24	18	19	0	18	19	0	18	19	0
25	25	26	2	25	26	2	24	25	1
26	18	20	0	18	20	0	20	22	0
27	19	20	2	19	20	2	19	20	2
28	22	23	2	21	22	1	23	24	3
29	21	22	0	21	22	0	21	22	0
30	26	27	2	26	27	2	25	26	1
31	25	27	1	25	27	1	24	26	0
32	28	28	0	28	28	0	27	27	0

The behaviour of the instance problem in the variation in production capacity is presented in Figure 39. Definitely losing production/recycling capacities in the facilities (because of technological problems or production risks) makes the model take positive values for the decision variable related to the quantity of added supplementary capacities to the lines and this subsequently increases the total cost of the system.

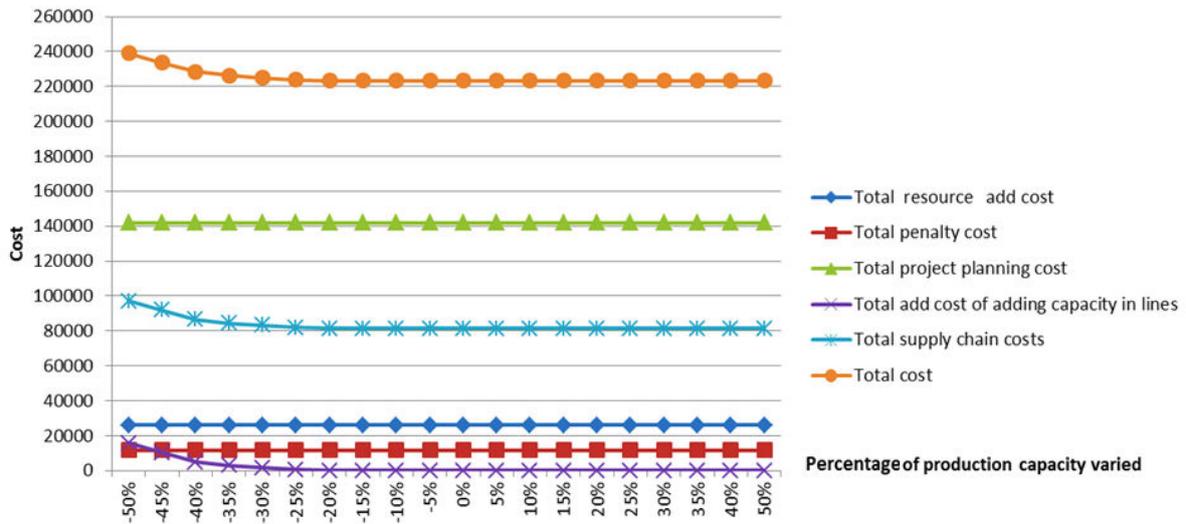


Figure 39- Presentation of the impact of the change in production/recycling capacity on project planning and supply chain cost.

Taking the “*production*” and “*transportation*” capacities as the sensitive parameters of the model, the results of the sensitivity analysis related to these two parameters lead decision makers to choose an alternative. Regarding Figure 38 and Figure 39, the optimal solution for the instance problem can be obtained from the data related to the case of the 15% reduction in transportation capacity. Therefore, modifying the transportation capacity to a 15% decrease can be recommended for the current instance problem. Similarly, a reduction of 20% in production capacity at the manufacturing centers can be proposed to the manufacturers to allow them to reassign this capacity elsewhere.

4.3 Development of a metaheuristic-based solution methodology

This section aims to present a metaheuristic-based search procedure that is applied to the proposed modeling framework. On the basis of study presented in (Tayyar et al., 2016), two main objectives have been taken into consideration in this context. They include *i.* development of a pre-processing phase and *ii.* deployment of the genetic algorithm:

4.3.1 Pre-processing phase

Before adaptation of the genetic algorithm to the model, the pre-processing phase has been delineated and utilized. Its objective is to simplify the method of the search procedure in encountering the modeling framework and enhance the working mechanism of the algorithm in obtaining the results. In general, this phase involves two steps:

a. *Converting a generalized constrained multiple-project scheduling problem to a constrained multiple-project scheduling problem:* In this respect, the precedence relations in the form of start-to-start, start-to-finish and finish-to-finish are reformulated as an equivalent finish-to-start and the start dates of activities are calculated by using the following relations 3-32-3-34:

$$\text{Start date}_j \geq \text{Finish date}_i - \text{Duration}_i + \text{Start to start time lag}_{ij} \quad 3-32$$

To convert a start-to-start precedence to a finish-to-start with wait condition.

$$\text{Start date}_j \geq \text{Finish date}_i - \text{Duration}_i + \text{Duration}_j + \text{Start to finish time lag}_{ij} \quad 3-33$$

To convert a start-to-finish precedence to a finish-to-start with wait condition.

$$\text{Start date}_j \geq \text{Finish date}_i - \text{Duration}_j + \text{Finish to finish time lag}_{ij} \quad 3-34$$

To convert a finish-to-finish precedence to a finish-to-start with wait condition.

It is worth noting that the inequalities 3-32, 3-33 and 3-34 are used in the form of equality in order to convert the no-wait start-to-start, start-to-finish and finish-to-finish to the finish-to-start no-wait precedence.

b-*Deploying Critical Path Method forward-backward passes, in order to correct and rectify the estimated earliest start and latest start of the activities:* Since all the time points belong to the interval from the activities' earliest start to the latest start time initially estimated by the managers, and may not provide the totally right time points to trigger the activities, the forward and backward procedures of the Critical Path Method (seen in Section 2.2.1) are used to correct and modify the estimated bounds and provide new feasible and proper time intervals. In this context, Figure 40 schematizes how a potential time point $t = 15$ from the estimated time window $[ET_i, LT_i]$ for a predecessor activity i could cause a failure in the start of a successor activity j .

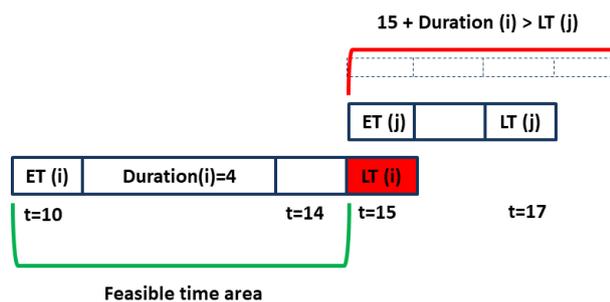


Figure 40- An illustrative example presenting the requirement for applying a forward-backward procedure of the CPM to correct the estimated bounds for execution of activities.

Pursuant to the objectives of modifying the estimated time windows, within this step a permutation of the activities is generated based on the random key representation

concepts seen in Section 2.9.2. The permutation list is transformed into what is called the activity list by applying the precedence constraints. Then, the new modified earliest and latest start dates are attained by deploying the forward-backward paths of the CPM on the activity list. The pre-processing procedure is described below in Algorithm 2:

Algorithm 2 : Pre-processing phase for correcting the initial estimated earliest and latest start time of the activities

1. Convert generalized precedence into finish-to-start relation by use of the expressions seen in Section 4.3.1.a
 2. Generate a permutation list of activities using random key representation
 3. Ordered \leftarrow order the activities based on the precedence relations
 4. **for** all *activity* in Ordered
 5. **if** predecessors of *activity* is not empty
 6. $X \leftarrow \text{duration}(\text{predecessor}) + \text{modified earliest start}(\text{predecessor}) + \text{time-lag predecessor}(\text{predecessor-activity})$
 7. modified earliest start (*activity*) $\leftarrow \max(X, \text{earliest start}(\text{activity}))$
 8. **else**
 9. modified earliest start (*activity*) $\leftarrow \text{earliest start}(\text{activity})$
 10. **endif**
 11. **endfor**
 12. Ordered \leftarrow reverse Ordered from end to start
 13. **for** all *activity* in Ordered
 14. **if** successors of *activity* is not empty
 15. $X \leftarrow \text{modified latest start}(\text{successor}) - \text{duration}(\text{activity}) - \text{time-lag successor}(\text{successor-activity})$
 16. modified latest start (*activity*) $\leftarrow \min(X, \text{latest start}(\text{activity}))$
 17. **else**
 18. modified latest start start (*activity*) $\leftarrow \text{latest start}(\text{activity})$
 19. **endif**
 20. **endfor**
-

4.3.2 Application of the genetic algorithm

After employing the pre-process phase, the approaches of the genetic algorithm are adapted to the problem. This section outlines the principles of the proposed search algorithm through six common questions (seen in Section 2.9), which are involved in the design of metaheuristic-based search procedures:

- 1- *Representation and generation of initial solutions*: Each individual of the algorithm is made up of different arrays and strings. Every part of the individual is used to save the results for different knowledge for a solution. This knowledge may include either the values of the decision variables, here, the decision variables of the supply chain planning and project scheduling, or specific information of a solution, such as the “ActivityPermutation” within

this study. In this context, it is worth mentioning that “ActivityPermutation” is a permutation of the activities built upon random key representation approaches. This list is used in the main procedure of the algorithm to determine the start date of the activities. The representation of a typical individual of the genetic algorithm in this study has been illustrated in Figure 41.

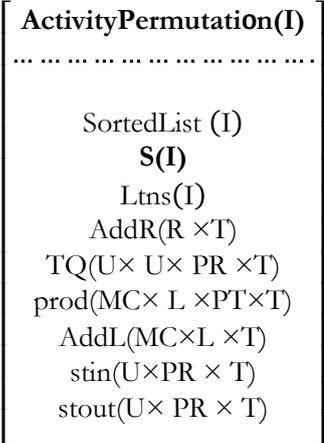


Figure 41- Presentation of an individual in the search algorithm with its key arrays.

The key element of the chromosome (arrays in boldface in the chromosome representation), on which the working mechanism of the search algorithm relies, is related to the part that determines the feasible start date for the activities. Indeed, the main intention of the search procedure is to define the feasible start dates for the activities of the projects in interaction with project planning constraints and supply chain constraints (generally transportation and production capacity constraints of the forward supply chain and the constraints related to the balance of the flows) and then to propagate the impact of the generated schedules into the resolution procedure throughout the algorithm. Figure 42 describes this mechanism.

As shown in the figure, the start dates of the activities that have been generated by considering the project planning constraints are verified throughout the production and transportation capacities of the forward supply chain network. In the cases where the generated start dates lead to the creation of demands that cause the transportation and total available production capacity of the forward supply chain network to be exceeded, the schedule of the activities are recalculated until an appropriate one that meets the production and transportation capacities is obtained. Obviously, with this strategy the generated schedules ultimately satisfy the constraints on executing the activities at the worksites under the project scheduling constraints as well as the forward supply chain network capacity limitations (output of **Step 1**, beginning of **Step 2**). Once such an admissible date has been determined, the other variables of the chromosome related to the production, stock and transportation of the items from the downstream (worksites of the projects) to the upstream supply chain (suppliers of the raw materials) are calculated and stored in the corresponding alleles (output of **Step 2**). At the next step, the algorithm seeks to determine

the feasible values for transportation of the waste which is generated at the worksites of the projects in order to recycle it in the proper recycling centers (output of **Step 3**). And the last step of the algorithm, (**Step 4**), calculates the lateness of the activities and the added quantity of renewable resources.

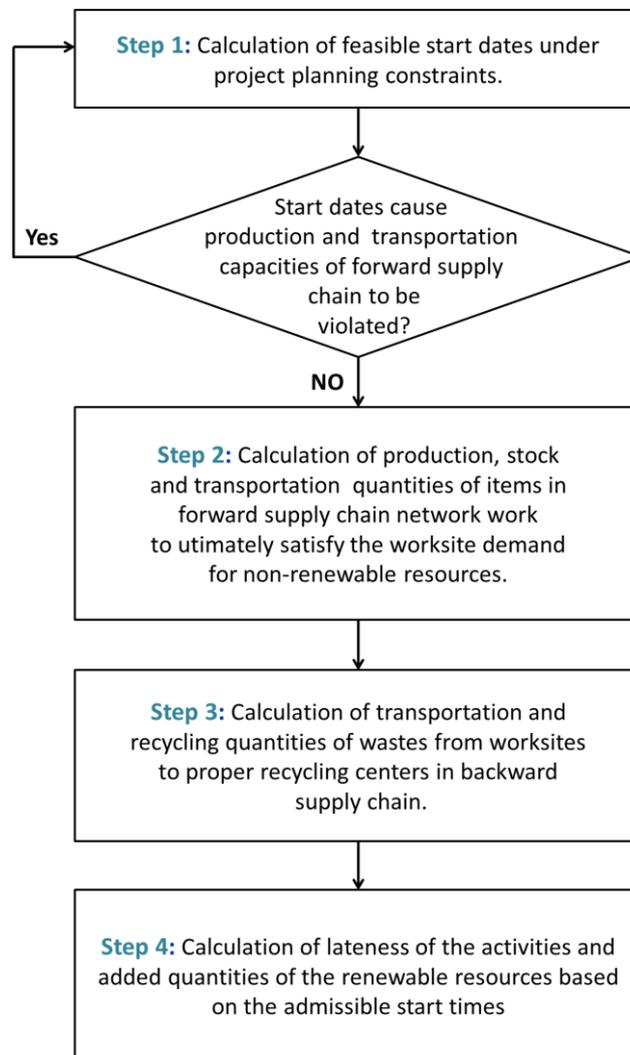


Figure 42- General working mechanism of the search procedure.

Regarding Figure 42, with the aim of generating the feasible start dates within **Step 1**, the procedure fundamentally uses the concept of random key representation. In this context, once a permutation of the activities has been generated, the “activity list” (denoted as SortedList in the chromosome) of the problem is formed on the basis of the permutation list by exerting the precedence constraints. Then, the Serial Scheduling Generation Scheme (SSGS), seen in Section 2.7.2.1, is used and adapted to the activity list in order to define the feasible start dates. It is worth mentioning that the determination of the feasible start dates

using the SSGS follows some principles that are developed in the course of this study to respond to the execution and scheduling circumstances of the activities. These principles can be seen in three major points: *i. execution time windows of the activities*: the start date of the activities must be in a time point from its modified earliest time to its modified latest start time. *ii. no-wait conditions*: the no-wait activities in the precedence relation must be performed immediately after their predecessors have been completely accomplished. In the cases where the available quantity of renewable resources is not sufficient, the required amounts are added to the resource portfolio. *iii. wait conditions*: the activities under wait conditions have the possibility of being started when their required renewable resource are totally on hand during their execution time. Nevertheless, in the situations where the renewable resources are not sufficiently available over the time windows (the time interval from the modified earliest start to the modified latest start), the missing quantities could be rented and added to the resource pool at any time point. Therefore, in order to specify a deterministic time point for the start of the activity, a compromise is made between delaying the activities and paying for added renewable resources. To do so, the algorithm calculates a “cost indicator” to decide which time would be less expensive in relation to the activity. This indicator for a presumed time point t is built up by calculating the total cost of adding the resources at time t over the processing time of the activity plus the penalty cost for late completion of the activity plus an inner penalty cost which penalizes the time t in which the added quantity of the resources exceeds the limitation in maximum addable value of the resources. Finally, out of the candidate time points, the time that holds the minimum value of the cost indicator is selected to be assigned to the activity as its start time. The pseudo code of the algorithm has been described below:

Algorithm 3: Determination of start dates for the activities

Step 1 of Figure 42:

1. Generate a permutation list of activities using random key representation
2. $OrderedList \leftarrow$ order the activities based on the precedence relations
- for** $activity$ in $OrderedList$
3. **if** predecessors of $activity$ is not empty
4. **for** all $predecessor$ of $activity$
5. finish time \leftarrow calculate finish time for predecessors of $activity$
6. $t \leftarrow \max(\text{finish time}, \text{modified earliest start}(activity))$
7. **endfor**
8. **else**
9. $t \leftarrow \text{modified earliest start}(activity) + \text{rand}(\text{modified latest start}(activity) - \text{modified earliest start}(activity))$
10. **endif**
11. wait=true
12. **if** any predecessors of $activity$ is no-wait
13. wait=false

```
14.   endif
15.   renewable resource is enough=true
16.   if demand of (activity) exceeds the resource availability from t to t +
      duration(activity)-1
17.     renewable resource is enough=false
18.   endif
19.   if wait=false
20.     if renewable resource is enough=true
21.       start time(activity) = t
22.       finish time ← calculate the finish time of activity
23.       update the availability of the resources
24.     endif
25.     if renewable resource is enough=false
26.       start time(activity)= t
27.       finish time ←calculate the finish time of activity
28.       add the required quantity of the renewable resources
29.     endif
30.   endif
31.   if wait=true
32.     if renewable resource is enough=true
33.       start time(activity)=t
34.       finish time ← calculate the finish time of the predecessors of activity
35.       update the availability of the resources
36.     endif
37.     if renewable resource is enough=false
38.       for t' =t to modified latest start(activity)
39.         Y ← Calculation of the cost indicator for t'
40.         start time(activity) ← find time point related to minimum(Y)
41.         finish time ← calculate the finish time of the predecessors of activity
42.         update the availability of the resources
43.       endfor
44.     endif
45.   endif
```

Step 2 deals with the planning of the supply chain network which is supposed to be measured level by level, from the worksites to the manufacturers and then to the suppliers of the raw materials. The general ideas of the definition of the search procedure in this step rely on the research work of (Dellaert et al., 2000). In this context, in every time period the total demand of the worksites for each type of non-renewable resource, which has been generated by the start of the activities, is calculated. Taking the transportation lead time to ship a typical non-renewable resource from its manufacturer to the worksite into account, the calculated amount of the resource demanded is transported to the project worksites using just-in-time. The demand is divided into random values among the manufacturers of the non-renewable resources (flows ending at the worksite which is carrying the product

from its potential origins) in a way so that the sum of the associated values with the flows is equal to the value of the demand; that is to say, the satisfaction of the demand.

In order to initialize the values for the stock (stock of outputs denoted by *stouts*) of the items in the corresponding actors of the supply chain network (for instance, in the manufacturing center), it is presumed that a random fraction of the generated demand (from the worksite of a project) at time t for the consumable resources (i.e. demand * random value between 0 and 1) can be produced in supplement at time t minus the production lead time and stocked in the manufacturing units. These created stocks can be used in the following time periods while the stock at the end and beginning period of the planning horizon has to be kept to zero. The stock of inputs (denoted by *stin* in the model) will be calculated on the basis of the bill of materials taking into account the supplementary quantities of the products that are created and stocked. This impact of generating the stocks will be imposed upon the actors of the supply chain network from the downstream manufacturers to the upstream ones.

Relying on the information from the bill of materials and the probable stocks, the workload for the transportation of the intermediate products as well as the raw materials and the production of the products on the production lines of the factories are determined for all the potential actors that can supply and produce the required items while considering the associated production and transportation lead times. If these workloads cause the transportation and production capacities of the manufacturers (as well as the supply capacity of the raw material suppliers) to be violated, the created start time for the activities will be rejected and the search algorithm will try to generate another solution (schedule) which satisfies these capacity constraints as well. Once such schedules are determined, the demand of the worksites will be divided among the potential manufacturers for their production and transportation while taking into account the production and transportation lead times. Similarly, the production and transportation of the required intermediate products and raw materials will be regarded by the potential manufacturing centers and suppliers of the raw material taking into account the transportation and production lead times.

As with Step 2, in **Step 3**, the potential destinations for sending the waste are proposed and a random fraction of the generated waste is divided among the potential flows while the transportation for the shipments of the waste from the worksite to the selected recycling center has been considered. Then, the transported quantities are assigned to the proper recycling lines at the destinations taking the recycling time into account.

