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SCENARIO BASED SCHEDULING FOR NEW AIRCRAFT DEVELOPMENT

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ABSTRACT
This paper investigates the problems of project scheduling at the design stage of the development of a civil aircraft. Such a complex system development is characterised by a dynamic environment and uncertainties concerning the duration of design activities. In order to leverage these uncertainties, we propose a scenario based approach to define and manage design schedules. These scenarios are created from detailed schedules and should allow project management functions to handles uncertainties and to anticipate the possible consequences of decisions which might affect design schedules.
In our proposal, the problem is considered as a discrete Constraint Satisfaction Problem. The proposed solution includes the energy allocation based approach and the mathematical definition of two new types of constraints for resources allocation. These foundations contribute to the identification of scenarios which are different design schedules alternatives.
To illustrate these proposals the capabilities of the first prototype developed are presented. This prototype is a management tool to compare different scenarios and to build schedules taking into account the dependencies between design teams and their respective constraints.
Our approach is aimed to be generic while remaining flexible enough to be implemented within the aerospace industry. It should facilitate cooperation between design teams and provide scenarios based on schedules for the decision support process at different managerial levels.

Keywords: Design, Scenarios, Scheduling, Project management, Resources allocation, Risk management.

1 INTRODUCTION
Product development complexity can be characterised on one hand by the large number of physical items to be integrated with multiple connections that might be difficult to control (structural complexity). On the other hand, it can also be characterised by process complexity, which deals with product development activities, taking into account items such as design procedures, skills organisation, work distribution, decision procedures, etc. and that is mainly characterised by the numerous interactions between development teams. Consequently, the development of a new civil aircraft can be considered as complex from a product and process point of view.
Development of complex products has been discussed by numerous papers and influential publication [1], [2], [3], . However, current development projects prove that there are still major challenges to be addressed in controlling target dates and resources allocated to a specific development project [4], [5]. The risk of overrunning is particularly high in aircraft industry where resources and budget engaged are important. Facing this situation some correctives actions might be taken (e.g. late allocation of resources based on outsourcing or hiring new personnel, planning changes) but it might affect the operational performances of the company
For design activities scheduling, a majority of methods assume that information to build schedules are available, stable and complete (e.g. activities duration). However, facts show that design process is exposed to a significant level of uncertainty. A method to deal with this uncertainty is using scenarios that described how original design schedules might be affected by specific event in the future. Scenario based scheduling is a management approach to compare different scenarios and to survey uncertainties related to the consequences of a decision or, more generally; the occurrence of an event.

This paper is based on real industrial cases provided by the major European aerospace company. These investigations are carried out in the frame of a R&D project named SPEED.
In the next chapter we describe the SPEED approach. Then, we update the state-of-the art of existing approaches for project scheduling with resource constraints already presented in [6], [7], adding with some new scenario based approaches to deal with uncertainties. In the same chapter we set the foundations of the model we use in this project, which will be defined accurately afterwards. Finally, we detail how scenarios are managed using this model and how these proposals have been implemented in a prototype called SPEED Tool.

2 SPEED APPROACH

SPEED approach is the result of analyses of internal procedures related to project management activities and on semi-structured interviews with team leaders and program management functions of a major European aerospace company. The SPEED project is based on a building-blocks approach in order to concentrate R&D efforts on the development on innovative features of the future solutions. These solutions will be implemented in a federative tool offering the possibility to navigate through dependencies between design teams and to identify decisions impacts on planning at different level of the organisation.
Each building-block, described on Figure 1, represent a group of functions to be provided to end-users through a federative tool.

