An original approach to assess the robustness of road freight transport plannings based on a dynamic risk identification

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Antoine Clement*, Didier Gourc and Daouda Kamissoko

Centre Génie Industriel,
IMT Mines Albi,
Université de Toulouse,
81000 Albi, France
Email: antoine.clement@mines-albi.fr
Email: didier.gourc@mines-albi.fr
Email: daouda.kamissoko@mines-albi.fr
*Corresponding author

Francois Marmier

ICUBE UMR CNRS 7357,
Université de Strasbourg,
67000 Strasbourg, France
Email: marmier@unistra.fr

Abstract: The road freight transport sector contributes significantly to the delivery of goods. Today, more than 90% of goods are conveyed using the road transport mode. In the same time, customers' requirements become more and more numerous and accurate, which increases the complexity of planner work. The aim of this work is to propose to planners robustness indicators measuring the chance the planned tour could respect the requirements. Based on a planning system giving several feasible daily schedules, our approach allows to dynamically identify the risks that could impact each planning and then simulate the influence of those risks on the plans' activities to assess the robustness indicators. They are composed of an indicator measuring the probability to respect the customers' requirements and two actionable data. These actionable data give to planners information on levers they could use to increase the robustness of the plan.

Keywords: risk identification; robustness; decision making; danger; daily schedule; road freight transport.

Biographical notes: Antoine Clement is currently an Associate Professor at the IMT Mines Albi, in France. He obtained his PhD in Industrial Engineering from the University of Toulouse, France, in 2019 entitled 'Proposal of robustness indicators based on risks consideration in order to evaluate tours for road freight transport'. His research interests include risk management, robustness and multicriteria decision making in the field of road freight transport.

Didier Gourc is currently a Professor at the IMT Mines Albi, in France. He obtained his PhD in Automated Systems Engineering from the University of Tours, France, in 1997. He has gained a strong industrial experience in software development, project management and consultancy on diagnostic of production process and project management organisation, since 1992. His current research interests include project risk management, portfolio management and project selection. He develops his research work especially in relation with the industry (pharmaceutical sector and transport sector).

Daouda Kamissoko is currently an Associate Professor at the IMT Mines Albi, in France. He obtained his PhD in Industrial Engineering from the University of Toulouse, France, in 2013. His research interests include risk management and multicriteria decision making in the field of infrastructure network and project management. He is the managing editor of the *International Journal of Decision Support System Technology*.

François Marmier is currently an Associate Professor at the University of Strasbourg, in France. His research interests include integration of human aspects, the uncertainty and the risk to make better decisions in projects, logistics and services. He is accredited to supervise research and he is now conducting research in the field of the Industry 4.0. He has also published several papers in various journals and international conferences.

1 Introduction and motivation

Many organisational and planning works have been done under implicit assumptions such as the stability of the context and the availability of all information at the time of planning. They consider that the execution will proceed according to what has been planned. This hypothesis is far from being true in the real world. Particularly, road freight transport (RFT) remains uncertain and fraught in the execution of the deliveries as unexpected events can arise all along the tour: activities can take longer to execute than planned caused for instance by traffic jam which can perturb driving activities, vehicles break down, drivers unavailability (Ghezail et al., 2010; Goren and Sabuncuoglu, 2008; Hu et al., 2017).

As a consequence, a schedule perceived as good assessed without considering potential disturbances can become, during its execution, worse than expected or planned. However, the preliminary evaluation of the quality of the plan is a complex activity. The stakes and the objectives can be various and sometimes antagonistic (Woodruff and BenDor, 2016; Hersperger et al., 2017; Avril et al., 2018). The criteria for measuring the quality of a planning are different according to experience and knowledge brought

by the decision maker: limitation of the amplitude of the rounds, balance of the working time between the drivers, CO_2 emission, cost of the schedule, economic profitability, health and safety of driver (Govaere et al., 2019).

In most works, authors do not necessarily take into account the impact of process disturbances and schedules often lack of robustness face to hazards (Mingers and Rosenhead, 2004). In recent years the number of work on robustness has increased significantly. This term is used in more and more field (Clément et al., 2018a) and especially in the field of planning (Davenport and Beck, 2000; Fischer et al., 2016; Thaman and Singh, 2017). Clément et al. (2018b) proposed a comparison of the definitions of robustness and resilience through a structured analysis of the literature. Robustness describes generally the ability of a system to perform well under different conditions or scenarios (Rebekka, 2017). It can be also defined as the (desired) insensibility of a system under different uncertain or non-anticipated events. A schedule is qualified as robust if its performance varies little under the influence of unexpected events.

Several authors (Davenport and Beck, 2000; Herroelen and Leus, 2005) divide schedule robustness into two classes: solution robustness and quality robustness. Solution robustness is defined as the insensitivity of the schedule to perturbations, and quality robustness aims to evaluate the insensitivity of the schedule performance. As an example of quality robustness in the project domain, Hazır et al. (2010) define project robustness as the insensitivity of activity start times of a schedule to variations of input data. They propose to use slack-based measures to assess project schedule robustness. In their works, Demeulemeester and Herroelen (2011) propose to measure the robustness schedule through the expected makespan and the service level (the project completion probability).

For robustness evaluation, several performance criteria can be used to compare alternative solutions. Face to the diversity of domains concerned by robustness scheduling, authors have proposed several examples of operational criteria to assess the robustness of a schedule according to multiple domains: worldwide airport network (Xiaoqian et al., 2017), aging domain: magnitude of deviation from the original state and time to peak value (Ukraintseva et al., 2016), machine scheduling (Ghezail et al., 2010; Gören, 2002), project management (Hazır et al., 2010).