In the last step, **Step 4**, the lateness of the activities and the total quantity of the added renewable resources have been calculated and saved in the chromosome. The pseudo code of these processes is provided in the following:

Algorithm 4: Planning for a closed-loop supply chain problem, the lateness of activities and the value of the added renewable resources

Step 2 of Figure 42:

1. **for** each *worksite* to worksites
2. **for** each *nr* to non-renewable resources
3. **for** each *t* to time
4. calculate demand of *worksite* for *nr* at time *t*
5. find origins that can supply the demand
6. **for** origin to origins
7. considering the transportation lead-time, assign random division of the demand to transportation from origin
8. extra=random fraction of demand
9. **if** $t > \text{start time}(\text{last activity of } \textit{worksite} \text{ that consumes } \textit{nr})$
10. extra=0
11. **endif**
12. considering production lead-time, assign the value of (demand) + (extra) – (available stock from the former time period) to production
13. calculate value of supplementary production capacity if necessary
14. calculate workload of the current solution on the supply chain (calculation for transportation of the required quantities from the potential upstream actors of the supply chain to origin and calculation for supplementary production capacities)
15. **while** workload of the current solution exceeds the capacities
16. reject the solution
17. generate a new schedule
18. retrieve the results from 4. to 13.
19. **endwhile**
20. **endfor**
21. **endfor**
22. **endfor**
23. **endfor**

Step 3 of Figure 42:

24. **for** each *worksite* to worksites
25. **for** each *w* waste
26. **for** each *t* to time
27. calculate generated waste *w* at *worksite* at time *t*
28. find destinations can receive the waste
29. **for** *destination* to destinations
- considering the transportation lead-time, assign random division of
- the generated waste to transportation of *w* to *destination*
- considering the recycling lead-time, assign the value of the transported waste to recycled quantity

```
30.             calculate value of supplementary production capacity if necessary
31.         endfor
32.     endfor
33. endfor
34. endfor
35. Retrieve the value of start time for activities
```

Step 4 of Figure 42:

```
36. for activity in activities
37.     calculate the lateness of activity
38. endfor
39. for t in time
40.     for r in renewable resources
41.         calculate the value of added r at t
42.     endfor
43. endfor
```

- 2- *Cost (fitness) function:* The fitness of the generated solutions is evaluated by their cost. The fitness function of the algorithm includes two terms: *i.* the cost of the solution, which is equal to the value of the objective function for the solution and *ii.* the penalty cost, for the individuals that are infeasible. It is worth mentioning that the infeasible solutions of the algorithm are penalized according to their degree of violation: see equations 2-30 and 2-31 from chapter 2. In this regard, in the cases where a low (small) degree of violation has been reached, the penalty terms will slightly increase the value of the cost function. Therefore, the fitness of the solution will be slightly decreased. In contrast, the penalty terms will significantly increase the value of the cost function when reaching a high degree of violation. In addition, the corresponding constant multipliers of the penalty terms are set to large-enough constant values according to the importance of their corresponding constraints on the instance problems. The seminal works on the application of the penalty terms in calculating the fitness function can be seen in (Xie and Dong, 2002) (Alba and Francisco Chicano, 2007) (Chang et al., 2010) (Fahimnia et al., 2012) (Lin, 2013) (Kong et al., 2015).
- 3- *Search operators:* After creating a set (population) of the solutions (individuals) and the calculation of the cost function for each of the individuals, the genetic algorithm uses the crossover operator to combine the contents of two parents in order to generate two new solutions. However, not all the individuals can participate in the reproduction; only the fittest ones (i.e. the elite solutions) are selected for this purpose. The selection of the elite solutions is made by the “selection operators”. One of the most widely used operators, which is utilized in this study as well, is known as the roulette wheel (Srinivas and Patnaik, 1994) (Maulik and Bandyopadhyay, 2000). By employing the roulette wheel, the fitness value is utilized to associate a probability of selection with each of the individuals (Holland,

1975). In this concept, if f_i is the fitness of individual i , its probability of being selected as an individual is equal to $p_i = f_i / \sum_{j=1}^N f_j$, where N is the number of individuals in the population.

It is worth noting that since the key element of an individual in the genetic algorithm adapted to this problem relates to the arrays defining the start time of the activities, the crossover operator is performed on the main string that results in calculating the start dates, that is, the permutation list of activities. In this regard, order 1 crossover, as one of the most successful operators in the literature (denoted by OX1) has been utilized to perform the reproduction (Starkweather et al., 1991) (Tseng and Liang, 2006). Using this operator, each of the new solutions (offspring/children) inherits the elements between the two crossover points from the corresponding parent in the same position as they are placed in the parent's gene. The remaining elements are taken from the other parent in the order in which they emerge in that parent, starting from the first position following the second crossover point and ignoring the elements that have already been presented in the offspring, Figure 43.

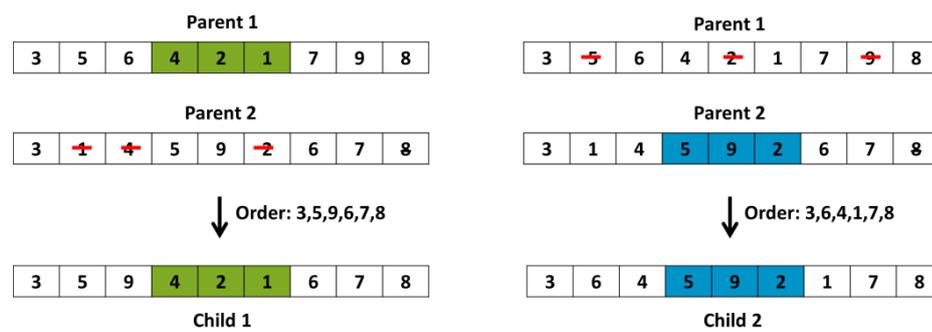


Figure 43- Illustration of the OX1 crossover operator.

As well as crossover operators, mutation operators have been used in order to create a possibility for the algorithm to move from a current solution to one of its neighbors. Getting the permutation list of the activities as the decisive part of the chromosome, a hybrid mutation operator between the swap, reversion and insertion operators has been exploited. The swap operator chooses two genes from the chromosome at random and it swaps their values, as shown in Figure 44, (Moon et al., 2002). The inversion operator selects a part of the chromosome and it orders the element of the selected part inversely, (Fogel and Atmar, 1990) and (Albayrak and Allahverdi, 2011). The insertion operator specifies two genes of the chromosome. Without changing the order, it replaces the one next to the other, (Fogel, 1988). These mechanisms are schematized in Figure 44.

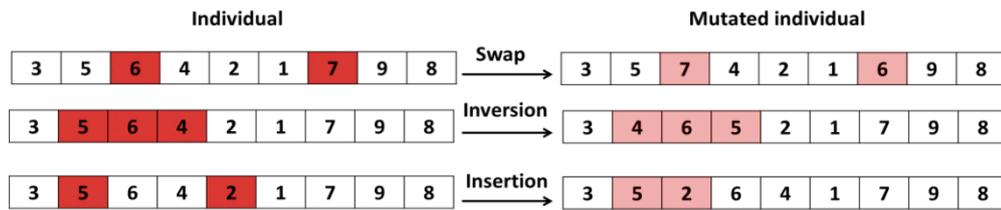


Figure 44- Illustration of the swap, reversion and insertion mutation operators.

It is worth mentioning that in order to manage the size of the population in the algorithm, the new individuals are added to the current population list. Then, all the individuals are sorted according to their fitness value. The fittest individuals are selected to form the members of the new population while the size of the population is kept equal to the number of the population size.

- 4- *Constraint handling*: As pointed out in Section 2.9.2, several methods such as the rejection, repair and penalization approaches have been used for handling constraints. As seen in (Orvosh and Davis, 1993) and (Chang, 2008), the advantage of the rejection and repair strategies is that only feasible solutions are generated in the search process. However, for highly constrained problems, these methods could make the resolution process difficult and inefficient in finding solutions. Furthermore, they may cause a strong bias toward the repaired local solution space. In order to eliminate these difficulties, penalization approaches have been used to deal with highly constrained problems.

The constraints of the problem are divided into two main categories involving soft constraints and hard constraints. The soft constraints are allowed to violate, and be fined by, the penalty terms within the fitness function whereas the hard constraints are supposed to be strictly respected without any violation. The soft constraints of the model involve: 1-The stock capacity in the forward supply chain and 2-The capacity constraints of the backward supply chain network.

The hard constraints include the following constraints: 1- Each activity should be executed exactly between its earliest and latest start time. 2- The precedence and resource constraints of the projects should be met. 3- The interruption of the activities is not allowed. 4- The no-wait activities must be started immediately after their predecessor activities have accomplished. 5- The demand of the worksites for non-renewable resources must be satisfied with a just-in-time approach. 6-Considering the transportation and production lead times, the required raw material and intermediate products should be supplied to their destinations of use in the required quantity. 7- The production workload must not exceed the initial available production capacity plus the maximum capacity which could be added. 8-The stock of the incoming and outgoing items in the supply chain actors should be equal to zero at the beginning and the end of the planning horizon.

According to the points that have previously been presented in “*Representation and generation of initial solutions*”, besides the rejection-repair approaches, penalization methods have been exploited to tackle the soft constraints of the problem.

- 5- *Stop criteria*: the stop criterion of the algorithm has been defined in the number of iterations. Therefore, once a maximum number of repetitive runs of the algorithm is reached, the procedure terminates.

Figure 45 summarizes the search procedure of the algorithm.

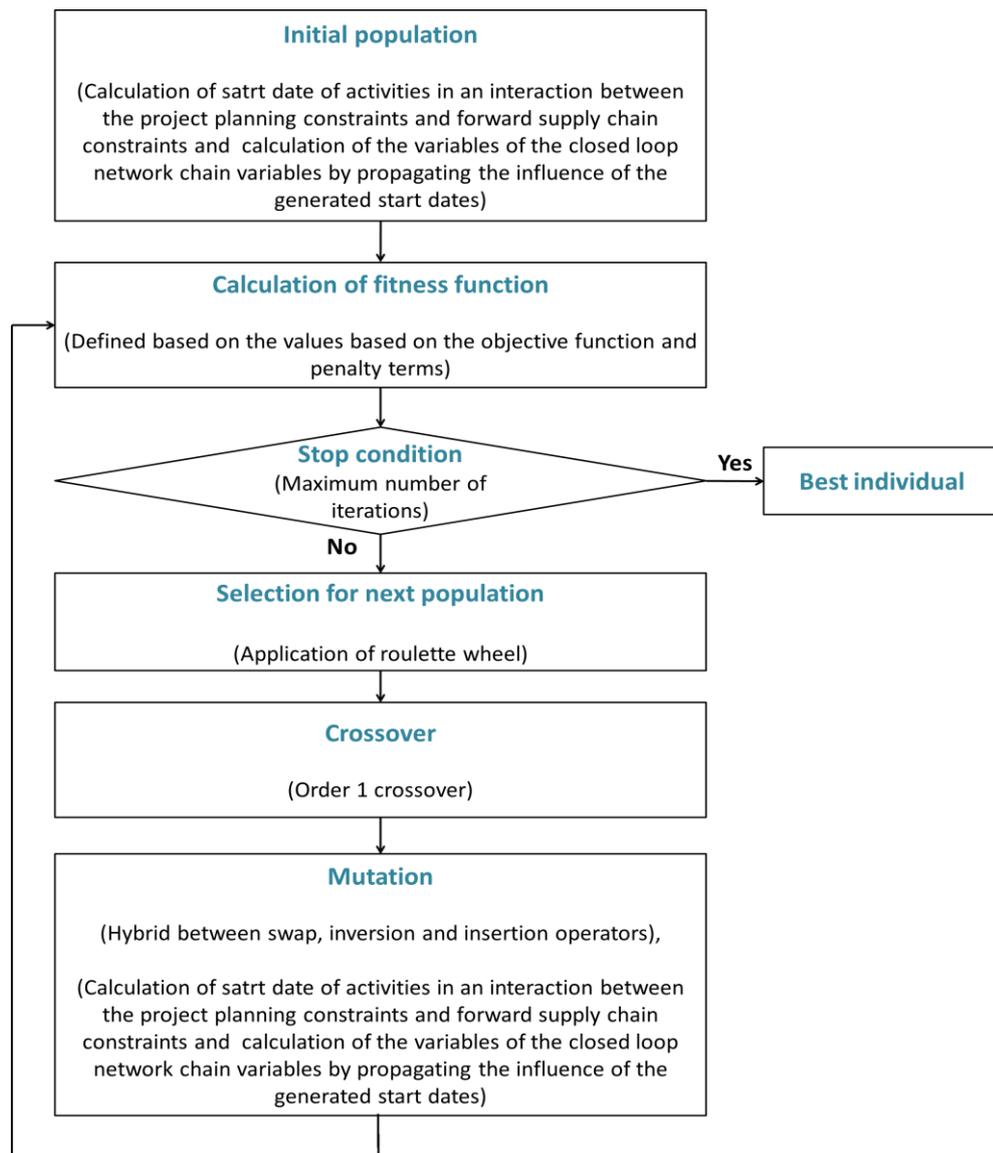


Figure 45- Flowchart of the GA adapted to the model.

6- *Parameter tuning (setting)*: As seen in Section 2.9.2, the performance of the metaheuristics depends to a significant extent on the values of their parameters. On the basis of the various values (levels) that every parameter (factor) of the algorithm could potentially hold, the aim of the parameter design is to assign the optimal values to the parameters so that they ultimately lead the algorithm to a high level of performance and make it robust against noise and variations. Instead of performing the full factorial experimentation for the design of the parameters, in which the responses (outputs of the algorithm) are used for all possible combinations of factors at their potential levels through $M = \text{Number of levels}^{\text{Number of factors}}$ experimentation, the fractional factorial experimentation has been brought into view. In fact, within fractional factorial experimentation, due to the time and cost, only a reasonable part of the experimentation has been chosen for stating the behaviour of the system (here, the algorithm). One of the methods that has been developed to support fractional factorial experimentation is the Taguchi method, (Taguchi, 1986). The Taguchi method relies on two main concepts: *i.* orthogonal arrays and *ii.* Signal-to-Noise ratio. The inclusion of orthogonal arrays in the Taguchi model allows the method to take a large number of influencing factors at their different levels into account and to conduct a limited number of experiments by considering the sufficient preservation of the information. Therefore, assuming a system in which four factors and three levels of value for the factors are encountered, instead of performing $3^4 = 81$ experiments, 9 experiments have been proposed according to the array L9 (3^{**4}) of the orthogonal arrays in the Taguchi model. Since in the present study, the algorithm possesses four factors which include the size of the population, the number of iterations, the crossover rate and the mutation rate, and also three different levels containing upper value, medium value, and lower value, therefore, the orthogonal array L9 (3^{**4}) is the proper array for the current application. This array is utilized in Table 17 - Table 19.

On the other hand, the signal-to-noise ratio in the Taguchi model measures the robustness of the responses. In this context, the term *signal* is introduced to measure the values of the responses (response variable) whereas the term *noise* measures the variability in the responses and represents the undesired components (standard deviation). By merging the signal and noise factors, the Signal-to-Noise (S/N) ratio is employed as a unified measurement for determining the robust values for the design factors, (Hajiaghahi-Keshteli et al., 2014). In this study, since the problem is related to minimizing the objective function, idiomatically “the smaller value is better”. Referring to the literature on the Taguchi method, for the cases where “the smaller is better”, the signal-to-noise indicator is calculated by using formulation 3-35:

$$S/N = -10 \log (\sum_i Y_i^2 / n) \quad 3-35$$

In the equation, Y holds the value of the response factor and n is equal to the number of experiments.

Using the signal-to-noise ratio, it is important to note that in training the algorithms, when different features may influence the algorithms' performance, the results might be completely dominated by the magnitude of the responses in their range. Therefore, it is recommended that the response values of the algorithm be normalized in order to bring all of the variables into proportion with one another. In the literature on scheduling problems (Gangadharan and Rajendran, 1993) (Ruiz and Stützle, 2007) and (Vallada and Ruiz, 2011) have used the Relative Percentage Deviation (RPD) index for rescaling the response values by the use of the expression 3-36:

$$\text{Relative Percentage Deviation (RPD)} = \frac{|\text{Response}_{\text{Algorithm}} - \text{Response}_{\text{Best}}|}{\text{Response}_{\text{Best}}} \times 100 \quad 3-36$$

In the formula, $\text{Response}_{\text{Algorithm}}$ stands for the values resulting from the algorithm in the given experiment and $\text{Response}_{\text{Best}}$ is the best response value that is obtained from any experiment of the instance problems.

4.3.3 Instance problems and design of the parameters

To illustrate the application of the proposed solution procedure and its effectiveness in the resolution of the test problems, three sizes of the problem including small, medium and large have been developed. The dimensions of the instances and the pattern for their data setting have been presented in Table 15. In addition, the levels of the GA parameters for each of the instances are outlined in Table 16.

Using Table 15 and Table 16, the Taguchi experiments have been carried out. The numerical results of this application for the different test instances have been presented in Table 17 through Table 19.

Table 15-Generation of random data for problem instances.

Parameters	Problem size		
	Small ($16^{*I} \times 3^{*R} \times 3^{*NR} \times 35^{*T}$)	Medium ($32 \times 4 \times 3 \times 35$)	Large ($64 \times 4 \times 3 \times 35$)
$Dnr_{i,nr}$:	$DU^* \sim (0, 2)$	$DU \sim (0, 3)$	$DU \sim (0, 4)$
Dr_{ir} :	$DU \sim (0, 2)$	$DU \sim (0, 5)$	$DU \sim (0, 10)$
FS_{ij} :	$DU \sim (0,1)$	$DU \sim (0,1)$	$DU \sim (0,2)$
SS_{ij} :	$DU \sim (0,1)$	$DU \sim (0,1)$	$DU \sim (0,2)$
SF_{ij} :	$DU \sim (0,1)$	$DU \sim (0,1)$	$DU \sim (0,2)$
FF_{ij} :	$DU \sim (0,1)$	$DU \sim (0,1)$	$DU \sim (0,2)$
Ar_r :	$DU \sim (2,7)$	$DU \sim (5,10)$	$DU \sim (10,20)$
Max_r :	$DU \sim (2,12)$	$DU \sim (5,25)$	$DU \sim (10,50)$
Pc_w :	$U^* \sim (2000,2500)$	$U \sim (2200,2700)$	$U \sim (2400,2900)$
$Cc_{r,w}$:	$U \sim (1100,1400)$	$U \sim (1100,1400)$	$U \sim (1100,1400)$
Rc_r :	$U \sim (120,1400)$	$U \sim (120,1400)$	$U \sim (120,1400)$
$Penc_i$:	$U \sim (250,350)$	$U \sim (250,350)$	$U \sim (250,350)$
$StinCap_u$:	$U \sim (0,30)$	$U \sim (0,60)$	$U \sim (0,120)$
$StoutCap_u$:	$U \sim (1,25)$	$U \sim (2,50)$	$U \sim (4,100)$
$TnCap_u$:	$U \sim (5,50)$	$U \sim (10,100)$	$U \sim (20,200)$
$LAvCap_{line(l,mc)t}$:	$U \sim (1,25)$	$U \sim (2,60)$	$U \sim (4,100)$
$MaxAdd_{line(l,mc)}$:	$U \sim (2,25)$	$U \sim (5,50)$	$U \sim (10,70)$
$Wl_{pt,l}$:	$U \sim (1,2)$	$U \sim (1,2)$	$U \sim (1,2)$
$Tc_{f(o,d,p)}$:	$U \sim (10,20)$	$U \sim (10,20)$	$U \sim (10,20)$
$Tl_{f(o,d,p)}$:	$U \sim (0,2)$	$U \sim (0,2)$	$U \sim (0,2)$
$Pl_{pro(l,mc,pt)}$:	$U \sim (0,1)$	$U \sim (0,1)$	$U \sim (0,1)$
$StinC_{pr}$:	$U \sim (0.2,20)$	$U \sim (0.2,20)$	$U \sim (0.2,20)$
$StoutC_{pr}$:	$U \sim (0.2,20)$	$U \sim (0.2,20)$	$U \sim (0.2,20)$
$StCof_{pr}$:	$U \sim (1,2)$	$U \sim (1,2)$	$U \sim (1,2)$
$ProdC_{pt}$:	$U \sim (1,300)$	$U \sim (1,300)$	$U \sim (1,300)$
$AddCL_{line(l,mc)}$:	$U \sim (60,300)$	$U \sim (60,300)$	$U \sim (60,300)$
$V_{b(p,p)}$:	$U \sim (1,5)$	$U \sim (1,5)$	$U \sim (1,5)$
Gp_{gi} :	$U \sim (0,2.8)$	$U \sim (0,2.8)$	$U \sim (0,2.8)$

*I: number of activities, *R: number of renewable resources, *NR: number of non-renewable resources and *T: number of time periods

DU^* : Discrete uniform distribution, U^* : Continuous uniform distribution

Table 16- Levels of the Taguchi design for different factors of the instance problems.