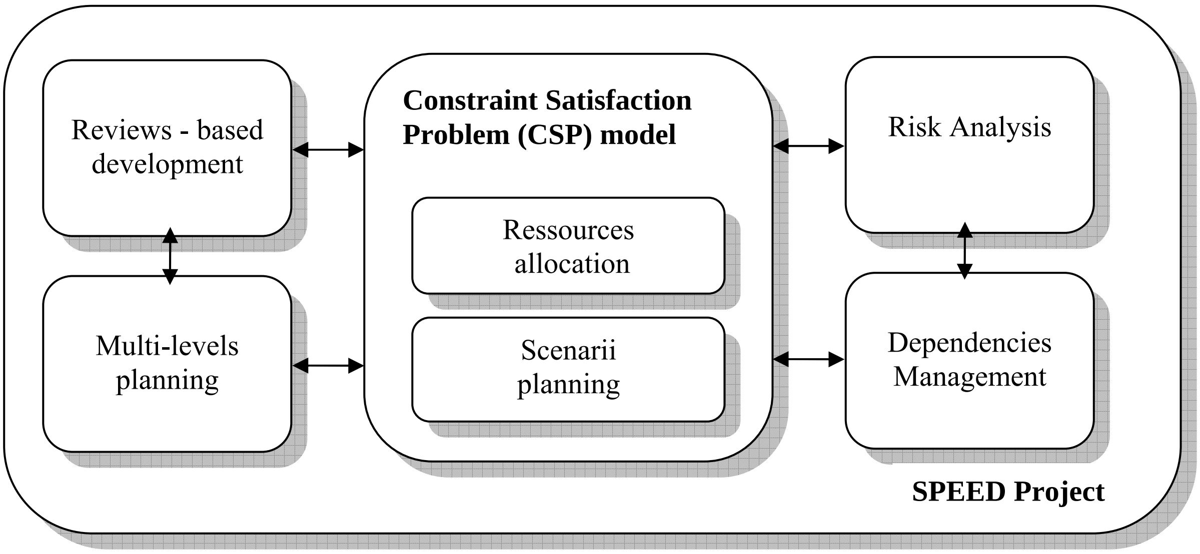

Figure 1, The building-blocks approach of the SPEED project

The approach relies on a Constraint Satisfaction Problem (CSP) model. Resources intensities (per activity and per period) are the main variables of the problem. Our scheduling problem can therefore be considered as a resources allocation problem, which is detailed in chapter 4.
The resource-constrained project scheduling problems are similar to the considered problem, but the objective is usually to find the best schedule that minimizes the makespan or the maximum lateness, with the help of a black-box one-step solving algorithm. In our case we provide a decision making support that helps the user to build iteratively a feasible solution that satisfies all constraints or most of them according to a predefined strategy. This type of tool will allow the user to build different scenarios and to perform scheduling simulations to validate the consistency of each scenario.
This type of scenarios will be related to tactical level schedules. Tactical level schedules are related to the time aspects of the project and major subsystems of the product under development. On the other hand, there is the strategic level, which deals with company plans for middle and long term; and the operational level, which is related to the detailed activities accomplished in the “lowest” level. In aeronautical companies, the strategic level schedules deal with middle and long term plans for a new project launch or the resources allocation for multi-project portfolio. Tactical level schedules are related to an aircraft development program and they can be realised in different managerial levels.

They can support resources allocation and they are key schedules for the program milestones cascading process. Finally, operational level schedules include details of the activities performed by design teams within a specific program.
Other types of scenarios are issued from the dependencies management and are related to operational level schedules. They enable the management of uncertainties affecting dependencies between design teams. In this paper, we do not detail these types of scenarios; nevertheless we will describe the dependencies management process, as it will include new type of constraints in our CSP model.
Another building-block of our approach is the risks analysis, which is a widely accepted management tool for the new product development. Risk analysis studies the impacts that an event could produce in the goals of the project. In our case, the process of risk analysis is used for the evaluation of both scenarios issued from tactical level schedules and operational level schedules.
Tactical level schedules and operational level schedules are organised following a hierarchy, which usually mirrors the organisation of the development teams. Cascading key milestones, activities and resources downstream in this hierarchy follows a review-based development, which will not be detailed.
Cascading process, as well as reporting activities across the different layers is performed through a multi-levels planning process. In this paper, the multi-levels planning aspects are not presented. Nevertheless, we will explain in the perspectives the current work we are developing that consists on aggregating scenarios in order to define schedules specific to the higher level.
But before detailing how these scenarios are managed in our project, we review in the following sections the existing contributions as well as the CSP model.