Factor	Number of levels	Project size		
		Small	Medium	Large
Population size (Npop)	3	Npop(1)=20 Npop(2)=25 Npop(3)=30	Npop(1)=70 Npop(2)=85 Npop(3)=100	Npop(1)=150 Npop(2)=175 Npop(3)=200
Maximum number of iterations (NIt)	3	NIt(1)=25 NIt(2)=30 NIt(3)=35	NIt(1)=80 NIt(2)=90 NIt(3)=100	NIt(1)=180 NIt(2)=195 NIt(3)=210
Crossover rate (CrR)	3	CrR(1)=0.6 CrR(2)=0.7 CrR(3)=0.75	CrR(1)=0.65 CrR(2)=0.75 CrR(3)=0.8	CrR(1)=0.75 CrR(2)=0.8 CrR(3)=0.85
Mutation rate (MuR)	3	MuR (1)=0.2 MuR (2)=0.25 MuR(3)=0.3	MuR(1)=0.2 MuR(2)=0.3 MuR(3)=0.35	MuR(1)=0.2 MuR(2)=0.35 MuR(3)=0.4

In the tables, the column “factor levels” presents the values set to the parameters of the algorithm using the design information of “orthogonal array levels” provided in the Taguchi method. The column “response value” shows the fitness value of the best solution found by the procedure in the experiment. On the basis of the obtained response values, the RPD is calculated and listed in the “RPD” column. The time elapsed for terminating the search procedure in the experiment is represented in the last column.. To present the convergence of the algorithm in the different sizes of the model, the graphs depicting the fitness value through the iterations of the algorithm have been created. Figure 46 shows three graphs related to the conducted instances.

Table 17 -Taguchi experiments for small-size problem instances.

Problem size: Small											
Experi- ment	Orthogonal array levels				Factor levels				Response value	RPD	Time (s)
	Npop	NIt	CrR	MuR	Npop	NIt	CrR	MuR			
1	1	1	1	1	20	25	0.6	0.2	91596,52	0	18
2	1	2	2	2	20	30	0.7	0.25	91596,52	0	21
3	1	3	3	3	20	35	0.75	0.35	91896,52	0.326454	27
4	2	1	2	3	25	25	0.7	0.35	91596,52	0	23
5	2	2	3	1	25	30	0.75	0.2	91896,52	0.326454	27
6	2	3	1	2	25	35	0.6	0.25	91896,52	0.326454	29
7	3	1	3	2	30	25	0.75	0.25	91596,52	0.326454	28
8	3	2	1	3	30	30	0.6	0.35	91596,52	0	32
9	3	3	2	1	30	35	0.7	0.2	91596,52	0	38

Table 18-Taguchi experiments for medium-size problem instances.

Problem size: Medium											
Experiment	Orthogonal array levels				Factor levels				Response value	RPD	Time (s)
	Npop	NI _t	CrR	MuR	Npop	NI _t	CrR	MuR			
1	1	1	1	1	70	80	0.65	0.2	215848.04	1.9017745	414
2	1	2	2	2	70	90	0.75	0.3	215848.04	1.9017745	590
3	1	3	3	3	70	100	0.8	0.35	214528.04	1.2786030	705
4	2	1	2	3	85	80	0.75	0.35	215443.04	1.7105742	620
5	2	2	3	1	85	90	0.8	0.2	214528.04	1.2786030	712
6	2	3	1	2	85	100	0.65	0.3	214963.04	1.4839664	691
7	3	1	3	2	100	80	0.8	0.3	211819.70	0	727
8	3	2	1	3	100	90	0.65	0.35	215848.04	1.9017745	756
9	3	3	2	1	100	100	0.75	0.2	214963.04	1.4839664	804

Table 19-Taguchi experiments for large-size problem instances.

Problem size: Large											
Experiment	Orthogonal array levels				Factor levels				Response value	RPD	Time (s)
	Npop	NI _t	CrR	MuR	Npop	NI _t	CrR	MuR			
1	1	1	1	1	150	180	0.75	0.25	423143.4	0.345930	2697
2	1	2	2	2	150	195	0.8	0.35	421852.3	0.039753	3527
3	1	3	3	3	150	210	0.85	0.4	422890.316	0.285912	4431
4	2	1	2	3	175	180	0.8	0.4	427379.733	1.350551	4210
5	2	2	3	1	175	195	0.85	0.25	422780.066	0.259767	4366
6	2	3	1	2	175	210	0.75	0.35	424080.066	0.568054	4613
7	3	1	3	2	200	180	0.85	0.35	421684.666	0	5150
8	3	2	1	3	200	195	0.75	0.4	425649.05	0.940129	4743
9	3	3	2	1	200	210	0.8	0.25	426286.45	1.091285	4593

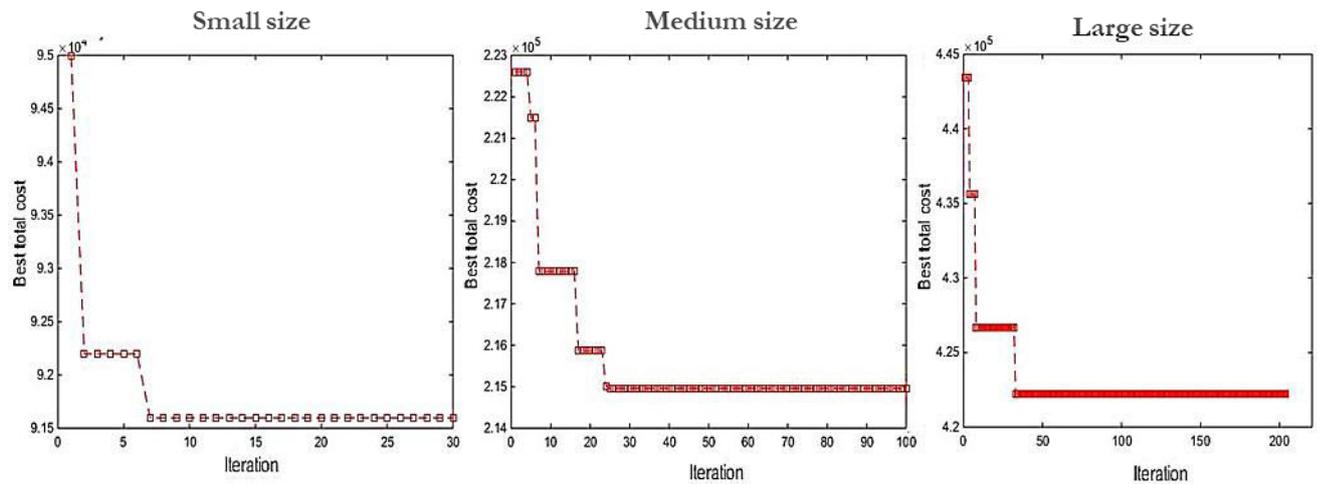


Figure 46- convergence of the algorithm in different instances, including small, medium and large sizes.

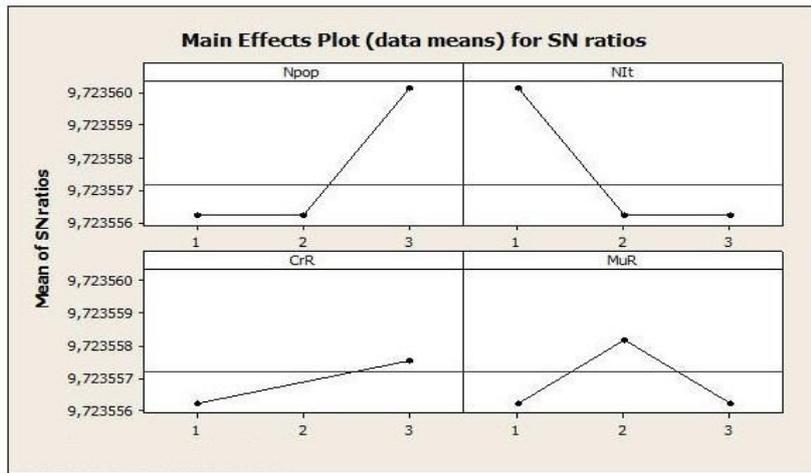


Figure 47- S/N ratio plots for experiments on small-size problems.

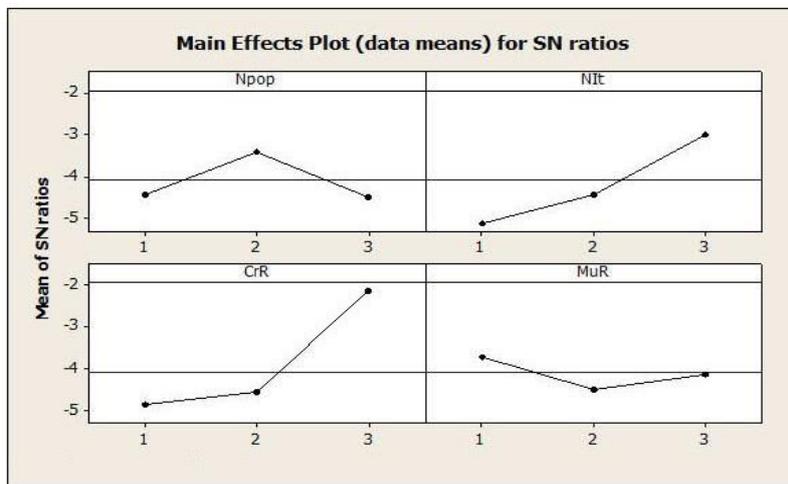


Figure 48- S/N ratio plots for experiments on medium-size problems.

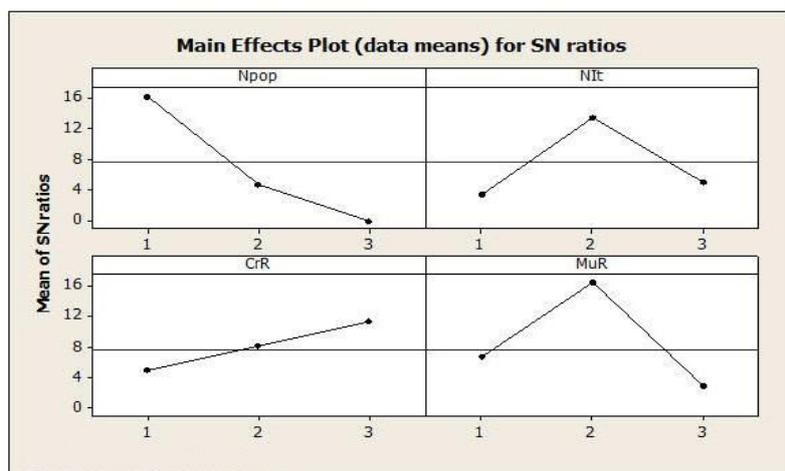


Figure 49- S/N ratio plots for experiments on large-size problems.

On the basis of the calculated normalized values of the algorithm response (presented in the RPD column), the Taguchi model analysis is carried out and the results of this application are displayed from Figure 47 to Figure 49 by the use of Minitab 16. According to the principles of the Taguchi design using the S/N ratio, the parameters are chosen from the positions in which their corresponding graphs hold the peak value. The results for the adjustment of the parameters are thus determined, as reported in Table 20.

Table 20 -Calibration of the parameters of the genetic algorithm for instance problems.

Size of the instance problems	Driving factors of the algorithm			
	Npop	NIt	CrR	MuR
Small size	30	25	0.75	0.25
Medium size	85	100	0.8	0.2
Large size	150	195	0.85	0.35

4.3.4 Performance of the algorithm

The performance of the algorithm is investigated from two points of view: *Time elapsed to find the results* and *Quality of the solutions*.

From the elapsed time point of view, a random set of data is generated for the small and large cases using the distributions given in Table 15. The data for the medium size instance is the same one which have been presented in Section 4.2.4. The model is solved by CPLEX using the generated data. The resolution time of the solver for small and medium instances is respectively 4 and 1265 seconds. For the large size instances, the solver ends up after 4h and 59 minutes without returning a solution. On the other hand, the elapsed time for solving the model instances, while using the results of the Taguchi method on the same data, is 16 seconds, 699 seconds and 4442 seconds respectively for small, medium and large sizes.

In terms of the solution quality, 50 more instances have been generated and the results obtained from the algorithm are compared to those of resolution by CPLEX. In this context, the gap of the solution is calculated by the use of equation 3-37. The seminal works on this subject can be seen in (Sajadieh and Shadrokh 2009) (Kannan et al., 2010) (Ghodratnama et al., 2010) and (Zoraghi et al., 2015). Since the resolution of the model by CPLEX solver is traceable for small and medium instances, 50 instances of these sizes have been regarded for the illustration of the algorithm's performance. Expression 3-38 is used to compare the best solution of the initial population (BI) with the best solution of the algorithm (BA), according to (Zoraghi et al., 2012). The results are summarized in Table 21 and Table 22.

$$\text{GAP} = \frac{\text{Genetic Algorithm}_{\text{Result}} - \text{cplex}_{\text{Result}}}{\text{cplex}_{\text{Result}}} * 100 \quad 3-37$$

$$\text{Improvement} = \frac{\text{BI} - \text{BA}}{\text{BI}} * 100 \quad 3-38$$

Table 21 –Results of the small-size problem.

Test	Objective function value by cplex	Fitness value of the initial solution	Fitness value of the best solution	Gap (%)	Improvement (%)
1	90692.136	94338.395	91596.52	1.0	2.9
2	90872.136	92376.52	91656.52	0.9	0.8
3	91353.136	92887.3533	92258.395	1.0	0.7
4	90873.536	93798.86	91656.52	0.8	2.3
5	105929.136	109308.395	106364.645	0.4	2.7
6	105839.336	109248.395	107244.645	1.3	1.8
7	90752.136	94458.395	91656.52	1.0	3.0
8	97736.136	100732.77	99629.2283	1.9	1.09
9	95194.656	96457.3533	95797.3533	0.6	0.7
10	104162.936	106078.395	104270.895	0.1	1.7
11	95285.256	98540.895	95827.3533	0.6	2.7
12	91326.336	94677.145	91656.52	0.4	3.2
13	103635.536	104094.645	103990.895	0.3	0.1
14	102165.536	105343.811	102243.8117	0.08	2.9
15	91163.136	94622.77	91616.52	0.5	3.2
16	91256.536	92337.3533	91646.52	0.4	0.7
17	91437.736	92486.52	91706.52	0.3	0.8
18	91879.136	92917.3533	92166.52	0.3	0.8
19	93360.136	93992.145	93406.52	0.05	0.6
20	90842.536	94797.145	91686.52	0.9	3.3
21	103541.746	104185.324	103780.452	0.2	0.6
22	101987.346	104125.522	102031.4578	0.04	2.1
23	92210.746	95252.5349	92518.4916	0.3	3.3
24	91456.244	92457.3541	91786.59	0.4	1.1
25	91824.156	92398.4721	91901.43	0.08	0.6

Table 22 –Results of the medium-size problem.

Test	Objective function value by cplex	Fitness value of the initial solution	Fitness value of the best solution	Gap (%)	Improvement (%)
1	196844.657	202379.2452	199894.9231	1.5	1.2
2	188374.537	201587.4252	189173.8113	0.4	6.1
3	202770.142	232752.6175	211882.41	4.3	9.0
4	184485.748	201881.12	187354.7232	1.5	7.2
5	178952.832	191496.3733	181668.04	1.5	5.1
6	175959.592	190809.7067	180138.04	2.3	5.6
7	173243.832	194497.0572	175923.04	1.5	9.5
8	183056.832	201592.03	190596.8733	3.9	5.4
9	174685.192	189353.04	178978.04	2.4	5.5
10	172491.232	193708.04	177563.04	2.8	8.3
11	199734.826	203389.1341	201239.5132	0.7	1.05
12	174387.992	186753.04	178708.04	2.4	4.3
13	203690.146	206849.9443	204052.4582	0.2	1.3
14	186282.232	196869.7067	189528.04	1.7	3.7
15	189641.032	201008.04	190278.04	0.3	5.3
16	191385.192	202396.3733	194596.3733	1.6	3.8
17	193381.992	204439.7067	197418.04	2.0	3.4
18	201987.842	224513.51	202526.24	0.2	9.8
19	178353.832	194411.3733	181068.04	1.5	6.9
20	187512.422	194285.0151	188512.2146	0.5	3.0
21	181541.845	192154.1287	185035,4412	1.9	5.8
22	175872.542	185413.391	178787.65	1.6	5.4
23	204571.156	207752.3421	205141.412	0.2	1.5
24	198571.181	206751.5266	203198.239	2.3	4.1
25	190623.124	200418.64	192102.29	0.7	5.1

According to the different generated instances, the gap and the improvement indicators ranges in [0.04 , 1.9] and [0.1, 3.3] for the small size of the problem. On the other hand, they are [0.2, 4.3] and [1.05, 9.8] for the instances of the medium size of the problem. Taking the results of the gap and improvement indicators into account, it could be mentioned that by accepting a slight increase in the gap of the solution and decreasing the algorithm's effort in calculation for small-size instances (by decreasing the population size and the number of iterations), the algorithm could be accelerated in terms of the resolution time.

4.4 Chapter conclusion and discussion

The main objective of the current chapter is to respond to **Q.2** and **Q.3** of this study. It presents an optimization model for concurrent planning of multiple projects in which both renewable and non-renewable resources are required. The renewable resources of the projects are available in a limited quantity. However, a limited quantity of these resources could be added to the projects. On the other hand, the activities of the projects are due on the due dates. The possibility of adding resources makes the model able to decide whether to rent additional capacities of renewable resources and avoid paying for high penalty costs or to pay low penalty costs instead of paying for high-cost additional resources. Four types of precedence, including finish-to-start, start-to-start, start-to-finish and finish-to-finish are considered in the modeling framework. Each of the precedence relations could be determined as wait or no-wait. The no-wait precedence implies conditions wherein a target activity in a precedence relationship must be followed immediately after the process of its sink activity while considering the extant time lag to be spent if necessary. Nevertheless, the wait situation eliminates this obligation. The model is developed for projects with just-in-time procurement of non-renewable resources (the pull-type project scheduling problems in the course of the current dissertation). Because of the mutual influence between project scheduling and resource ordering issues, especially in planning under just-in-time reception of non-renewable resources, the problem of scheduling for the projects is proposed to be integrated with the problem of planning the supply chain network which is responsible for supplying the resources.

In the supply chain network, the required consumable resources are produced and transported to the worksites to optimality through the forward flows and then the generated waste of the project worksites is shipped to the proper recycling centers through the backward supply chain. Both the forward and backward supply chain networks encompass the limited capacities for the transportation and the stock of the items. Each of the manufacturing and recycling centers holds an initial production/recycling capacity. However, the model presumes that these capacities could be increased by a limited value over every time period of the planning horizon.

The objective of the model is to minimize the total performance cost of the system involving the scheduling of the projects and the planning for the supply chain network. Using a resolution algorithm on the basis of the principles of linear relaxation, the primary resolution of the model is done by the CPLEX solver in a case study from the CRIBA project. The results of the algorithm and the sensitivity analysis of the parameters have been presented in this chapter. Then, in order to deal with the large-size instances of the model, the deployment of the genetic algorithm has been studied. The proposed search procedure attempts to define the feasible start dates based on the project scheduling constraints and the constraints of the forward supply chain. Afterwards, the backward supply chain's functioning and the calculation of the activities' lateness and the added renewable resources are adapted to the created dates. The optimization procedure of the algorithm is presumed to be terminated after the accomplishment of a given value of iterations. In addition, the order 1 crossover and a hybrid operator between swap, insertion and reversion have been presumed as respectively the crossover and mutation operators of the algorithm. On the other hand, the parameters of the algorithm are tuned by use of the principles of the Taguchi method.

In this regard, three different dimensions of the instance problems including the small, large and medium sizes are considered and the algorithm parameters are tuned for each of the instances. The performance of the proposed search procedure is investigated with a set of the generated test instances.

“We shape our tools and thereafter our tools shape us.”
Marshall McLuhan

5. Implementation of a decision support tool

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5.1 Chapter introduction

This chapter aims to characterize the decision support tool that is provided to support the modeling framework proposed in the course of this study. Various *components* of the application, its *architecture* and *license* specifications as well as an *implementation of a case* are outlined in the current chapter.

5.1.1 Development of a web-based decision support system

According to (Ghasemzadeh and Archer, 2000) “A Decision Support System (DSS) is an interactive, flexible, and adaptable computer-based information system, specially developed for supporting the solution of a non-structured management problem for improved decision making. It utilizes data, provides an easy-to-use interface, and allows for the decision maker’s own insights. A DSS to support the main stages in the framework requires a carefully designed model management module to handle models of the many different types, which may be chosen. Its implementation requires considerations of the model representation and integration.” During the last decade, web technologies have had a great impact on design, development and implementation processes for all kinds of DSSs and these systems are employed by organizations as a decision-making tool for their employees as well as their customers. According to (Bharati and Chaudhury, 2004), DSSs on the web have engendered three main changes in the environments in which they are employed: change in the user community, change in the underlying technology architecture and change in the problem domain. With the advent of these systems, their use is no longer restricted to managers or users who are experts in business-related problems. CRIBA Logistics is a web-based application that implements the modeling approach described in Chapter 4. It allows users to:

- 1- Create a new project for planning the CRIBA project(s) with the corresponding supply chain network.
- 2- Launch the pre-processing phase in order to improve the earliest and latest start times estimated by users and to enhance the efficiency of the application.
- 3- Run the project and retrieve the results in Excel spreadsheets.

5.1.2 Architecture and license

The CRIBA logistics application can be used with Linux or Microsoft Windows operating systems. The communication between the client and the server of the application is provided by using the Representational State Transfer (REST) architectural style. REST can be understood as a set of principles for the design of network applications. These principles describe how network resources are defined and taken into account. The idea of using REST is to apply HTTP (Hyper Text Transfer

Protocol) to make inter-machine calls rather than using complex mechanisms such as Common Object Request Broker Architecture (CORBA), Remote Procedure Call (RPC), or Simple Object Access Protocol (SOAP) to connect machines. Figure 50 shows the architecture of the CRIBA Logistics web application. It consists of three levels: 1- Front-end, 2- Server-Software and 3- Back-end. Each of the levels is outlined in the following:

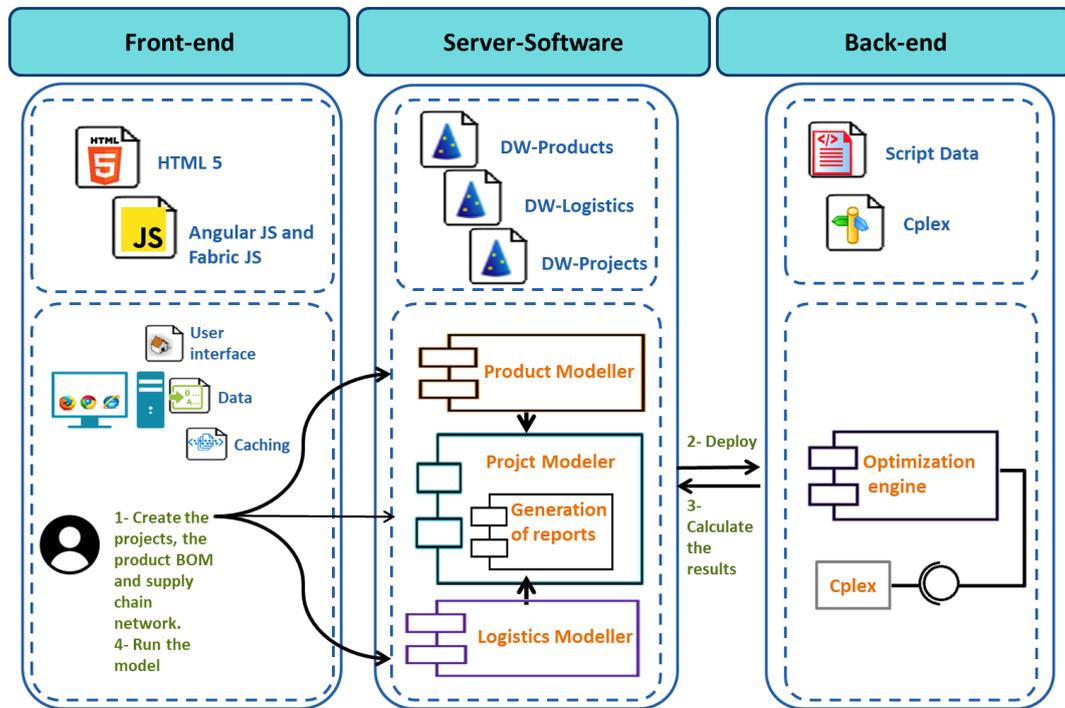


Figure 50- The architecture of the CRIBA Logistics application.

1-Front-end: The front-end side is the upper layer of the architecture that is visible and interactive for the users. The graphical interface of the application is developed by use of HTML 5 (Hyper Text Markup Language 5) and JavaScript (AngularJS and Fabric.js). HTML 5 is a markup language that allows developers to structure and present the contents on the World Wide Web. JavaScript is a scripting language that is used in interactive web pages. AngularJS is a free and open-source JavaScript framework that allows developers to use HTML as a template language and also extends the HTML syntax to express the components of the application clearly and succinctly. Fabric.js is a JavaScript library that makes it possible to create graphics (templates) on web pages.

2- Server-Software: The role of the server-software is to accept the requests for the actions and execute them. Indeed, it manages and synchronizes events and requests. In this regard, the Dropwizard framework is used in the CRIBA logistics application. It brings together the strong libraries of Java in a package including Jetty (to integrate an HTTP server set directly into the application), Jersey (to build the application in REST style) and Jackson (to process with JSON files).

3- *Back-end*: The external server is the part of the web-based DSS where the functionalities and logics are implemented. These features support the remote connection, authentication and data transfer that is provided and apply the concepts of the optimization model. To create these functionalities, the application relies on the programming language Apache CXF implemented in the Java and Optimization Programming Language (OPL).

All components of the application are subject to AGPL (GNU Affero General Public License) licenses. The AGPL is designed to guarantee the freedom to use, share and change all versions of an application or any part of the programming. It protects the rights of the user under two agreements: 1- to assert the author's rights to the software and 2- to offer users this license which gives them the legal authorization to copy, distribute and/or modify the software. As the AGPL is a copyleft license, it removes the transformation of free software into proprietary software.

5.1.3 Implementation of a use case

In order to illustrate the know-how in the use of the application, the implementation of a case is presented in the following section.

5.1.3.1 Creating the network of the supply chain with multiple projects

Figure 51 shows the host page of the application. It includes an editor icon (Project Editor) and two modeler icons (Products Modeller) and (Logistics Modeller). The "Project Editor" icon allows users to create and manage their own projects for planning the single/multiple CRIBA project(s) integrated with the supply chain network. The "Products Modeller" and "Logistics Modeller" icons respectively allow users to design the product view, which is used for establishing the bill of materials, and the logistics view, which builds the logistics network linked to the project worksites.

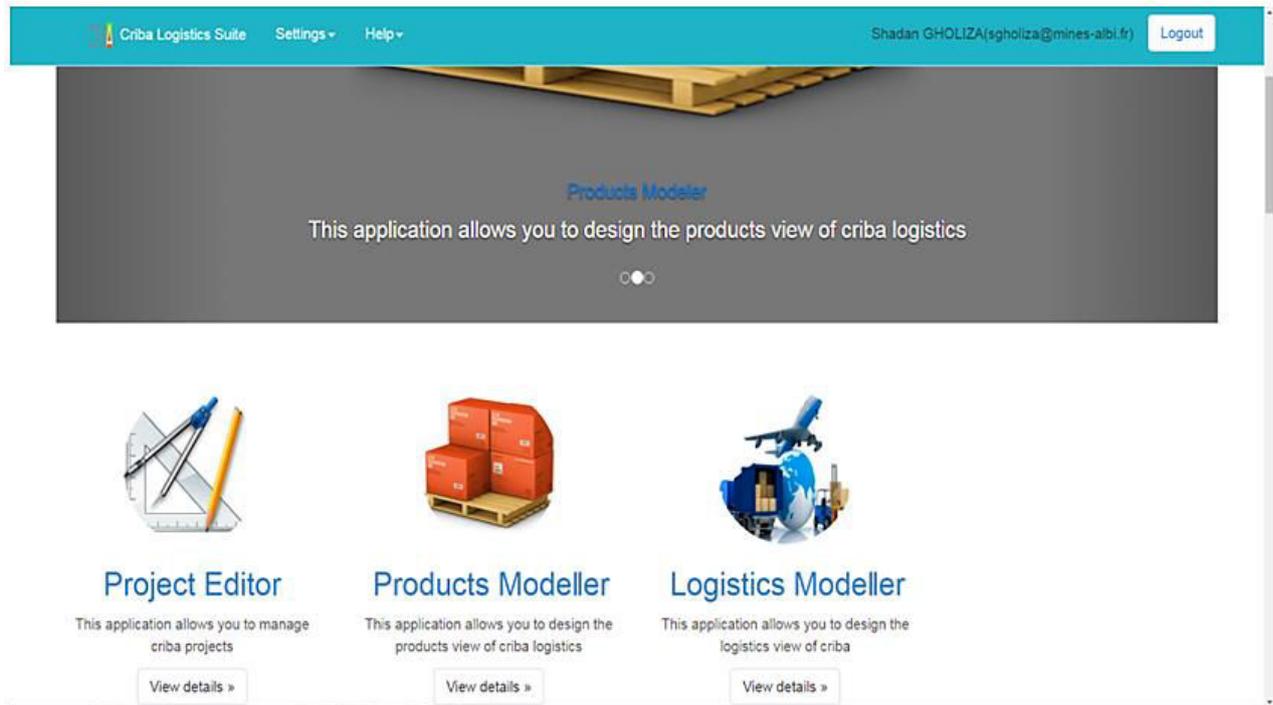


Figure 51- Presentation of the home page of the CRIBA logistics application.

The "Project Editor" link directs users to a new page allowing them to:

- I. Establish a new project for planning the project(s) with the corresponding supply chain network as well as connecting to projects previously created by users by using the "Projects management" tab.
- II. Consult and collaborate with other users of the CRIBA Logistics application using the "Users management" tab, (Figure 52).

In the following text, the functionalities of the "Projects management" tab are discussed. The "Create new project" link allows users to build a new project which is a project for planning a single or multiple CRIBA project(s) with the corresponding supply chain network. By clicking on the link, the users can: (i) define the name of the project, (ii) add a description to the project, (iii) select the time unit for the planning horizon, and (iv) characterize the renewable resources of the project with the name of the resources, the initial availability of resources, the cost of renting the resources and the maximum amount that can be rented as a supplement, Figure 53.



Figure 52- Presentation of the Project Editor interface.

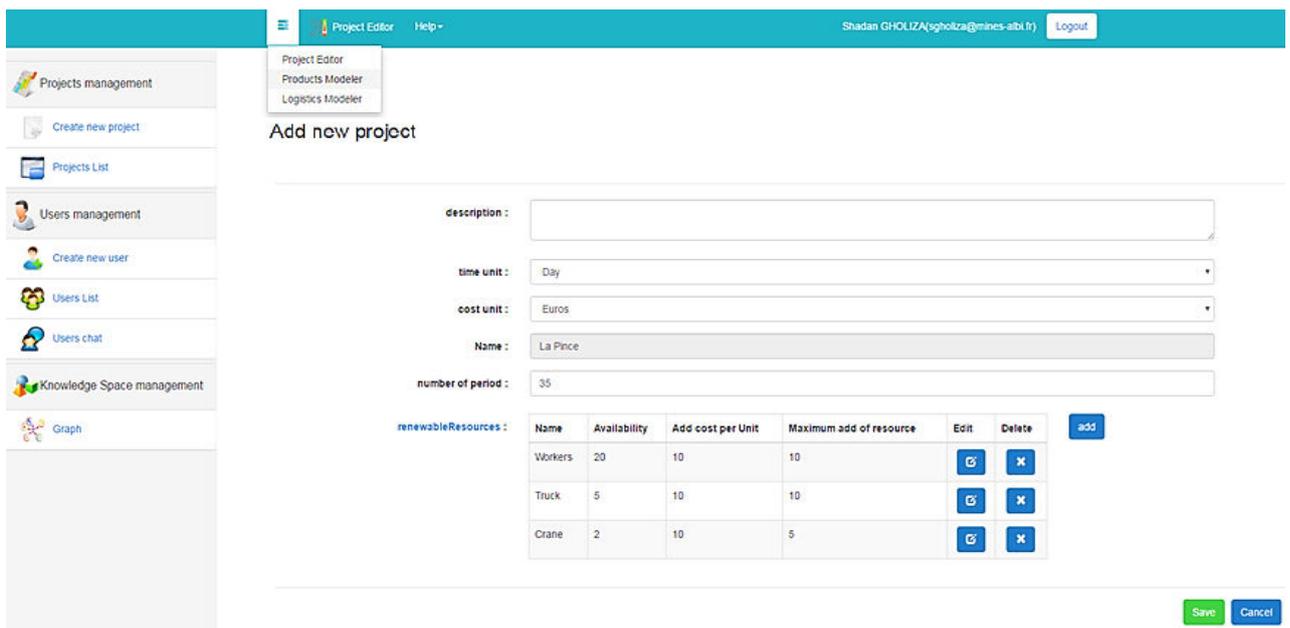


Figure 53- Screen shot of the "Create new project" page.

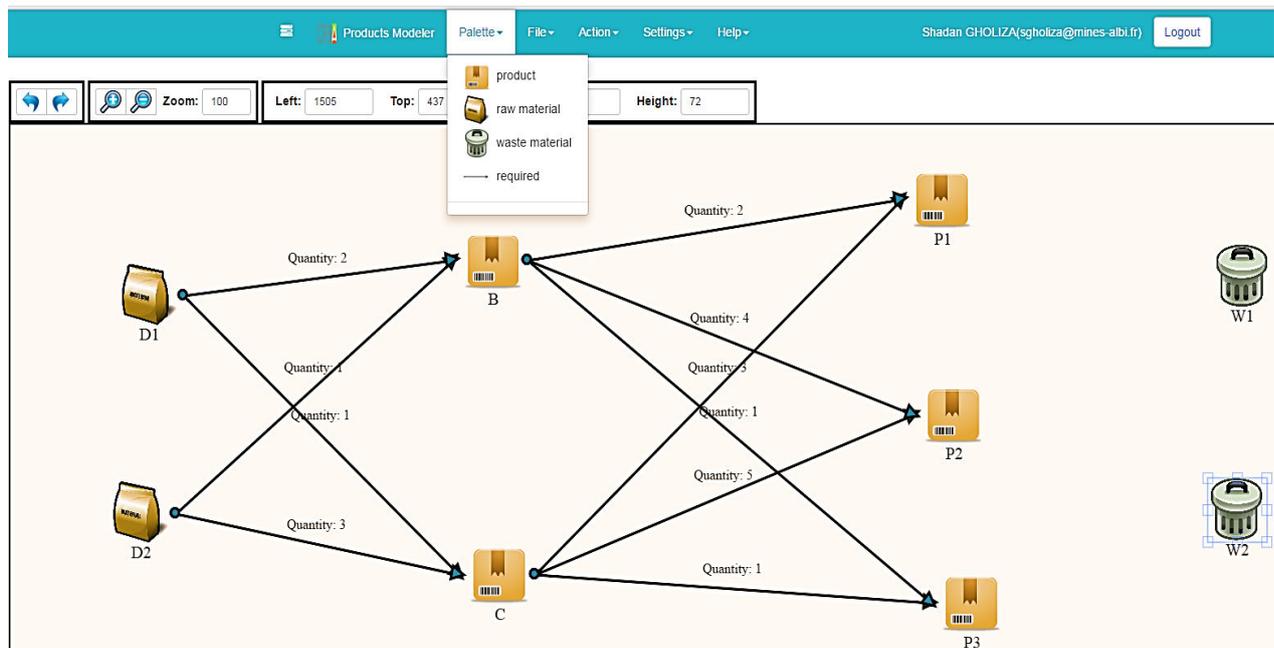


Figure 54- Screen shot of the "Products Modeller" page with an example of the bill of materials.

After entering the data into the queries, the users can click on the "Save" button to register the manipulations and continue the next steps or they can click on the "Cancel" button to abort the request.

The next step after the creation of the project is to establish the bill of materials. By clicking on the "Modeller" button of the application located in the upper left corner of the project edit page and by using the "Products Modeller" link, the users are led to establish the bill of materials, Figure 54. On the page that appears after clicking on "Products Modeller", the "Palette" tab provides four entities to present the different items which can be included in the supply chain network: (i) products, (ii) raw material, (iii) waste material and (iv) required, seen in Figure 54. In order to use each of the entities, the users click on them in the palette list and drag and drop them in the interface. Having added all the items, they can create a relationship between the components and the final product by use of the "required" entity and then enter the information in the corresponding queries by double-clicking on the entities. Figure 55 presents the queries that must be entered for a product-type entity. At the end of this step, the users synchronize the manipulations by clicking on the "Synchronize" link available from the "Action" button, seen in Figure 56.

The next step after establishing the product view is to construct the logistics view. The users click on the button of the modeller of the application and then choose the "Logistics Modeller" link, as shown in Figure 57. At the "Logistics Modeller" interface, the Palette icon provides a set of entities that can be used to build the integrated logistics network with the project working site(s). They include: (i) supplier, (ii) production unit, (iii) work site, (iv) recycling center, and (v) flow, which is an entity that connects the units together.

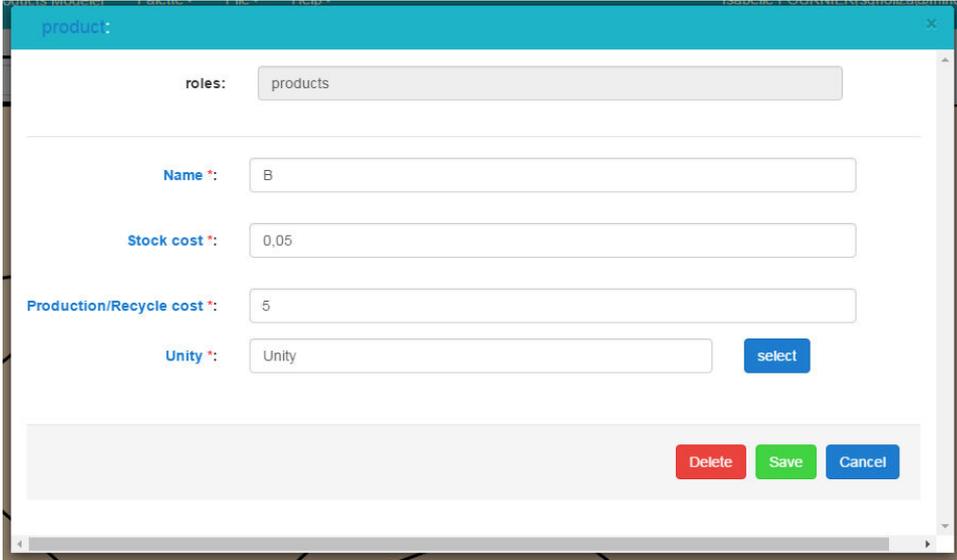


Figure 55- Product view with the requested data to enter.