3 A DECISION MAKING SUPPORT APPROACH FOR THE DESIGN SCHEDULING PROBLEM

3.1 State-of-the-art in scenario planning applied to design schedules

Schoemaker [8] defines scenario planning as a "disciplined method for imagining possible futures".
Usually, "scenario planning" methods are defined for strategic level utilisation. They can include an important variety of quantitative and qualitative information [9]. But their use at tactical and operational levels is avoided due to the complexity of these types of methods [10].
Scenarios could be generated using different type of models. In the case of the GLORIA [11], a method developed in the frame of a R&D project of EDF, the kernel model is created using Bayesian Networks, which enables the decision makers to measure the "domino" effect that an event could have on the project. This method is used to create different scenarios and to measure how each scenario respects the project's objectives. Nevertheless it does not give any accurate information concerning time and cost aspects.
Time aspects in projects can be modelled using activity networks or critical path methods. The purpose of critical path methods is to concentrate attention on a sub-set of tasks with a direct influence on the minimum total project lead-time. Some variants of standard activity networks, like PERT with Alternatives models have been developed [12] in order to deal with different alternatives. Nevertheless, the number of scenarios that can be built with these models are limited because of the fact that the user has to model each modification as a new path of the PERT.
Risk management tools can closely be associated to classical project management tools. A method has been proposed in order to generalise risk management practices at operational levels, see [13], so project manager can generate and assess different scenarios.
Others research teams are focused on schedule risks management and have proposed to use different kind of schedules and management styles according to uncertainty levels[14].

3.2 State-of-the-art in project scheduling with resource constraints

References related to scheduling problems modelling and resolution methods include [15], [16], [17], [18]. A project-scheduling problem is usually defined as a "problem concerned with the scheduling of a number of jobs that are subject to precedence constraints" [18]. When resources to perform jobs are taken into account, we refer to a Resource-Constrained Project-Scheduling Problem (RCPSP) [19], [20], [21], [22], [23]. Belhe and Kusiak have analysed this type of scheduling problem taking into account the specificities of design activities [24].

Dealing with resources, two types of problems are usually distinguished. On one hand disjunctive scheduling problems, where a resource can not realise more than one task during a period. On the other hand, cumulative scheduling problems, where a resource can perform more than one task during a period if maximum available resource quantity is respected [25].
Most methods in cumulative resource problems deal with known activity durations and constant resource allocation (See [26] for an exception), therefore activities shape is fixed and no flexibility is accepted, becoming a problem closely related to packing problem [27]. Besides, most of them usually focused on minimizing the makespan (time the last job leaves the system). Nevertheless, a more realistic approach in aircraft manufacturing consists in stating that project completion time (as well as associated intermediate milestones) is a constraint and the objective is to minimize the energy required to reach this target.
In next two chapters we describe two important facts of the new aircraft development that will help the reader understand the model described in chapter 4.

3.3 The organisation structure based on design teams

In order to manage structural and functional complexities during large systems development, design activities have been divided in entities called design teams, which are mapped against the product architecture. For a limited period time, these entities (usually grouping 40 to 60 persons) integrate different skills with common objectives linked to the development of a subsystem. Design teams have been an efficient answer for the needs of time to market period reduction and developing cost reduction. Nevertheless, the organisation structure based on design teams has stressed the need of respecting internal resources and time constraints. Therefore, the importance of dependencies with other design teams has been reduced, consequently loosing a systemic vision of the entire product.

3.4 Dependencies management in complex product development

Dependencies between design teams can be identified through data and information exchanged and generally physically formalised through a deliverable. In order to begin an activity a design team might need a data coming form another design team. From a scheduling point of view, this exchange is usually formalised by a milestone. For the customer, it is generally a milestone that linked to the begin date of an activity, while for the supplier this milestone can be placed earlier that the end of the activity related to the deliverable.