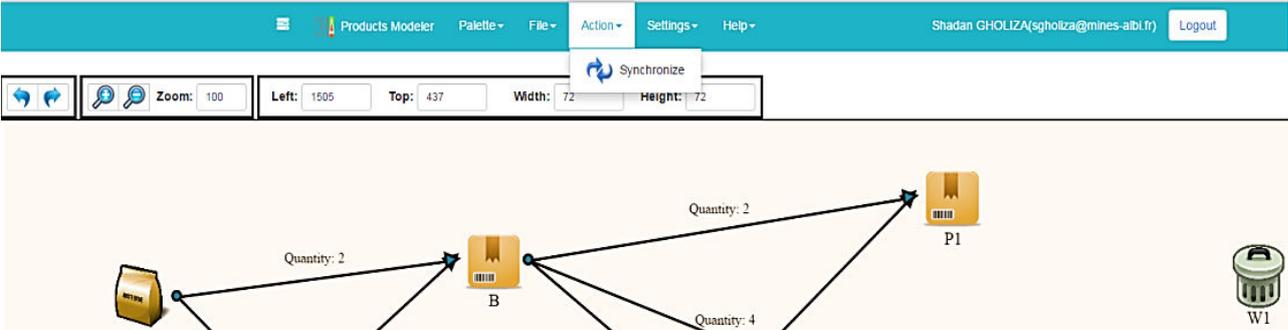


Figure 56- Presentation of the "Action" button and the link to synchronization.

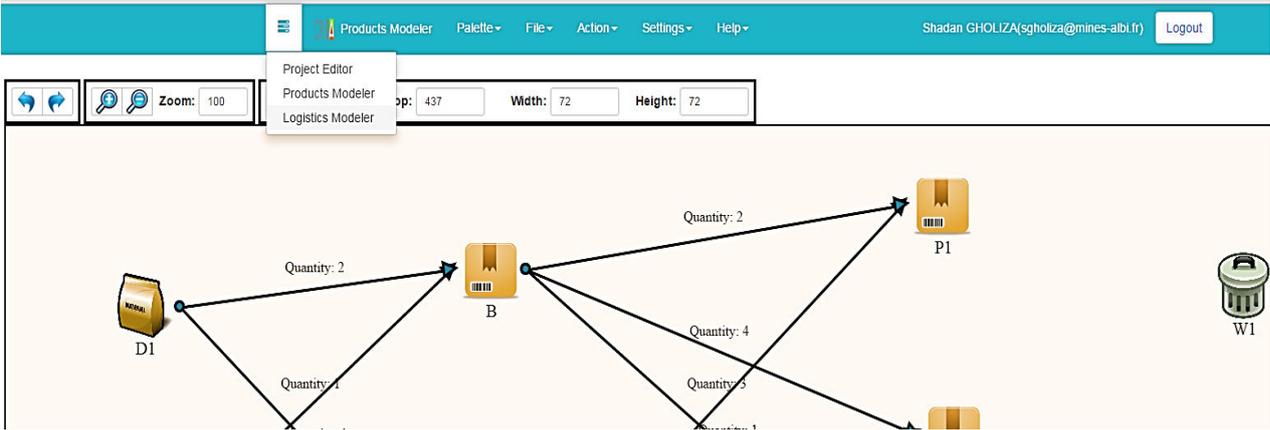


Figure 57- Presentation of the link to the “Logistics Modeller”.

In addition, the entities (vi) Start Event, for presenting the start-of-site activity, (vii) End Event, for presenting the end-of-site activity, (viii) Task, for representing activities carried out in the

project worksites, (ix) No-Wait transition to present an immediate precedence relationship between two activities, and (x) Transition, in order to present a normal (wait) precedence relationship, are used for defining the logistics view as well as the activity networks, seen in Figure 58. By clicking on each of the palette entities, the users can add them to the interface. Once all the entities are added, they can double-click on the entities in order to enter the corresponding data. The queries for the data entry are associated with the different parameters of the model that are seen in Section 4.2. Figure 59 and Figure 60 illustrate the queries required for the suppliers and production units.

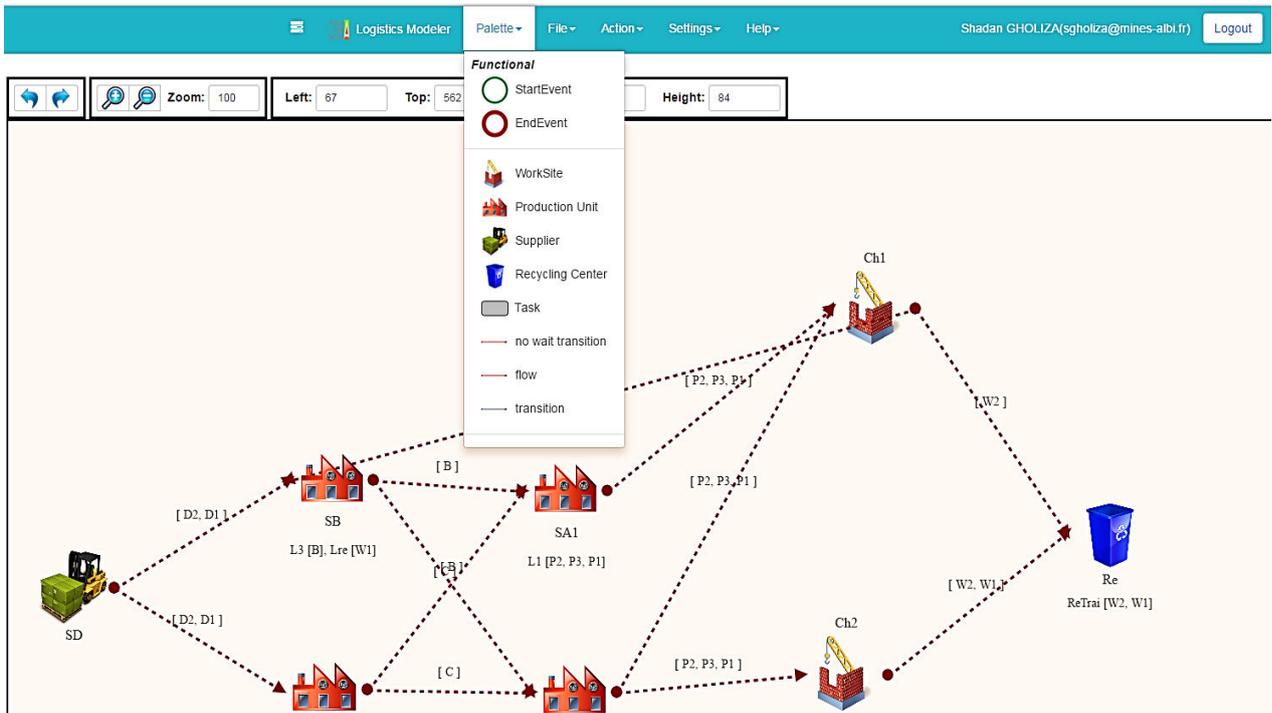


Figure 58- Screen shot of the "Logistics Modeller" page with an example.

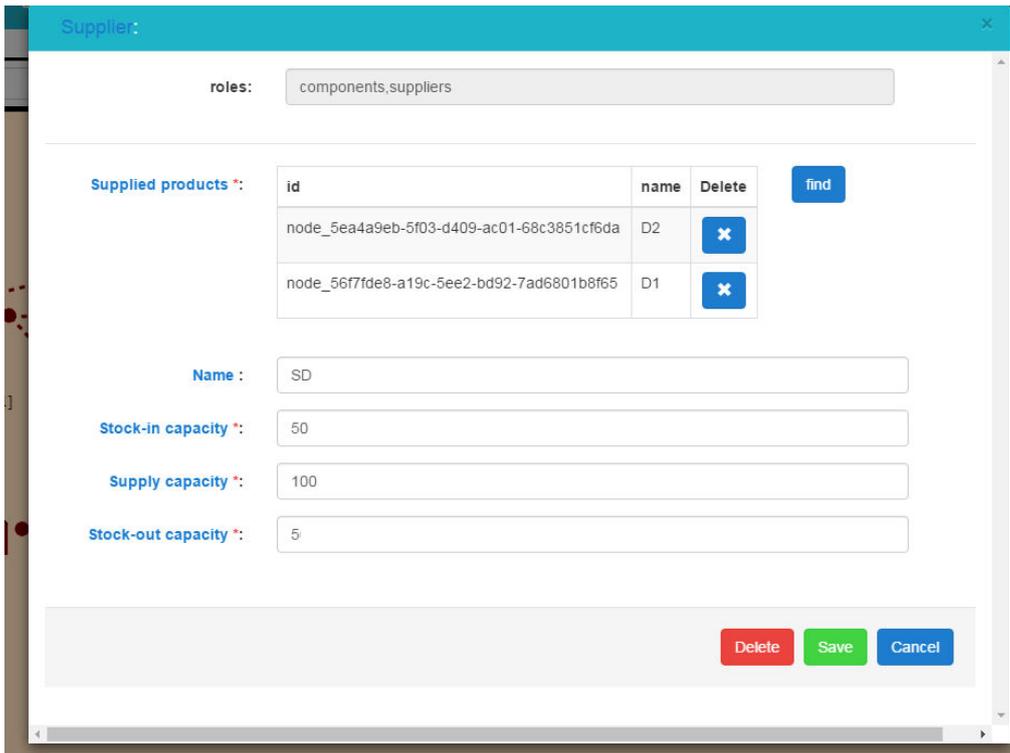


Figure 59- Screen shot presenting the queries of "Supplier".

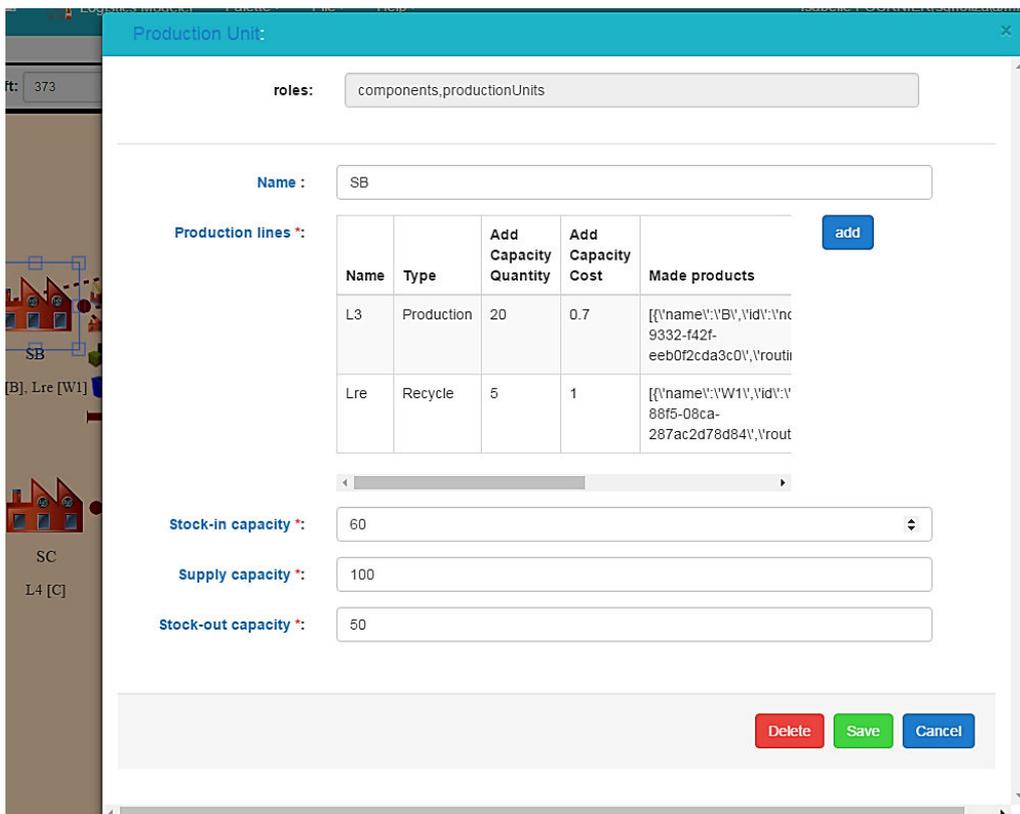


Figure 60- Screen shot presenting the queries of "Production Unit".

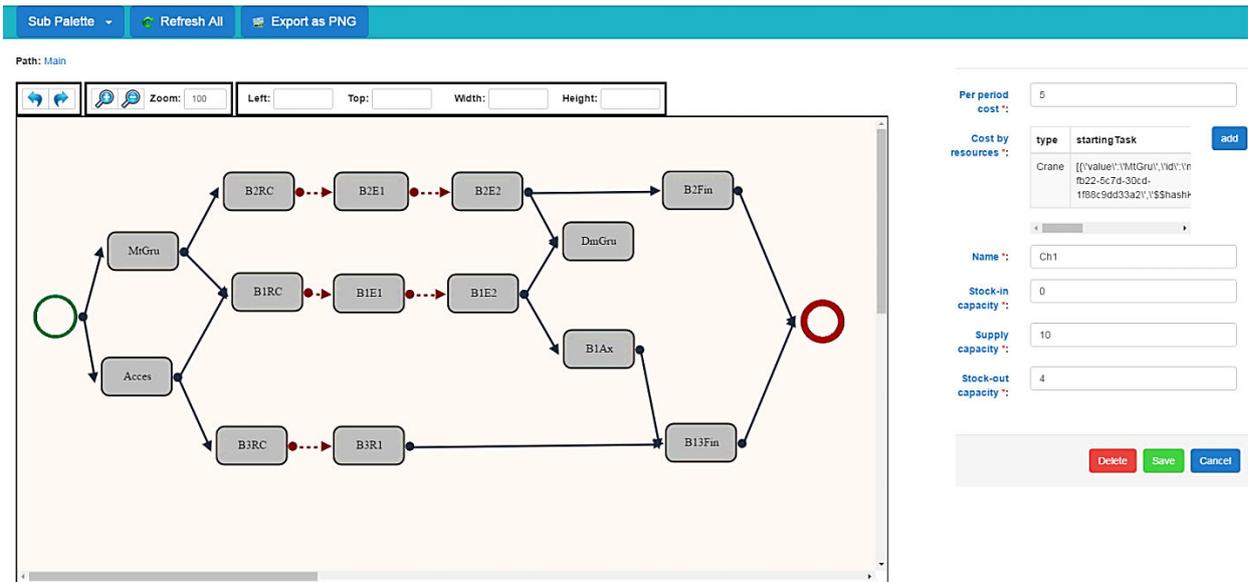


Figure 61- Screen shot of the page that appears after double-clicking on “Worksite Units”, including an example.

The screenshot displays a form titled 'Cost Related to Each Activity (Euro)'. It includes input fields for 'Due-date' (23), 'Penalty cost' (1), 'Earliest start time' (15), 'Latest start time' (28), and 'Processing time' (1). Below these are two tables for resource management.

Consumable resources:

name	quantity	Delete
P2	1	<input type="button" value="x"/>
P3	1	<input type="button" value="x"/>
P1	2	<input type="button" value="x"/>

Produced wastes:

name	quantity	Delete
W2	0.4	<input type="button" value="x"/>
W1	0.4	<input type="button" value="x"/>

Figure 62- Screen shot presenting part of the required data to enter by double-clicking on the “Activity” entities.

Double-clicking on the worksite entity directs users to an interface allowing them: (i) to enter the parameters necessary for the planning of the CRIBA projects and (ii) to define all the activities of the projects by right-clicking on the interface and choosing the proper entities from the pick-list, Figure 61.

In order to define the activities of the project, the users click on the interface. A list opens that allows them to select the start/finish activities of the worksites as well as the normal tasks. Having added all the activities, the users create the precedence relationship between the activities. To do so, they click on each of the added entities. A list appears that allows them to choose either "no wait transition" or "transition" to make their proper connections.

In this interface, once the users double-click on an activity, a window appears which allows them to determine certain characteristics for the execution of the activities, Figure 62. They include: name, description, due date, penalty cost, earliest start, latest start, processing time, consumable resources, renewable resources and waste. At the end of this step, users save the created view by clicking on the "Save" button and then synchronize the view by clicking on the "Synchronize" link from the "Action" tab.

5.1.3.2 Execution and retrieving the results

To start the execution of the created project, the users select the "Project Edit" tab and choose their project from the "Project list". Clicking on the "Run" button leads the users to the execution of the model for the created project, (Figure 63).

During the execution of the application, two phases of resolution are solved: (i) the pre-processing phase and (ii) the main phase of the resolution. The improved earliest and latest start times as well as the values of the decision variables of the optimization are saved in Excel spreadsheets. Examples of the outputs are presented in Figure 64 - Figure 66.

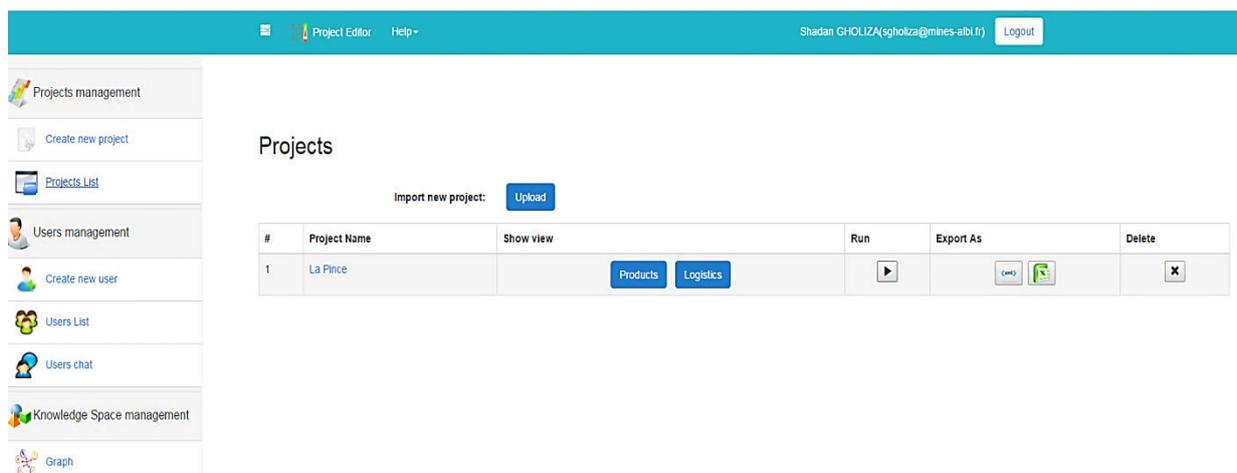


Figure 63- Screen shot of the interface for executing the application.

Activities			
ID	Description	Modified earliest start	Modified latest start
0	MtGru	7.0	16.0
1	Acces	15.0	17.0
2	B2RC	16.0	18.0
3	B1RC	17.0	18.0
4	B3RC	19.0	26.0
5	B2E1	17.0	19.0
6	B2E2	18.0	20.0
7	B1E1	18.0	19.0
8	B1E2	19.0	20.0
9	B3R1	21.0	28.0
10	B2Fin	20.0	30.0
11	DmGru	20.0	28.0
12	B1Ax	20.0	21.0
13	B13Fin	22.0	29.0

Figure 64- Presentation of the output of the pre-processing phase with the CRIBA Logistics application.

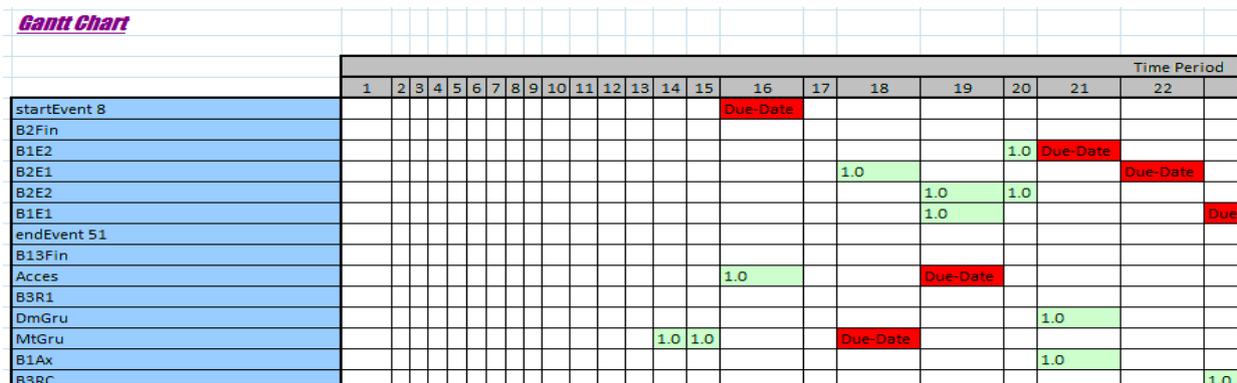


Figure 65- Gantt chart of the activities provided by the CRIBA Logistics application.

Unit Result_SB		Routing						
		1	2	3	4	5	6	7
L3	Production of B	1.0			20.0	20.0	20.0	20.0
	Total Production	N/A			20.0	20.0	20.0	20.0
	Available capacity	N/A	20.0	20.0	20.0	20.0	20.0	20.0
	Used capacity	N/A			20.0	20.0	20.0	20.0
	Added capacity	N/A						
Lre	Total capacity	N/A		20.0	20.0	20.0	20.0	
	Production of W1	1.0						
	Total Production	N/A						
	Available capacity	N/A	5.0	5.0	5.0	5.0	5.0	5.0
	Used capacity	N/A						
Lre	Added capacity	N/A	1.0	1.0	1.0	1.0	1.0	1.0
	Total capacity	N/A	1.0	1.0	1.0	1.0	1.0	1.0

Used Articles for Result_SB		Origin	Destination	Product	1	2	3	4	5	6
Transported		Ch1	SB	W1						
Transported		SD	SB	D2	20.0	60.0				
Transported		SD	SB	D1	40.0	80.0		100.0		
Stocked		N/A	SB	W1						
Stocked		N/A	SB	D2				40.0	20.0	
Stocked		N/A	SB	D1				40.0		60.0

Produced Articles for Result_SB		Origin	Destination	Product	1	2	3	4	5	6
Transported		SB	SA2	B					8.0	
Transported		SB	SA1	B						15.73
Stocked		N/A	SB	B				20.0	32.0	36.26

Figure 66- Screen shot showing the display of the results for "Production unit" type entities.

5.2 Chapter conclusion and discussion

This chapter has presented the web-based application that has been developed to support the modeling framework of the dissertation. The specificities of the application on the architecture and licenses are discussed and the implementation of the CRIBA projects are illustrated in the chapter. The optimization procedure of the application encompasses two main phases: the pre-processing phase and the main phase. The major goal of the pre-processing phase is to improve the earliest and latest starts that are estimated for the activities and, therefore, to increase the efficiency of the application. The results of the pre-processing phase have been deployed in the main phase in order to provide the ultimate resolution of the model through the created use case.

“This chapter came to an end but the story goes on...”
Translated from the ghazalyat of Saadi Shirazi

6. General conclusion and perspectives

Planning is one of the crucial steps in project management, and its strong influence on the success of projects has long been recognized by managers and coordinators of projects. Depending on the different viewpoints of organizations, successful planning for projects can be achieved if they have performed optimally within the time, cost, and quality factors and/or with the efficient allocation of resources. Planning for the assignment of resources becomes more complex for the organization in the cases where a set of multiple projects is managed simultaneously. Indeed, in such situations, the challenge is to allocate the available resources among the projects while optimally satisfying the executive criteria of the projects. In general, two types of resources, including renewable and non-renewable resources, are used in scheduling the projects. Renewable resources such as machinery and labor are available at the project worksites in limited quantities. However, non-renewable resources are supplied to the worksites by the corresponding supply chain network through its limited capacity of procurement.

The global objective of this study is to develop a decision-making tool to help managers in planning multiple projects to optimality while dealing with resource allocation issues. To determine the planning framework of the model, several specifications have been assumed that are generally defined on the basis of the existing gap in the literature and the requirements of managerial organizations for planning practical cases. Generally, they encompass the three points mentioned below:

- *Planning for just-in-time reception of non-renewable resources at the project worksites:*
Due to the growing interest of organizations in performing according to “pull” strategies in acquiring required materials, the procurement of non-renewable resources for various projects has also been accomplished with a “just-in-time” method. The requirement for

determining a planning framework for such situations leads the framework of project scheduling problems to be extended from one planning solely for the projects to the integrated planning of the projects and the supply chain network, which produces and procures the required resources for the projects. The interest for this integration stems from three points of view summarized as following:

- Project planning constraints impacting supply chain network planning: taking the executive constraints imposed on the effectuation of projects into account, factors such as the given time windows, precedence relationships between the activities and also dedicated due dates for the completion of the activities implicitly create the constraints for the operations of the supply chain network. Consequently, the optimization of the supply chain network without integrating project scheduling constraints will end up being unachievable.
 - Supply chain network constraints impacting the scheduling of projects: On the other hand, the limitations and constraints of the supply chain network, such as the transportation, production and stock capacities of the supply chain actors, as well as the transportation and production lead times, inductively influence the procurement of the final products to satisfy the demand which can be generated at the project worksites. Therefore, the generation of demand at the worksites, that is to say the schedules of the activities, necessitates considering the constraints of the supply chain network in production, stock and transportation capacities.
 - Inherent project scheduling constraints: The schedules of the activities at the project worksites also depend on the inherent constraints of projects in terms of the availability of renewable resources. Therefore, the optimal planning of the system and the ability to provide a planning solution which is applicable to both the supply chain network and the schedules of the projects can be attained in their concurrent planning and in undertaking the optimization criteria subject to the constraints of both the projects and the supply chain planning.
- *Trade-off between time and the assignment of the renewable resources:*
The model attempts to build up equilibriums between time costs and renewable resource costs. To this end, it presumes that the activities are due on given deadlines. However, the model assumes that a limited quantity of the renewable resource has to be temporarily allocated to the projects over the time periods in which the demand for the resources may exceed the available amounts. These assumptions make the model capable of deciding to either rent the auxiliary resources and avoid paying the high penalty costs originating from late completion of the activities or to pay for low penalty costs instead of paying for the high cost of adding resources.

- *Inclusion of green criteria in planning projects:*

In order to respect environmental concerns and develop the decision-making tool responsive to these issues, the model incorporates the collection of waste generated at the worksites and its recycling in appropriate recycling centers that are located either in the recycling departments of the manufacturing centers or in the individual recycling centers in the closed-loop supply chain network.

The planning framework of the problem has been mathematically modeled by the use of operation research approaches. The application of the model is verified with a case study related to the CRIBA project. Since the constrained project scheduling problems belong to the NP-hard class of optimization problems, two resolution algorithms have been developed and are used to deal with the complexity issues of the model:

- The first algorithm aims to reduce the number of binary decision variables that are involved in the resolution of the instance problem using the exact procedures. Having considered that the total number of binary decision variables of the model is equal to $\sum_{i=1}^I (L_i - E_i)$, the algorithm attempts to reduce the total number of binary variables that are involved in the resolution of the problem instances by tightening the interval $[L_i, E_i]$ for each of the activities. The algorithm and its application are presented in Chapter 4 Section 4.2.5.1.
- The second algorithm is based on the principles of genetic algorithms. In the early stage of the algorithm, the search procedure attempts to determine a set of solutions by meeting the project-planning constraints as well as the capacity constraints of the forward supply chain network and it promotes the influence of the created start dates in the model to deal with the planning of the system. Then, the procedure attempts to improve the quality of the created solution throughout the different iterations of the algorithm. The parameters of the algorithm are calibrated by utilizing the principles of the DOE seen in the Taguchi method. In this regard, three different dimensions of the instance problems, including small, large and medium sizes, are used and the algorithm parameters are tuned for each of the instances. Finally, the performance of the proposed search procedure is investigated with a set of generated test instances. The results of the study are outlined in Section 4.3.3 and 4.3.4 of Chapter 4.

In order to extend the use of the model to users who are not familiar with operation research, a web-based decision support system has been developed. Chapter 5 offers an example to illustrate the deployment of the developed web-based application.

The statements on the perspectives and future developments of the study are discussed within the current chapter. They fall into six headings:

- *Involvement of uncertainty:*
In the proposed modeling framework, all of the parameters are supposed to be deterministic. However, this is not the case in most real-world situations. In fact, in practical cases of scheduling projects, poor estimation of the duration of activities and the executive time windows, as well as the availability of resources, imposes a degree of uncertainty on the planning parameters of the model. Furthermore, due to a lack of information, the driving factors of the supply chain such as the transportation and production capacities and/or the supply lead times can be subject to uncertainty. Therefore, for the future development of the modeling framework, the involvement of uncertainty in the duration of activities and the transportation capacity of the supply chain are of interest. In this context, the employment of uncertainty programming approaches such as stochastic programming and robust optimization could be promising.
- *Development of socially and environmentally responsible models:*
Reviewing the state of the art in scheduling projects by the use of optimization approaches, it is clear that problems of cost and time criteria have been largely studied. In addition, the models with quality issues as well as the minimization of tardy jobs have also been well reviewed by researchers. Nevertheless, the constrained project scheduling problems with environmentally and socially responsible objectives have yet to be determined in the form of optimization models and, to the best of our knowledge, the literature shows a deficiency in this context. In line with environmentally responsible purposes, the current study deals with the management of waste in its collection from the project worksites and the recycling of waste in the proper recycling centers. Meanwhile, other practices with environmental concerns, such as limiting the greenhouse gas emissions per unit of product supplied by the different modes of transportation from the different suppliers can be regarded as new developments in these models. In addition, the integration of social factors, such as labor unemployment in planning for the projects, could be included in the modeling framework.
- *Extension of constrained project scheduling with objectives in resource leveling and assignment:*
In the proposed modeling framework, an initial availability of renewable resources has been assumed for the projects and the resources are assigned to the activities based on their initial availability and the amounts which can additionally be rented. However, the objectives of the model regarding resource leveling problems are to minimize the fluctuation in patterns of resource usage (seen in Section 2.3.2.1) which could provide guidelines for future extensions of the model. In addition, approaches for solving resource investment problems, (seen in Section 2.3.2.2), with the aim of defining the total quantity of resources required for performing the projects within the dedicated deadlines, could be of interest.
- *Extending the assumptions of the model:*
The framework of the model could be extended on the basis of supply chain network parameters such as the transportation modes, discount levels for purchasing raw materials

and intermediate products, setups in production, lot sizes, etc. In addition, it could be developed from viewpoints of project scheduling parameters such as the multi-mode, multi-skill and generalized resource issues seen in Section 1.3, Section 2.3.1.3.1 and Section 2.3.1.3.3.

- *Development of additional search procedures and their implantation in decision support systems:*
In this context, the study is still open to being developed with new search procedures for scheduling projects and planning the supply chain network. Furthermore, the application of other metaheuristic-based algorithms could be undertaken. The implementation of the developed metaheuristic-based resolution approaches in decision-support systems could also be of interest for future studies and development of the present work.
- *Directions for the CRIBA Project:*
According to the principles of the CRIBA project as determined in the demonstration of the project, (CRIBA project, 2010), in order to increase the satisfaction of the people living in the buildings undergoing thermal renovation activities, it is presumed that the inhabitants of the buildings will be staying in their buildings during the inside and outside renovation activities. However, several strategies could be applied to minimize the disruption for the residents. These could be applied to a complete renovation of a complex throughout all its facades or throughout a key unit including the paths of access to the complex. Therefore, the structure of the Work Breakdown Structure (WBS) of the projects and the determination of the precedence of the renovation activities will play a consequential role. In this context, the dependency between the configuration of the panels and the internal and external thermal renovation activities could provide the guidelines for structuring the renovation activities in order to increase the satisfaction of the inhabitants.
In addition, the application of Integrated Building Design approaches (IBD), in order to improve the confort and productivity of building occupants by considering the integrated design strategies and taking into account the interactions among all of the building's systems, could be of interest. On the other hand, the use of Building Information Modeling (BIM) softwares that create the models to share knowledge and information about the facility can form a reliable basis for decisions through the lifecycle of buildings under thermal renovation practices of the CRIBA Project.

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7.1 Contexte et problématique du travail

La planification constitue une des étapes importantes de la gestion de projets. Son influence sur la réussite des projets a été largement reconnue. S'adaptant à une organisation, une planification réussie des projets doit viser une réalisation optimale des activités du projet en considérant les facteurs de temps/ coût/ qualité ainsi que l'affectation efficace des ressources. Cette affectation des ressources devient plus complexe pour une organisation qui doit réaliser plusieurs projets en parallèle (multi-projet). Dans ce cas, l'effort des organisations porte principalement sur l'allocation du capital entre les projets tout en poursuivant les objectifs de planification optimale de chacun des projets (Browning and Yassine, 2010) et (Singh, 2014).

En général, deux types de ressources sont demandées pour réaliser des activités. Les ressources, comme les produits utilisés pour la construction et les matières premières sont dites non-renouvelables. Une fois utilisées, elles ne sont plus disponibles. Ces ressources sont généralement fournies par un ou plusieurs fournisseurs à travers un réseau appelé « chaîne logistique ». En tenant compte des politiques de gestion de la demande, au cours des dernières années, les entreprises ont eu une motivation croissante pour réduire le fardeau des stocks, en particulier pour les ressources peu demandées à forte valeur ajoutée, (Stevenson et al. 2005) et (Günalay, 2010). Ce travail de thèse s'intéresse à la planification des multi projets avec un approvisionnement en juste-à-temps des ressources non-renouvelables. Ceci oblige à synchroniser la planification des projets avec celle de la chaîne logistique.

Les ressources telles que la main d'œuvre ou les engins de chantier sont dites renouvelables. Une fois la tâche réalisée, elles redeviennent disponibles pour effectuer d'autres tâches. Dans la littérature de l'ordonnancement de projets, la planification des ressources non-renouvelables se retrouve sous deux approches : la planification des projets à contrainte de ressources (en Anglais : Resource Constrained Project Scheduling Problem, RCPSp) et la planification des projets à contrainte de temps (en Anglais : Time Constrained Project Scheduling Problems, TCPSP), (Klein, 1999). Dans le RCPSp le montant des ressources est limité et la planification de projets se fait au mieux en tenant compte de ces limites et des contraintes de précédence, (Pritsker et al., 1969) et (Hartmann and Briskorn, 2010). Dans les modèles TCPSP, les projets ont une date d'achèvement imposée (deadline) et des quantités supplémentaires de ressources peuvent être mobilisées afin de respecter ces dates de fin imposées (Dekro and Herbert, 1989).

Dans notre étude, les dates de fin des projets et de certaines tâches sont souhaitées et il y a des coûts à payer si ces dates sont dépassées. Il est possible de mobiliser des quantités supplémentaires de ressources non-consommables. Nous devons trouver le meilleur compromis entre les coûts de retards et les coûts des ressources supplémentaires. Nous retenons ainsi les principes des deux problèmes RCPSp et TCPSP et nous les appliquons dans un modèle unifié.

En outre, aujourd'hui avec l'augmentation de la préoccupation mondiale pour la protection de l'environnement et la préservation des ressources naturelles, la nécessité d'un développement durable est devenue un facteur inévitable pour les organisations, (Robichaud et Anantatmula, 2011)

et (Hurt et Thomas, 2009). Bien que la planification des ressources (spécialement des ressources renouvelables) soit largement documentée dans la littérature en management de projets, à notre connaissance, peu de travaux abordent les aspects de la durabilité des ressources sous forme d'un modèle d'optimisation mathématique. Au cours de cette étude, nous supposons que les déchets produits sur les chantiers des divers projets doivent être collectés et recyclés dans des lignes de recyclages. Ces lignes de recyclage sont soit présentes sur un site de production pour faciliter la réutilisation des composants, soit associés à un centre dédié au recyclage.

Dans le but de définir un cadre la modélisation qui correspond aux besoins décrits ci-dessus, la première question qui émerge est (Q.1), « Quels paramètres importants influencent la planification de multi projets dont les ressources non-renouvelable sont approvisionnés en juste à temps et comment affecter ces ressources renouvelables en considérant les aspects recyclage des déchets ? » La réponse à cette question nous conduit à analyser les exigences et à établir les hypothèses du modèle. Afin de planifier le système de manière optimale nous avons retenu les approches de modélisation mathématique.

Dans ce contexte, la deuxième question qui s'est posée (Q.2) est « Comment formuler le modèle d'optimisation et quelles méthodes peuvent être appliquées pour résoudre les instances de ce modèle ? ».

Comme l'optimisation mathématique limite l'applicabilité du modèle aux gestionnaires qui connaissent ce type d'optimisation, la question qui se pose ensuite (Q.3) est « Comment rendre le modèle proposé utilisable par et pour les gestionnaires des organisations qui ne sont pas forcément familiers avec l'optimisation mathématique ». La réponse à cette question est de développer un système d'aide à la décision au travers d'une application web. Les utilisateurs pourront y créer leurs propres projets, modifier les données et récupérer les résultats après résolution.

Ces trois questions sont abordées au travers d'un projet appelé CRIBA (Construction et Rénovation Industrialisée Bois et Acier) subventionné par l'ADEME. L'objectif du projet est d'industrialiser le processus de rénovation énergétique des bâtiments et de réduire la consommation d'énergie des bâtiments jusqu'à 25 Kwh/m²/an en utilisant des panneaux isolants avec des menuiseries intégrées. Les panneaux préfabriqués en usine sont transportés sur les chantiers en juste à temps et ils sont posés sur les façades extérieures des bâtiments. Après avoir installés les panneaux, les anciennes menuiseries des bâtiments sont enlevées et sont transportées dans des centres de recyclage. Le cadre général de la modélisation de la problématique de thèse est présenté sur la Figure 7, (Section 1.3).

Les Figure 11 et Figure 12 (Section 1.4) schématisent les processus de la rénovation des bâtiments dans le contexte du projet CRIBA. Les travaux de cette thèse s'appliquent ainsi sur la planification tactique du projet CRIBA, Figure 67 (Section 1.4.2). Ils comprennent les décisions sur la planification des tâches, l'affectation des ressources renouvelables, la planification de production et le transport des ressources non-renouvelables ainsi que le transport et le recyclage des déchets produits par les chantiers.

7.2 Revue de la littérature

7.2.1 Méthode de résolution des modèles de planification des projets

Les méthodes de résolution des problèmes de planification de projets à contrainte de ressources/ temps peuvent se classer en quatre catégories incluant 1- La modélisation PLNE et la résolution par des méthodes exactes, 2- Les bornes inférieures, 3- Les heuristiques, et 4- Les méta-heuristiques:

7.2.1.1 La modélisation PLNE et la résolution par de méthodes exactes :

Le modèle de base de RCPSP est présenté par (Pritsker et al., 1969). En utilisant la notation en trois champs de (Brucker et al., 1999), le problème se présente sous la forme de $PSm|prec|C_{max}$ où le premier champ indique la disponibilité de m type de ressources renouvelables. Le second champ indique des contraintes de précédence et C_{max} donne l'objectif du modèle qui est la minimisation de la durée totale du projet. En outre, le modèle TCPSP présenté par (Dekro and Herbert, 1989) peut s'exprimer comme un modèle de planification du projet où la capacité des ressources renouvelables peut augmenter pour pouvoir satisfaire une deadline qui est imposé sur le projet. Le modèle vise à satisfaire les contraintes de précédence et l'objectif à minimiser est le coût de l'ajout des ressources.

Les approches exactes de type séparation-et-évaluation et la programmation dynamique sont utilisés pour traiter ces modèles dans la littérature. L'idée de base de la séparation-et-évaluation consiste à créer un arbre de recherche avec des nœuds et des branches qui explorent l'espace de solution du problème pour trouver la solution optimale. Dans une version simple de cette approche, les nœuds et les branches peuvent être utilisés respectivement pour montrer l'ordonnancement des tâches et les contraintes de ressources-précédence, (Bartusch et al., 1988) et (De Reyck and Herroelen, 1998). Les versions développées de cette procédure sont implantées dans les logiciels commerciaux pour répondre aux besoins en recherche et en pratique.