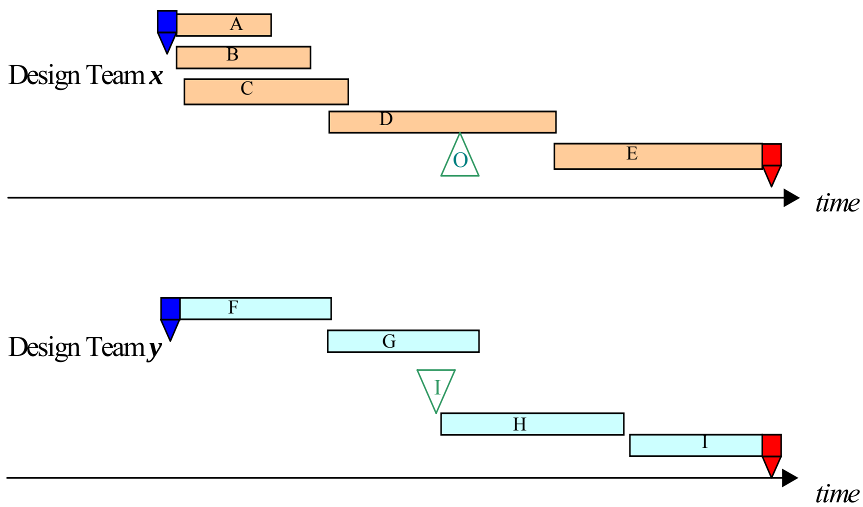

Figure 2, A contract definition in customer and supplier's schedules.

These deliverables exchanges are often subject to negotiations. Consequently, dependencies management often refers to contracts management.
The chart below shows the process for contract request/acceptation.

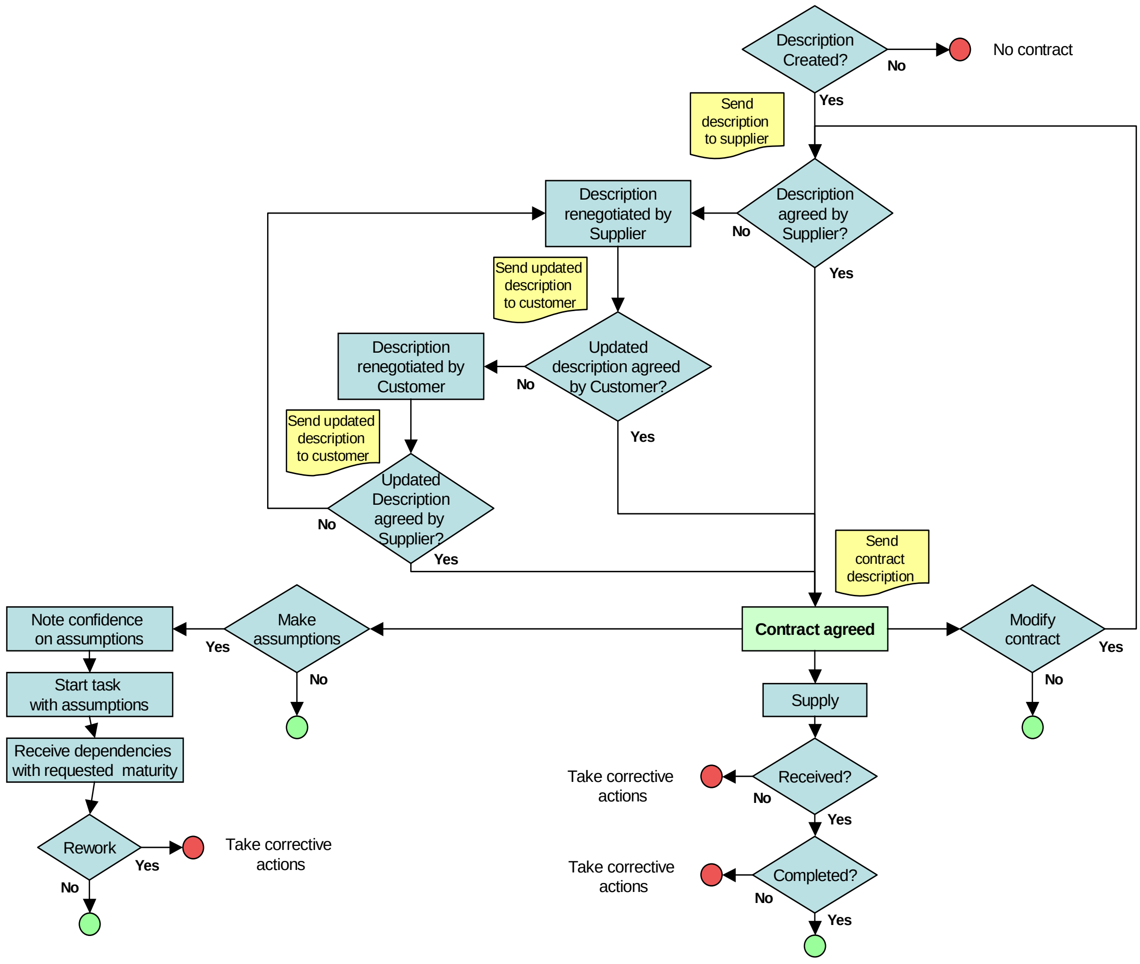

Figure 3, The contract request/acceptation process.

Firstly, the customer completes the description of the required deliverable, indicating the delivery date and requested maturity level. When the supplier receives the request, he can either accept it or decide to renegotiate some aspects. Usually the renegotiations are focused on delivery dates or maturity levels (for more details about maturity related to engineering data, see [28]. If the supplier renegotiates the contract, the modifications will then be sent to the customer, who can also choose to accept or renegotiate them. This process continues until the contract has been accepted by both parties. When this has been done, a “contract form” is sent to both parties and schedules are updated.

In the case where supplier’s activity is not completed before the contract due date, the delivery is considered to be part of a preliminary information exchange. In concurrent engineering based product development, preliminary information acquires an important meaning [29]. In former works we have developed the relationship between activity definition and contracts defining preliminary information [6], [7]. This relationship stands on the energy allocation problem based approach.

4 A CSP MODEL FOR TACTICAL LEVEL SCHEDULING

4.1 The energy allocation problem based approach

Energy characterizes a quantity of work and is then proportional to time and to the strength/intensity of the resource able to perform it. More formally energy is commonly expressed as the integration of *a* resource intensity on time:

$$e^{[t_1,t_2]} = \int_{t_1}^{t_2} a(t).dt \qquad (1)$$

Energy (or a work quantity) is classically represented in a two-dimension diagram by the area located under the resource consumption intensity curve, and between two dates. Under the assumption the problem is discretised into equal periods, the following drawing represents a possible realisation of an activity *I*; let us notice that intensity may only vary from a one period but never inside a period.

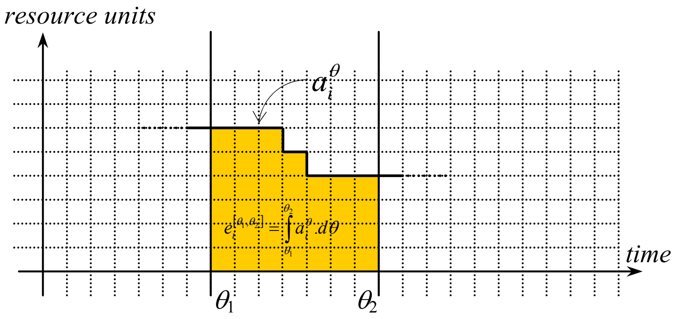

Figure 4, Energy represented in a resource-time diagram

In the particular case where $a_i^\theta = a_i \quad \forall\theta$ (intensity is constant), the definition of the intensity can be simplified: $e^{[\theta_1,\theta_2]} = (\theta_2 - \theta_1).a_i$

Energy is particularly interesting for tackling our scheduling problem in which work quantities that define the activities are well defined and can be considered as data, while durations and resource allocations are decision variables.

The energy concept enables to build special constraint propagation algorithms (cf. for example, [30], [31], [32]) useful both to characterize the problem consistency but also to improve the resolution process, by reducing dynamically the domain of remaining variables, after each decision step. The main idea of this so-called energy-based resolution approach is to deduce restrictions on time location and resource allocation for one activity by taking into account the resource availability and the minimal resource consumption of the remaining concurrent activities. This kind of reasoning has been successful in many scheduling problems (cf. [33]). We will describe in the following sections how these ideas can be exploited in our model.

4.2 A discrete CSP model

We propose to model our allocation problem as a discrete Constraint Satisfaction Problem (CSP). A CSP is mainly characterised by a set of variables, their domains, and a set of constraints [34].

We implement some mechanisms of constraint propagation using a Constraint Logic Programming (CLP) environment. CLP extends Logic Programming and provides a flexible and rigorous framework for solving CSP models.