La programmation dynamique est un paradigme algorithmique qui permet de décomposer un problème en différents sous-problèmes et de résoudre les problèmes décomposés l'un après l'autre. Les solutions de chaque sous-problème sont combinées en une solution complète afin de déterminer la solution finale du problème principal, (Carruthers and Battersby, 1966).

7.2.1.2 Les bornes inférieures:

Les calculs de bornes inférieures ont un objectif triple : i. Ils fournissent des valeurs pour les problèmes dans lesquels la valeur optimale est absente. ii. La valeur calculée présente une mesure pour juger la performance des algorithmes qui génèrent des solutions semi-optimales. Conformément à cet objectif, si l'écart entre la limite inférieure et la valeur calculée est « serrée », l'effort de calcul par l'algorithme peut être justifié. Et, iii. Les bornes inférieures peuvent être

utilisées dans une approche exacte comme l'algorithme de la séparation-et-évaluation. Dans ce contexte, (Christofides et al., 1987) présente une procédure pour calculer une borne inférieure pour le modèle RCPSP en utilisant les concepts de la relaxation continue.

7.2.1.3 Les heuristiques:

Selon (Blazewicz et al., 1983), (Elmaghraby et Kamburowski, 1992) et (Neumann et al., 2002), les modèles de planification de projets à contrainte de ressources sont NP-difficiles. La complexité de ces problèmes empêche de résoudre les problèmes de grandes tailles en utilisant les méthodes exactes comme la séparation-et-évaluation. De ce fait, des solutions efficaces peuvent être obtenues avec un effort raisonnable en utilisant des approches heuristiques et méta-heuristiques.

Les heuristiques sont généralement adaptées au problème et à ses spécificités. Dans le contexte de la planification de projets, elles se divisent en deux catégories : 1-*les heuristiques de résolution de modèles à contrainte de ressource*, comme les algorithmes basés sur les règles de priorité : les solutions sont définies en utilisant des règles de priorité et les schémas de génération de l'ordonnancement incluant le schéma de génération de planification en série (SSGS) et le schéma de génération de planification parallèle (PSGS), (Kelley, 1963) et (Kurtulus and Davis, 1982). 2-*les heuristiques de résolution des modèles à contrainte de temps*, comme les heuristiques basées sur la relaxation Lagrangienne, (Drexel and Kimms, 2001).

7.2.1.4 Les méta-heuristiques:

Les méta-heuristiques sont des procédures indépendantes du type de problème. Elles partent d'une ou plusieurs solutions initiales, qui peuvent résulter d'une heuristique, et les transforment en une autre en exécutant un ensemble de règles. La Figure 23 résume les méta-heuristiques les plus utilisées pour la planification des projets en se basant sur 264 papiers figurant dans les bases de données Web of knowledge, ScienceDirect et SpringerLink. D'après la revue de la littérature, l'algorithme génétique est l'algorithme le plus appliqué dans le domaine de la planification des projets. Le mécanisme de fonctionnement de cet algorithme est présenté en Figure 27. L'avantage de l'algorithme génétique est dans sa recherche intrinsèquement parallèle et sa forte capacité à explorer et à exploiter l'espace des solutions. Néanmoins, comme les autres approches méta-heuristiques, il faut un réglage précis des paramètres, en particulier le taux de croisement, le taux de mutation, la taille de la population et les critères d'arrêt (comme le nombre d'itérations). En planification de projets, la représentation d'une solution s'appuie généralement sur une liste de permutation sur laquelle s'appliquent les opérateurs de voisinage, croisement et mutation. Un algorithme de type SSGS permet ensuite de générer les dates des tâches conformément aux contraintes du projet.

7.2.2 Planification pour l'approvisionnement des ressources non-renouvelables dans la planification des projets

L'approvisionnement de ressources non-renouvelables sur un projet représente la base du couplage entre un modèle de planification de projets et celui de planification d'une chaîne logistique. Afin de faire une revue de la littérature sur l'approvisionnement des ressources non-renouvelables dans la planification des projets, les différents mots clés concernant ce sujet et les combinaisons de ces mots ont été rentrés dans les bases de données suivantes : Web of Knowledge, ScienceDirect, SpringerLink et Google Scholar. Les mots clés comprennent les termes « supply chain planning », « environmental responsible project scheduling », « optimization », « resource constrained project scheduling problem », « multi project scheduling », « resource investment problems », « material ordering », « production planning » et « ordering the resources in project scheduling ». Le tableau 23 (Section 3.3) résume toutes les recherches existantes dans ce domaine depuis 1980 jusqu'à 2016.

(Aquilano et Smith, 1980) présente le problème intégré de la planification de projet avec la commande de matériel. Les auteurs indiquent la nécessité de considérer les délais de commande dans la planification de projet ainsi que les quantités de matériaux stockables sur les chantiers. Leur travail présente un ensemble d'algorithmes développés pour traiter le modèle.

Dans une étude postérieure, Smith-Daniels et Aquilano adaptent cette approche à des cas réels (Smith-Daniels et Aquilano, 1984). Les auteurs imposent une limite pour la disponibilité maximale des ressources renouvelables. Ils présentent une heuristique qui traite la planification des ressources renouvelables et non renouvelables.

(Smith-Daniels et Smith-Daniels, 1987a) développent un modèle PLNE pour maximiser la Valeur Actuelle Nette (VAN) dans les modèles de planification de projet afin de valoriser le coût du capital et des matériaux.

Par la suite, (Smith-Daniels et al., 1987b) présente un modèle PLNE dans lequel un délai d'approvisionnement des ressources et un deadline sont considérés. L'objectif de la planification est défini comme la minimisation du coût total de l'exécution du système. Une heuristique sur la base de l'algorithme de (Wagner and Within, 1958) est développée pour résoudre le modèle.

Dans le travail suivant, (Dodin et Elimam, 2001) étend le travail de (Smith-Daniels et al., 1987) pour intégrer la variabilité dans la durée des activités en minimisant le coût d'exécution des projets.

(Sajadieh et Shadrokh, 2009) considèrent différents seuils de commande des matériaux. Le modèle détermine l'ordonnancement des tâches afin de minimiser le coût total de réalisation des projets. Les auteurs utilisent un algorithme génétique pour résoudre le modèle.

(Zoraghi et al., 2012) propose un modèle de programmation en nombre entier mixte pour gérer la commande de matériaux dans la planification de projet en considérant un deadline associé au projet. Les auteurs appliquent un algorithme hybride entre l'algorithme génétique et le recuit simulé pour résoudre le modèle mathématique. En outre, ils utilisent la méthode Taguchi pour régler les

paramètres de l'algorithme proposé. Afin d'évaluer la performance de l'algorithme, ils comparent les résultats de l'algorithme avec les résultats des problèmes de test résolus par le logiciel LINGO.

(Fu, 2014) considère un problème de planification de projet multi modes intégré à la commande des matériaux. Dans ce modèle, la disponibilité des ressources renouvelables est limitée. Cependant, cela ne suppose pas une capacité limitée pour fournir les ressources non renouvelables sur le site de travail du projet. En outre, le modèle considère une deadline pour l'exécution du projet. Le but du modèle est de minimiser le coût total du système. Ce coût comprend les coûts d'utilisation des ressources renouvelables, le coût du matériel, le coût de la commande, le coût de stockage, le coût de l'expédition et la pénalité de retard. Un algorithme génétique est utilisé pour résoudre le modèle.

Zoraghi et al. (2015) étendent leurs travaux antérieurs, (Zoraghi et al., 2012), en considérant le délai d'approvisionnement des ressources non-renouvelables et la planification des ressources renouvelables limitées en quantité. Les auteurs utilisent deux méta-heuristiques hybrides basées sur un algorithme génétique et un recuit simulé pour résoudre le problème intégré. En outre, des méthodes statistiques sont utilisées pour régler les paramètres des deux algorithmes.

(Tabrizi et Ghaderi, 2015) développe l'étude de (Sajadieh et Shadrokh, 2009) pour inclure des capacités limitées de stockage sur le site de travail du projet. Ils utilisent le solveur GAMS 22.1 pour résoudre les instances du modèle.

Tabrizi et Ghaderi (2016) considèrent ensuite l'incertitude dans la durée des activités ainsi que le coût d'exécution. Ils développent un modèle robuste qui cherche à minimiser le coût total d'exécution des activités et la maximisation de l'ordonnancement de tâches. NSGA-II et une version modifiée de l'algorithme d'évolution différentielle multi-objectif ont été utilisés comme approche de solution dans le modèle. Les paramètres de l'algorithme sont ajustés par la méthode de Taguchi et l'application de l'algorithme est vérifiée en comparant les résultats obtenus à partir de l'algorithme et les résultats obtenus à partir de la méthode du ϵ -constraint.

7.2.3 Planification d'une chaîne logistique verte

(Sarkis et al., 2011) présente la gestion de la chaîne logistique verte comme intégrant les préoccupations environnementales dans les pratiques inter organisationnelles de la gestion de la chaîne logistique, y compris la logistique inverse.

La chaîne logistique inverse gère les flux liés au retour des déchets, des produits abimés ou non conformes depuis les clients vers les centres de recyclage en les couplant avec les flux directs, c'est-à-dire les flux reliés à l'approvisionnement des matériaux et produits demandés vers les clients (Kumar et al., 2009). La planification des flux directs comprend la planification d'achat des matières premières, la planification de production et la planification de distribution et transport, (Sun et al., 2010), (Bengtsson and Nonås, 2010), (Akkerman et al., 2010) and (Wei et al., 2017).

7.2.4 Positionnement des travaux

En se référant au tableau 2 (Section 3.3), nous pouvons conclure que les travaux de recherche sur ce sujet constituent une petite partie de la littérature. Il existe encore des besoins pour développer des modèles adaptés aux situations pratiques, en particulier sur notre sujet de recherche dans la planification des projets avec l'acquisition en juste à temps des ressources non renouvelables.

Le modèle de notre étude développe un cadre de planification de multi projets qui hérite de certaines spécifications de problèmes à contraintes de temps (jalons imposés sur les activités) et de problèmes de planification de projets à contraintes de ressources (disponibilité limitée de ressources renouvelables et ajout limité de nouvelles capacités de ces ressources), (Contribution 1). Afin de planifier la réception des ressources non renouvelables sur les chantiers en juste à temps, la planification de la chaîne logistique (planification de production, stock et transport) est intégrée à la planification des projets, (Contribution 2). En outre, afin de rendre le modèle adapté aux facteurs décisionnels durables et écologiques, la collecte et le recyclage des déchets produits dans les chantiers sont considérés (Contribution 3). La résolution du modèle est faite par un algorithme exact et un algorithme de type génétique (Contribution 4).

7.3 Modélisation et résolution

7.3.1 Description du modèle

L'objectif mathématique du modèle est de minimiser le coût total du système, c'est-à-dire, les coûts liés aux projets et les coûts liés à la chaîne logistique. Le modèle considère un ensemble de projets à effectuer en parallèle (multi projet). Les projets doivent se partager une quantité limitée de ressources renouvelables (pour CRIBA, cela concerne essentiellement main d'œuvre et certains engins de chantier). Cependant, il est possible d'augmenter, dans une certaine mesure, les capacités disponibles de ces ressources en les payants. Parmi les ressources renouvelables, certaines de ces ressources ont un coût d'utilisation élevé (ex : location d'une grue). Pour ces ressources, le modèle vise à raccourcir l'intervalle de temps pendant lequel elles sont présentes sur les chantiers.

Chaque projet est constitué d'un ensemble d'activités. Ces activités possèdent certains attributs : durée, date de début au plus tôt, date de début au plus tard, demande de chaque type de ressources renouvelable, demande de chaque type de ressource non-renouvelable et quantité de déchets produits. De plus, une date jalon est associée à certaines activités. En cas de dépassement de cette date, il y a un coût de pénalité supplémentaire pour chaque période de retard.

La chaîne logistique du modèle contient quatre types de partenaires : les fournisseurs de matières premières, les fabricants (avec ou sans centre de recyclage des déchets, potentiellement sur plusieurs niveaux), les chantiers et les centres dédiés au recyclage des déchets.

Les fournisseurs fournissent les matières premières aux fabricants de produits finis ou intermédiaires sous contrainte de capacité limitée de transport. Les produits intermédiaires ainsi que les produits finis sont fabriqués dans les centres de fabrication ayant une capacité limitée de production. Pour accroître la fiabilité, les centres de fabrication sont flexibles pour augmenter leur

capacité de production. Cependant, cette capacité supplémentaire est limitée. Deux types de stock sont pris en compte. Ils comprennent des stocks d'entrées et des stocks de sortis. Le stock d'entrée comprend les articles qui sont reçus dans une unité. Ils seront utilisés pour des objectifs de production/recyclage, par exemple des matières premières ou des produits intermédiaires. D'autre part, le stock de sorties stocke des éléments qui fabriqués dans une unité, en attente de livraison à un autre acteur. Les déchets produits sur les chantiers sont censés être expédiés aux lignes de recyclage. Ces lignes sont situées soit dans les centres de recyclage, soit dans les centres de fabrication qui possèdent également des lignes de recyclage. La capacité de recyclage peut aussi être étendue. Toutefois, la capacité supplémentaire est limitée par une valeur donnée. Les hypothèses supplémentaires du modèle sont établies comme suit :

- La préemption des activités n'est pas autorisée.
- La durée de réalisation des activités a une valeur fixe et connue à priori.
- Quatre types de précédence (fin-début, fin-fin, début-début et début-début) existent dans le modèle.
- Entre certaines tâches, il existe des relations d'enchaînement immédiat : la tâche B doit démarrer dès que la tâche A est terminée.
- Les demandes de chaque activité pour chacune des ressources renouvelables et non renouvelables sont connues. La quantité de production des déchets par chacune des activités est connue a priori.
- Les fenêtres de temps [date de début au plus tôt -plus tard des activités] et les dates jalons sont estimées par des experts.
- Les acteurs de la chaîne d'approvisionnement sont choisis par le processus décisionnel supérieur au niveau stratégique.
- Les capacités de transport, de production et de stockage ainsi que l'ajout maximal de capacité sur les lignes de production / recyclage sont connues à priori.
- Des délais de transport et production/recyclage sont intégrés dans le modèle.

III.II Formulation mathématique

Le modèle mathématique est présenté dans (Gholizadeh-Tayyar et al., 2016). La fonction objective du modèle minimise le coût total du système. Elle comprend deux types du coût : (i) les coûts liés aux projets, incluant le coût des chantiers, les coûts liés à l'utilisation des ressources renouvelables dont le coût du loyer est élevé, le coût total de pénalité pour l'achèvement tardif des activités et le coût total de l'ajout des ressources renouvelables supplémentaires, et (ii) les coûts liés à la chaîne logistique qui incluent le coût total de transport des articles, le coût de stockage des articles d'entrées et de sortis, le coût de production / recyclage et le coût lié à l'ajout de capacités supplémentaire de production / recyclage.

Les contraintes sont présentées comme suit (voir Section 4.2.3):

- (i) Une seule date de démarrage est imposée pour chaque tâche des projets.
- (ii) Chacune des tâches doit démarrer entre les dates de début plus tôt et plus tard.
- (iii) Les contraintes de précédence (quatre types généraux de précédence et deux types de précédence d'enchaînement immédiats ou non) doivent être respectées.
- (iv) L'interruption des tâches n'est pas permise.
- (v) Une valeur de retard est calculée pour les tâches qui dépassent leur deadline.
- (vi) La demande des tâches pour les ressources renouvelables ne doit pas dépasser la quantité disponible des ressources plus la quantité qui peut être louée.
- (vii) L'ajout supplémentaire des ressources renouvelables est limité.
- (viii) La demande des tâches pour chaque type de ressource non-renouvelable doit être satisfaite en considérant le délai de transport.
- (ix) En considérant des délais de transport et de production, les contraintes de conservation de flux pour les articles d'entrées et de sorties dans chaque unité de la chaîne logistique sur chaque période de temps doit être respecté.
- (x) La charge de production ou de recyclage sur les lignes de production ou de recyclage ne doit pas dépasser la capacité disponible plus la capacité qui peut être ajoutée.
- (xi) La capacité rajoutée de production ou recyclage est limitée.
- (xii) La capacité de transport est limitée.
- (xiii) Le niveau de stock des articles d'entrée et sorti au début et fin de horizon de planning est égale à zéro.

7.3.2 Résolution du modèle

Le modèle proposé est résolu par deux approches : (i) Algorithme exact basé sur l'approche de relaxation continue et (ii) Algorithme génétique.

(i) *Algorithme exact basé sur l'approche de relaxation continue :*

Dans cette approche, le logiciel Cplex version 12.6.1 est utilisé. Comme la complexité des PLNE est liée au nombre de variables de décision binaires (Wolsey et Nemhauser, 2014), la réduction des efforts de calcul pour la résolution de ces problèmes peut s'obtenir en diminuant le nombre total de variables de décision binaires. Dans le modèle mathématique proposé, le nombre total des variables binaires du problème est égal à $N = \sum_{i=1}^I (L_i - E_i)$, où, L_i est la date de début au plus tard de la tâche i , et E_i est la date de début au plus tôt de la tâche i . De ce fait, un moyen efficace de diminuer N est de resserrer l'intervalle $[L_i, E_i]$ pour chaque tâche, (Gholizadeh-Tayyar et al., 2014) à l'aide d'un pré-traitement. Il est ici basé sur la relaxation des variables entières.

La première étape de la procédure modifie la date de début au plus tôt en minimisant la valeur correspondante pour chaque activité. D'autre part, la deuxième étape maximise les dates de début afin de calculer les nouvelles dates de début au plus tard. Cette procédure est décrite par l'Algorithme 1 de ce mémoire (Section 4.2.5.1). Les valeurs

obtenues sont exploités pour la résolution finale. Les résultats de l'application de cet algorithme sur un test du modèle sont présentés dans le Tableau 13.

(ii) Algorithme génétique:

Sur la base du travail présenté dans (Tayyar et al., 2016), cette méthode de résolution comprend deux phases: (i) Phase de prétraitement, (ii). Application de l'algorithme génétique (GA).

(i). Phase de prétraitement :

La procédure de prétraitement inclue deux étapes : (a) Convertir les précédences fin-fin, début-début et début-fin en une précédence fin-début, et (b) Déployer la méthode CPM afin de corriger et modifier les dates estimées de début au plus tôt et plus tard des tâches, Algorithme 2 (Section 4.3.1).

(ii). Application de l'algorithme génétique (GA) :

Les éléments clés du chromosome, Figure 41, sont liés à la détermination de la date de début possible pour les tâches. L'objectif principal de GA adapté au modèle est de définir les dates de début pour les activités des projets dans une interaction entre les contraintes de planification du projet et les contraintes de la chaîne logistique avancée (les contraintes de capacité du transport et de la production de la chaîne logistique et les contraintes liés à la conservation des flux) et puis de propager l'effet des dates de débuts générées sur la chaîne logistique inverse afin de planifier le transport et le recyclage des déchets. Les Algorithmes 3 et Algorithme 4 (Section 4.3.2) décrivent ce mécanisme de calcul.

L'aptitude des solutions générées est évaluée par leur coût. Il comprend deux termes: *a.* Le coût de la solution, qui est égal à la valeur de la fonction objective pour la solution et *b.* Le coût de la pénalité, pour les solutions qui ne sont pas faisables.

Après avoir créé une population des solutions et le calcul de la fonction d'aptitude pour chacun des individus, l'algorithme génétique utilise l'opérateur de croisement d'ordre 1 pour combiner le contenu de deux parents afin de générer des enfants. La sélection des solutions élitiste est utilisée dans l'opérateur de Roulette Wheel. De plus, un opérateur hybride entre les opérateurs d'échange, d'inversion et d'insertion est implanté afin de définir l'opération de mutation.