The activity-scheduling problem that we consider is defined with some assumptions:

The manager of a design team responsible of the development of the subsystem will define a set of activities $I_v = \{i=1..n\}$ that are necessary in order to fulfil the requirements of the next review v. These activities must be scheduled between the two consecutive reviews $v\text{-}1$ and v.

In our model, the time horizon between these two reviews is discretised into H time periods $\theta = 1..H$. Review $v-1$ will be realised at the beginning of the period $\theta = 1$ while review v will be realised at the end of the period $\theta = H$. Periods are typically weeks, supposing that any activity requires at least one period to be achieved even in the case of a maximal resource allocation.

4.3 Activities definition

As we saw before, activities are mainly defined by their energy: e_i denotes the energy required to perform *I*, between its starting date t_i and its finishing date c_i. We consider full elastic preemptive activities [35]: the duration of an activity *I* is not known in advance and its intensity a_i^θ can vary during the realisation. Then the number of resources units allocated to *I* may become null at some periods θ, excepted for t_i and c_i. We also suppose this intensity to be integer, considering that elementary resource units are persons. As a consequence the intensities $\{a_i^\theta\}$ are the main variables of the problem, one per activity and per period. The scheduling problem is thus transformed into an allocation problem.

Activities may be submitted to individual time window constraints, defined by an earliest start period r_i and a latest ending period d_i, with $1 \leq r_i \leq d_i \leq H$.

4.4 Resources definition

We make the assumption that the problem considered is a mono-resource problem.

As reviews dates are given by the managerial upper level, the maximal resource availability A^{θ} is also supposed to be fixed at this decision level. A^{θ} is an integer number that represents the maximal number of persons in the team who may work concurrently at any period θ.

4.5 Constraints to be respected

The first three types of constraints of our model are easy to express:

4.5.1 Activity energy constraint

As the energy e_i to be consumed for processing each activity *I* is a data, any solution must respect:

$$\sum_{\theta=1}^{\theta=H} a_i^{\theta} = e_i \quad \forall I = 1..|I_v|. \tag{2}$$

4.5.2 Cumulative resource constraint

The maximal resource availability curve A^{θ} is also a data and we can state for each period:

$$\sum_{i=1}^{i=|I_v|} a_i^{\theta} \leq A^{\theta} \quad \forall \theta = 1..H. \tag{3}$$

4.5.3 Time window constraints

If such constraints are needed, it is easy to initialize to zero any variable a_i^{θ} for each activity I in any period that do not belong to the time window of i:

$$a_i^{\theta} = 0 \text{ for } \theta \in [1, r_i - 1] \cup [d_i + 1, H]$$

The next two constraints are related to interdependencies between two activities. On one hand, we present an interdependency constraint that deals with a pair of activities belonging to the same design team schedule: the Energy-Precedence Constraint (EPC). On the other hand, we deal with interdependencies between two design teams: Contract Dependencies Constraints (CDC), which are usually formalised by contracts and are often designed us dependencies due to the fact that interactions are usually defined as a supplier/customer type relationship.

4.5.4 Energy-Precedence Constraints (EPCs):

Classically a scheduling precedence constraint between two activities *{I, j}* forces some activity *I* to be finished before some activity *j* begins. It is expressed as the potential inequality $t_j - t_i \geq p_i$ or, which is equivalent: $t_j \geq c_i$.

In a concurrent engineering context, a full parallel execution of design end development activities is desired but not always possible since it could violate the resource availability constraint or because it may exist interdependencies between some pairs of activities. In the latter case an activity *I* is forced to be in a state where it has already consumed a minimal energy e_{ij} (with $e_{ij} < e_i$) before activity *j* can start. This energy corresponds to the minimal work that has to be done in activity *I* to produce reliable data used for starting activity *j*. For that reason we call it an Energy-Precedence Constraint (EPC). Let us note that the traditional scheduling precedence constraint is a particular EPC in which $e_{ij} = e_i$.

EPCs are the most difficult constraints to express with allocation variables $\{a_i^{\theta}\}$ in place of the time variables $\{t_i, c_i, p_i\}$. In order to include these constraints in our model some specific propagation routines have been developed.

4.5.5 Contract Dependencies Constraints (CDCs)

Consider a dependency that involves two design teams and activities *i* and *j* for each team. These activities will have a new temporal constraint defined by a due date. It is a special temporal constraint since the due date is not related to the completion of the activity but to the realisation of a certain amount of work, in other words a constraint related to a dependency oblige to expend an amount of energy before a date. Indeed the Contract Dependency Constraint (CDC_{ij}) is defined by two data: $\{t_{ij}, e_{ij}\}$

For the activity *i* of the first design team:

$$\sum_{1}^{t_{ij}} a_i^{\theta} = e_{ij} \ \ and \ \sum_{t_{ij}+1}^{H} a_i^{\theta} = e_i - e_{ij} \tag{4}$$

While the earliest time of the activity j of the second design team is fixed and equal to t_{ij}. Therefore:

$$a_j^{\theta} = 0 \ \ \forall \theta \in [1..t_{ij}]$$

These constraints are boundaries that our scenarios shall respect

Based on these constraints, different schedules can be created with different configurations for resources allocation in order to support decision making at the different project stages.

5 SCENARIO BASED SCHEDULING FOR DECISION MAKING SUPPORT

The scenario management process developed in the frame of SPEED project includes scenario generation, scenario evaluation and decision support. A scenario is a description of the original schedule, the possible events that might affect it and their impacts. A risk associated to each scenario.

For the scenario generation phase, two ways to generate scenarios are available based on the CSP model. On one hand, following a predefined heuristic solving strategy, our prototype, described later on, is able to propose different scenarios. This automatic scenario generation process can be steered by modifying the order in which decision variables are instantiated and by the order in which values are enumerated for each variable instantiation (maximum values first, minimums or midpoints, etc).

On the other hand, the user can build iteratively a feasible scenario that satisfies all constraints. Each scenario should point out available time margins and tight periods. But, we know that in many cases the problem is over-constrained (no schedule can satisfy the whole set of constraints), and there is a need for a customisable solving strategy in which the expertise of the decision maker may be exploited by taking into account some hierarchy of constraints to be relaxed (e.g. outsourcing or hiring new personnel, renegotiating contracts or modifying reviews, etc.). Relaxing some constraints is another way to find new scenarios that attain a worthy balance between time constraints and resources constraints from an internal point of view but also from a systemic point of view (e.g. respecting contracts with external teams). Scenarios that are generated following a relaxation process will satisfy only a subset of the defined constraints.

Moreover, scenarios generated with these methods can be analyses through sensitivity analysis by modifying one or several variables and analysing the impact on other variables and constraints. In our case energy of each activity is a predefined data for the CSP. Increasing or decreasing energy amount for different activities will allow us to generate new scenarios.

Lastly, the user can invert the process in order to create new scenarios. Indeed, the user defines a value for each variable relaxing some constraints. This method is called a goal-seek analysis due to the fact that the user can build a schedule respecting all its goals but without taking into account some external constraints. This type of analysis is usually used when no resources are allocated to a design team. In this case, design team manager defines an accurate schedule and defines the amount of resources necessary for the completion of activities.

Once the scenarios are generated, an evaluation is performed based on a risk analysis process. For each scenario occurrence likelihood is defined as well as an impact factor. A combination of both factors allows the user evaluate each scenario and make comparisons between different scenarios as well as to order hierarchically a set of scenarios.

Managing scenarios related to tactical level schedules is the main capability of our proposal. In order to enhance the decision support process, it also offers the possibility to define dependencies between design teams and to navigate through these dependencies. Contracts related to these dependencies will

be included in the schedules allowing the identification of decisions impacts and effects on different design teams by managers.
It also offers the possibility to realise a risk analysis of the dependencies that have been defined in the tool, calculating the probability of not respecting a contract related to a dependency and measuring the impact of a violated contract.
Figure 3 shows some snapshots of our prototype in the case of an over-constrained problem solved by the user interactively.