Les contraintes du problème sont divisées en deux catégories : des contraintes souples et des contraintes dures. Les contraintes souples peuvent être violées. Dans ce cas, elles induisent des pénalités dans la fonction de coût, alors que les contraintes dures doivent impérativement être respectées.

Les contraintes souples du modèle sont: 1-La capacité de stockage dans la chaîne d'approvisionnement avancée et 2-Les contraintes de capacité du réseau de la chaîne d'approvisionnement inverse.

Les contraintes dures incluent : 1- Chaque activité doit être exécutée exactement entre sa date de début au plus tôt et au plus tard, 2- les contraintes de précédence et de ressource doivent être respectées. 3- L'interruption des activités n'est pas autorisée. 4- Les activités avec enchaînement immédiat doivent être lancées immédiatement après l'accomplissement des activités précédentes. 5- La demande des chantiers pour les ressources non renouvelables doit être satisfaite en juste à temps. 6 - Compte tenu des délais de transport et de production, la matière première et les produits intermédiaires requis doivent arriver à leur point d'utilisation avec la quantité requise. 7- La charge de travail en production ne doit pas dépasser la capacité de production initiale disponible plus la capacité maximale pouvant être ajoutée. 8-Les stocks des éléments entrants et sortants chez les différents acteurs de la chaîne logistique doivent être égaux à zéro au début et à la fin de l'horizon de planification.

L'algorithme s'arrête après un nombre maximum d'itérations. Les paramètres de l'algorithme sont ajustés en utilisant la méthode Taguchi (Section 4.3.3) pour trois tailles du modèle (petite, medium et grande), Tableau 24- Tableau 25. L'algorithme est testé sur 50 instances. La performance de l'algorithme est rapportée sur les Tableau 26 et Tableau 27. La convergence est analysée sur laFigure 46.

7.4 Implémentation du système d'aide à la décision

CRIBA Logistics est une application web qui implémente l'approche de modélisation décrite dans les Sections 7.3.1 et Section 7.3.2, méthode (i) permet aux utilisateurs de :

- Créer et modéliser un nouveau projet pour la planification des chantiers avec leur chaîne logistique.
- Lancer la phase de prétraitement afin d'améliorer la date de début la plus tôt et plus tard des tâches estimées par les utilisateurs et de ce fait améliorer l'efficacité de l'application.
- Exécuter la résolution et récupérer les résultats dans les feuilles Excel en utilisant la première méthode de solution.

Un éditeur (Project Editor) et deux modeleurs (Product Modeller et Logistics Modeller) sont développés :

Project Editor permet aux utilisateurs de créer et de gérer leur propre projet de planification des multi projets de la rénovation énergétique des bâtiments. Les icônes « Product Modeller » et « Logistics Modeller » permettent respectivement de concevoir la vue nomenclature des produits et la vue logistique c'est-à-dire le réseau des fournisseurs, fabricant, centres de recyclage liés aux sites de travail des projets.

7.5 Conclusion

L'objectif global de ce mémoire est de développer un outil de prise de décision pour aider les gestionnaires à planifier des multi projets avec leurs chaînes logistiques. D'une part, les projets se partageant des ressources renouvelables présentent en une quantité limitée. D'autre part, les ressources non-renouvelables sont fournies avec une capacité limitée d'approvisionnement de la chaîne logistique. Pour déterminer le cadre de la planification du problème, plusieurs spécifications ont été retenues. Elles sont généralement définies en fonction du gap existant dans la littérature et les exigences des organisations. Généralement, le modèle englobe trois points mentionnés ci-dessous :

- *Approvisionnement en juste à temps des ressources non-renouvelables sur les chantiers des projets:*
En raison de l'intérêt croissant des organisations pour supprimer les stocks des produits peu demandés et à forte valeur, ces ressources sont livrées en juste à temps sur les chantiers. Cela conduit à étendre le cadre de la planification du problème. Il faut non seulement planifier les projets mais faire une planification intégrée des projets et leurs chaînes logistiques. La motivation pour cette intégration est due aux trois points suivants :
 - Les contraintes temporelles du projet affectent la planification de la chaîne logistique :
La prise en compte des contraintes imposées pour l'exécution des projets, des facteurs tels que les fenêtres de temps pour l'exécution des tâches, des relations de précédence entre les tâches et le deadline des activités créent des contraintes sur les opérations de production et d'approvisionnement de la chaîne. Par conséquent, l'optimisation de la chaîne logistique doit intégrer les contraintes de planification.
 - Les contraintes de la chaîne logistique ont un impact sur la planification des tâches des projets :
Les limites et contraintes de la chaîne d'approvisionnement telles que les capacités de transport, de production et de stockage ainsi que les délais de transport et de production influent sur la livraison des produits finaux sur les chantiers. Par conséquent, le démarrage des tâches des chantiers et l'approvisionnement des ressources demandée nécessitent de considérer les contraintes de la chaîne logistique.
 - Les contraintes de gestion des ressources renouvelable des projets affectent la planification de la chaîne logistique et des projets : l'ordonnancement et la planification des activités sur les chantiers dépendent également de la disponibilité des ressources renouvelables.
- *Compromis entre la durée des projets et l'affectation des ressources renouvelables :*
Dans ce modèle, certaines tâches ont des dates de fin souhaitées et il existe des pénalités de retards si ces dates ne sont pas respectées. D'autre part, les ressources renouvelables disponibles initialement sont en capacité limitée mais il est possible d'acquérir des capacités supplémentaires (location, intérim). Le modèle tente de créer un équilibre entre les coûts

de pénalité dûs au dépassement des dates de fin souhaitées et les coûts d'ajout des ressources renouvelables.

- *Inclusion des critères verts dans la planification des projets:*

Afin de respecter les préoccupations environnementales, le modèle prend en compte le transport des déchets des chantiers et leur recyclage dans les centres appropriés. Ces centres sont situés soit dans les centres de fabrication, soit sont des centres spécialisés de recyclage.

Le problème de planification est modélisé sous forme d'un système d'équations et résolu par des approches de recherche opérationnelle. Une application du modèle a été réalisée sur un cas relatif au projet CRIBA. Étant donné que les problèmes de planification de projet sous contraintes appartiennent à la classe NP-difficile des problèmes d'optimisation, deux algorithmes de résolution sont développés et utilisés pour traiter les problèmes : un algorithme exact basé sur la relaxation continue qui essaye de réduire la complexité de résolution des problèmes de test du modèle et une méta-heuristique du type de algorithme génétique qui présente une procédure de construction de solution semi-optimale.

Les perspectives sont développées ci-dessous.

- *Implication de l'incertitude:*

Dans le modèle proposé, tous les paramètres sont déterministes. Cependant, ce n'est pas le cas dans la plupart des situations réelles : la durée des activités, les fenêtres de temps pour l'exécution des tâches et la disponibilité des ressources sont souvent estimées avec un certain degré d'incertitude. En outre, en raison du manque d'information, les paramètres de la chaîne logistique tels que les capacités de transport et de production, les délais d'approvisionnement peuvent être incertains. Par conséquent, pour le développement futur du cadre de modélisation, introduire de l'incertitude quant à la durée des activités et à la capacité de transport de la chaîne d'approvisionnement est intéressante. Dans ce contexte, la programmation stochastique ou l'optimisation robuste pourraient constituer des pistes prometteuses.

- *Développement de modèles sociaux et environnementaux responsables:*

En regardant l'état de l'art sur la planification de projets avec des approches d'optimisation, nous pouvons constater que les problèmes liés aux coûts et au temps ont été largement étudiés. Par ailleurs, les chercheurs ont également considéré les modèles prenant en compte les aspects qualité ainsi que la minimisation des travaux en retards. Néanmoins, les problèmes de planification de projets avec des objectifs environnementaux et sociaux n'ont pas encore mis sous la forme de modèles d'optimisation. A notre connaissance la littérature montre une certaine lacune dans ce contexte. Dans le cadre de la responsabilité environnementale, l'étude actuelle traite de la gestion des déchets. Cependant, d'autres pratiques en matière d'environnement telles que la limitation des émissions de gaz à effet de serre par unité de produit fournie par les différents modes de transport des divers fournisseurs peuvent être considérées dans les développements de ces modèles. De plus,

l'intégration des facteurs sociaux tels que le chômage dans la planification des projets pourrait être également incluse.

- *Extension de la planification des projets contraints avec des objectifs dans le nivellement et l'affectation des ressources*

Dans le modèle proposé, les ressources renouvelables sont affectées aux activités en fonction de leur disponibilité initiale et des capacités qui peuvent être louées en plus. Pour minimiser les fluctuations d'utilisation des ressources, les problèmes de nivellement des ressources peuvent fournir des pistes pour de futures extensions du modèle.

- *Extension des hypothèses du modèle*

Le cadre du modèle pourrait être étendu en jouant sur les paramètres du réseau de la chaîne d'approvisionnement, comme les modes de transport, les niveaux de rabais pour l'achat des matières premières et des produits intermédiaires, la production ou l'achat par lots etc. De plus, le modèle peut être enrichi en considérant qu'il existe plusieurs manières d'exécuter une tâche ou en ayant des ressources (humaines en particulier) ayant des compétences multiples.

- *Développement et implémentation de procédures supplémentaires de résolution dans les systèmes de l'aide à la décision*

Dans ce contexte, l'étude reste encore ouverte pour de nouvelles procédures de résolution pour la planification des projets et la planification du réseau de la chaîne logistique. En outre, l'application d'autres algorithmes basés sur des méta-heuristiques pourrait être entreprise.

- *Directions pour le projet CRIBA*

Dans le projet CRIBA qui fait l'objet du démonstrateur (projet CRIBA, 2010), les habitants restent dans leur logement pendant les travaux de rénovation énergétique. Ceci pose de nombreuses contraintes (par exemple : synchroniser les travaux sur la façade extérieure et la rénovation intérieure pour minimiser la gêne). D'autres stratégies peuvent être envisagées pour accroître la satisfaction des habitants (exemple : relogement provisoire) et la performance du projet de rénovation (coût, délai).

De plus, l'application des pratiques de Integrated Building Design (IBD) pourrait être intéressante. Il s'agit d'améliorer le confort des occupants et la performance du bâtiment en considérant des stratégies de conception intégrée et en tenant compte des interactions entre tous les systèmes du bâtiment. En outre, l'utilisation de logiciels de modélisation de Building Information Modeling (BIM), qui assurent le partage des connaissances et des informations sur les bâtiments, peut constituer une base fiable pour accélérer la structuration et la modélisation du projet de rénovation énergétiques d'un bâtiment. Le but serait de développer l'usage de la planification couplée dans les phases d'appel d'offre.

Glossary

Analytic Hierarchy Process (AHP) is a method that uses hierarchical decomposition to deal with multi-criteria decision making in complex problems showing the relationships of the criteria and alternatives.

AngularJS is a JavaScript structural framework for dynamic web applications. It can be added to an HTML page in order to use HTML as the template language and its syntax to express the application's components.

Apache cxf provides an open-service framework to build and develop services using frontend programming interfaces.

Bill of Material (BoM) presents a list of the raw materials, intermediate products, components and the quantities of each of these items that are required to produce a final product.

Continuous Replenishment Program (CRP) is a concept for improving the flow of products in the supply chain network. It focuses on reducing inventory levels, decreasing stocks and boosting efficiency in warehousing.

Common Object Request Broker Architecture (CORBA) is an architecture and style for creating, distributing, and managing distributed program objects in a network. It enhances the collaboration between systems.

Earned Value (EV) indicates how much of the resources, budget and time should have been spent while considering the amount of work done up to the present.

GNU Affero General Public License is a free, copyleft license for software development objectives that is provided to ensure cooperation with the community for network server software. It provides the possibility to distribute and modify the versions while keeping track of the changes and the date of the changes.

Hyper Text Markup Language (HTML) is a standard markup language which is used to create the pages displayed on the World Wide Web.

Hyper Text Transfer Protocol (HTTP) is a protocol used in the World Wide Web to determine how messages will be formatted and transmitted and what actions have to be taken in response to various commands.

JSON is used for data interchanging. It is based on a subset of the JavaScript language. It enables the system to store information in an easy-to-access way.

Just-in-Time (JiT) is a demand-driven strategy in which the product is sent to the destination of use once a demand has been created. Its objective is to eliminate product inventory.

Project Management Process (PMP) addresses the various phases of the project lifecycle. It includes scope management, schedule management, budget management, quality management, team management, stakeholder management, information management, risk management and contract management.

Optimization Programming Language (OPL) provides a programming language and syntax that support all expressions needed to code and solve problems in both mathematical and constraint programming.

Operation research (OR) applies methods of mathematical models, statistics and algorithms to help decision makers in improving the performance of systems.

Remote Procedure Call (RPC) is a protocol that enables users to request a service from a program located in another computer in a network without having to know the specifications of the network.

Representational State Transfer (REST) is an architectural style and an approach that describes how networked resources are defined and addressed in the development of web services. Since REST does not require much bandwidth, it is practical for using on the Internet.

Return On Investment (ROI) measures the efficiency of an investment. It is also utilized to compare the efficiency of the various investments.

Simple Object Access Protocol (SOAP) is a XML-based messaging protocol that is used to exchange information among computers.

Schedule Variance (SV) measures the difference between the earned value and planned value. Positive values of SV show that the project is ahead of schedule.

Work Breakdown Structure (WBS) according to (PMBOK, Fourth Edition, 2008), WBS is defined as a deliverable-oriented hierarchical decomposition of the work to be executed by the project team.

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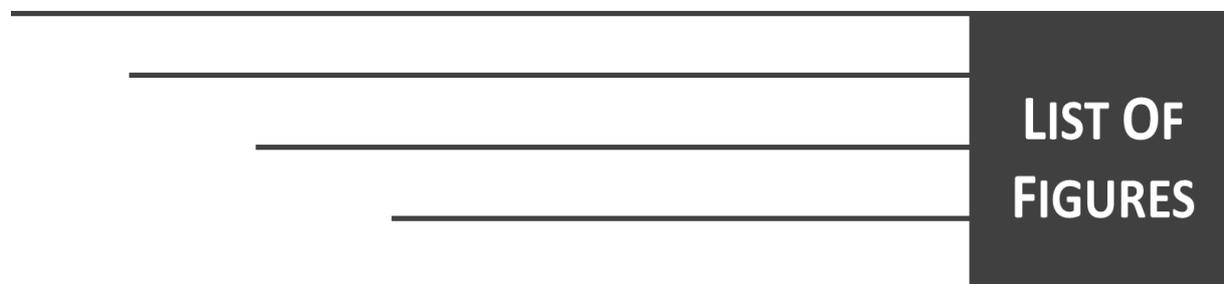


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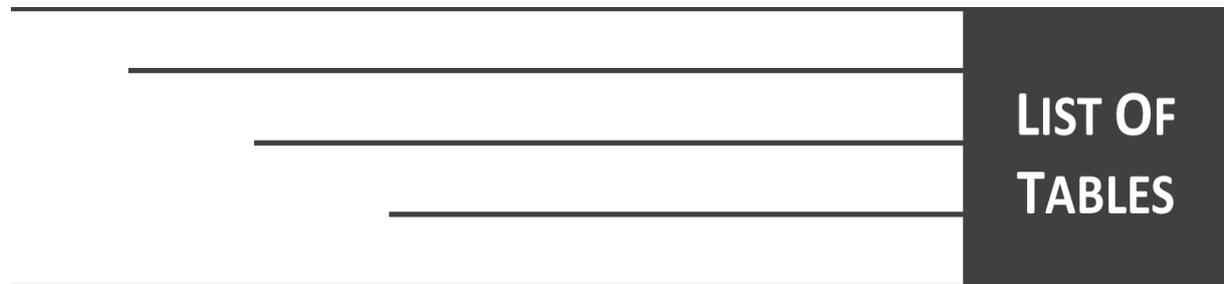


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Résumé court en Français

Une approche basée sur l'optimisation pour la planification simultanée de multi projets et réseaux logistique : application aux projets de la rénovation de bâtiments

Le contexte d'application de cette recherche a été le projet CRIBA. CRIBA vise à industrialiser une solution intégrée de rénovation et d'isolation de grands bâtiments. De ce fait, une part importante de la valeur ajoutée est transférée des chantiers de rénovation vers des usines de fabrications devant être synchronisées avec les chantiers.

La planification est l'une des étapes importantes de la gestion de projets. S'adaptant à une organisation, elle vise une réalisation optimale en considérant les facteurs de temps, coût, qualité ainsi que l'affectation efficace des ressources. Cette affectation est d'autant plus complexe lorsqu'un ensemble de projets se partagent les ressources, renouvelables ou non renouvelables. L'objectif global de notre étude est de développer un outil d'aide à la décision pour un décideur visant à planifier plusieurs projets en intégrant l'allocation des ressources renouvelables, et la planification des flux de ressources non-renouvelables vers ces projets. Dans ce cadre, les ressources non renouvelables telles que les machines et la main-d'œuvre ont une disponibilité initiale limitée sur les chantiers. Cependant, nous supposons que des quantités limitées supplémentaires peuvent être achetées. En outre, nous prenons en compte la volonté des coordinateurs des projets pour l'approvisionnement des chantiers en juste à temps (just in time), en particulier pour les ressources peu demandées, encombrantes et à forte valeur. Ceci oblige à étendre le cadre du modèle de la planification des projets en incluant la planification de la chaîne logistique qui approvisionne les ressources non renouvelables des chantiers. Enfin, pour répondre au besoin d'outils décisionnels responsables sur le plan environnemental, le modèle prévoit le transport et le recyclage des déchets des chantiers dans les centres appropriés. Un modèle linéaire mixte du problème est ainsi posé. Puisqu'il rentre dans la classe des modèles d'optimisation NP-durs, une double résolution est proposée. D'abord à l'aide d'un solveur puis une meta-heuristique basée sur un algorithme génétique. De plus, pour faciliter l'utilisation du modèle par des utilisateurs peu familiers avec la recherche opérationnelle, un système d'aide à la décision basé sur une application web a été développé. L'ensemble de ces contributions ont été évaluées sur des jeux de test issus du projet CRIBA.

Mots clés: Optimisation combinatoire, Planification de multi projets, Planification de chaîne logistique, Algorithme génétique, Rénovation énergétique de bâtiments.

Short English abstract

An optimization-based framework for concurrent planning of multiple projects and supply chain: application on building thermal renovation projects

The application context of the current study is on a CRIBA project. The CRIBA aims to industrialize an integrated solution for the insulation and thermal renovation of building complexes in France. As a result, a significant part of the added value is transferred from the renovation sites to the manufacturing centers, making both synchronized.

Planning is one of the important steps in project management. Depending on the different viewpoints of organizations, successful planning for projects can be achieved by performing to optimality within the time, cost, and quality factors as well as with the efficient assignment of resources. Planning for the allocation of resources becomes more complex when a set of projects is sharing renewable and non-renewable resources. The global objective of the study is to develop a decision-making tool for decision-makers to plan multiple projects by integrating the allocation of the renewable resources and planning the flow of non-renewable resources to the project worksites. In this context, non-renewable resources such as equipment and labor have a limited initial availability at the construction sites. Nevertheless, we assume that additional limited amounts can be added to the projects. In addition, we take into account the interest of the project coordinators in supplying the non-renewable resources in a just-in-time manner to the projects, especially for low-demand resources with a high price. This requires extending the framework of the project planning by including the planning of the supply chain which is responsible. Finally, in order to meet the requirements for environmentally responsible decision-making, the model envisages the transportation and recycling of waste from project sites to appropriate centers. A mixed integer linear model of the problem is proposed. Since it falls within the class of NP-hard optimization models, a double resolution is targeted: first, using a solver and then a metaheuristic based on the genetic algorithm. In addition, in order to facilitate the use of the model by users unfamiliar with operational research, a web-based decision-making support system has been developed. All the contributions are evaluated in a set of case studies from the CRIBA project.

Key words: Combinatorial optimization, Resource- and time-constrained multi-project scheduling problem, Closed-loop supply chain planning, Genetic algorithm, Building energy efficiency.