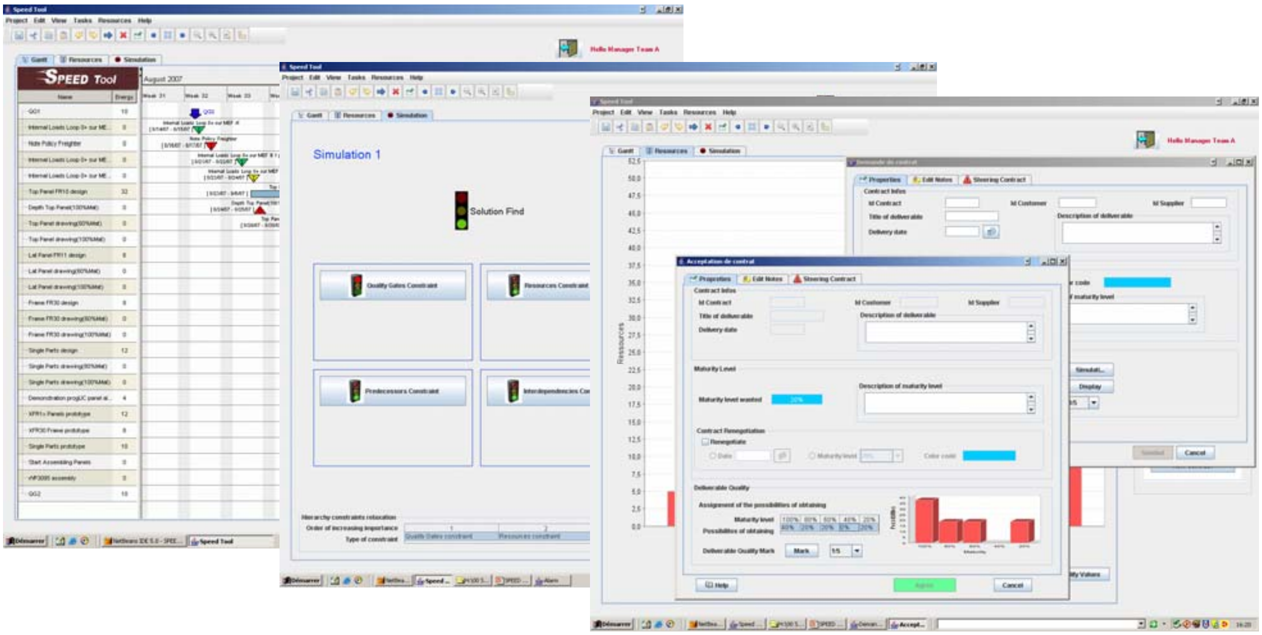

Figure 5, SPEED Tool illustrations.

So far, 2 prototypes have been developed to illustrate some specific features the proposed approach on operational use-cases. Based on prototypes' evaluation and feedback, an advanced prototype will be released in 2007.

6 CONCLUSIONS AND FURTHER WORK

SPEED tackled scheduling problems at the design stage of a complex product development. We propose scenarios based approach in order to deal with the uncertainties of this type of projects. The proposed approach should enable the generation and assessment of scenarios based on accurate and detailed schedules. They are built using fully elastic activities with defined energy quantity and considering activities durations and resource allocations as decision variables. The generation of the scenarios stands on a Constraint Satisfaction Problem model. This model includes two new types of constraints. On one hand the Energy-Precedence Constraints (EPCs), which is a new constraint type that models a partial precedence between activities based on the work quantity needed to define preliminary information. On the other hand, the Contract Dependencies Constraints (CDCs), in order to take into account dependencies between design teams. Indeed, our approach aims to facilitate the cooperation in a complex design organisation by enabling the propagation of scheduling constraints through different design teams' schedules. These two types of constraints reflect some practices that we have identified in a new product development of a major European aerospace company.
Currently, we are working on two aspects:
On one hand, we are testing different ways to implement propagation mechanisms in our CLP environment in order to improve the efficiency of the constraint propagation techniques. These techniques are checked using real use cases in order to evaluate and improve run-time performances.
On the other hand, we are improving the capabilities that offers the scenarios based approach in two directions. Firstly, we are developing a method for aggregating scenarios and therefore create new scenarios for higher managerial levels. The evaluation of these scenarios will support the decision making process and could stress some combinations of basic scenarios that impact seriously project goals and objectives. Secondly, we are working on a procedure to capitalise scenarios built before

project launch. In order to launch the project, a scenario will be chosen that will be considered as the baseline. During the project running phase and when real progress status are established, the system should discover analogies with scenarios previously capitalised. Consequently risks might be identified depending on the different status observed.

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