In the same perspective, Rebekka (2017) listed a lot of aggregated criteria to evaluate the robustness such as: mean, (empirical) variance or standard deviation, relative regret values or decision rules (maximin-rule, maximax-rule, minmax-rule) when sequential decisions have to be performed face to several scenarios (Rebekka, 2017). The indicators proposed by Schatteman et al. (2008) focus on the difference between the baseline schedule and the realised schedule. It can also be proposed to measure the weighted sum of the differences between their respective activities' start times or the number of activities that are delayed by the occurrence of unexpected events during the plan execution. These metrics concern an a posteriori evaluation, which is done after the execution of the schedule.

As in the work of Schatteman et al. (2008), many other contributions are interested in the measure of a posteriori robustness, after the tour is finished or at least after the occurrence of the disturbance. In this context, some works focus on reactive scheduling, which focus on the generation of repairing strategies after a baseline schedule has become unfeasible (Rebekka, 2017; Herroelen and Leus, 2005). Reactive scheduling' approaches address modifying, repairing, improving of the baseline schedule

after unexpected events occurred. The dynamic context of schedule can induce several modifications that could have negative impacts on the global performance of a company on quantitative dimensions (return on investment: ROI) and also on managerial aspects. As a consequence, regular modifications of the baseline can be disturbing for team members and drivers.

Transport systems are constantly subjected to disturbances (Andersson et al., 2017) which can have a negative impact on the different activities of the transport system. As identified in several papers (Andersson et al., 2017; Mattsson and Jenelius, 2015; Rodrigue et al., 2016; Rodrigue, 2017; Leobons et al., 2019), disruptions in the transport system can be various. Mattsson and Jenelius (2015) propose a useful distinctions between internal and external cause of disruption and between accidental events and intentional interferences. Table 1 lists some examples of causes of disruptions according to several authors (Andersson et al., 2017; Mattsson and Jenelius, 2015; Rodrigue et al., 2016; Rodrigue, 2017; Leobons et al., 2019) implemented in the categorisation proposed by Mattsson and Jenelius (2015).

Table 1 Categorisation of disruptions causes to transport system according to Mattsson and Jenelius (2015)

	Accidental event	*Intentional interference*
Internal	Mistakes and accidents causes by staff or users, technical failures, components that break down, faulty constructions, overload, driver or warehouse man accident, object loss, unavailability of manutentionary equipments, staff not available to receive the shipment, warehouse is full, planning mistake due to inattention the unloading area is occupied by other vehicles,	Labour market conflict, sabotage, incorrect planning done deliberately
External	Natural phenomena including various degrees of weather and natural disasters, traffic jam due to heavy traffic, accident infrastructure failure, infrastructure maintenance	Pranks, sabotage, theft, terrorist actions of war, traffic jam due to congestion, sports events, cultural events, riots

The risk of disturbances in the road freight transport can be very variable in terms of frequency and magnitude. Andersson et al. (2017) propose a classification of disturbances composed of four main types: system killers, catastrophic events, expected risks and contingencies. The two first types system killers and catastrophic events refer to disturbances with large magnitude and for which there is limited capacity to manage. The expected risks induce small consequences on the transport system but are relativity common, so the planners generally anticipate their occurrence when they design the plan. The contingencies are less frequent and the consequences can be more or less important. For these disturbances, there are no plans but it is often

possible to manage these disturbances. We consider the contingencies can be classified in two categories: risk that can be identified and listed and those who are totally unpredictable for which occurrence mechanisms are not known, 'black swans' in the word of Taleb (2010). For those who are identifiable and due to the relative high level of consequences of the disturbances of contingencies type we consider that it is necessary to develop mechanisms for anticipating and assessing those impacts on transport system and particularly on plans produced. The aim is to give planners information on the ability of the plan produced to provide correct transport services to users.

The problem addressed is to aid the planners to choose a schedule, among all those allowing the delivery of goods to clients that satisfies as well as possible the objectives of the company in terms of economic, environmental and health and safety indicators while maintaining a good probability to respect the customers' requirements despite possible disturbances. As we saw above, several works in the literature review address reactive scheduling problem.

In this paper, we propose an alternative way, which is based on proactive scheduling approach. Our objective is mainly to design schedules that are able to maintain good performances, as expected by the planner and the company manager, even if one or more disturbances occurs during the execution. To achieve this goal, we propose a methodology to generate several schedules with their assessment according to a list of predetermined indicators, including an indicator of robustness.

We propose a preliminary list of the usual hazards in the field of road freight transport. This list is organised by category according to the origin of the dangers:

- Resources, including:
    a humans, as for example drivers, warehouse clerk, customer site manager: unavailability, absence, delay
    b means, as for example vehicle, road infrastructure: breakdown, unavailability (the previous round is not finished)
    c additional equipment's, as for example loading equipment, parking zone: unavailability, breakdown.
- Infrastructures, as road infrastructure: bursting point, faulty.
- Weather conditions: heavy rainfall, snowy episode, strong winds, snow-covered, flooding, ... which can lead to risks of saturation of roads or closing of roads.

For this, after a preliminary dangers identification, an automatised process based on the planned schedule is proposed to identify and characterise the risks that can arise during the execution of the tour. Then, the robustness evaluation is performed by a risk simulation process which consists in applying the risk scenarios to the initial schedule in order to analyse the whole consequences of risk occurrence. For each scenario identified, several KPI's are evaluated. Finally, these results are proposed to the planners who are now able to choose the best schedule thanks to the explicit knowledge of the robustness of each plan.

This article deals with a vehicle routing problem in road freight transport, in the literature several indicators are used to characterise a schedule. Patier and Routhier (2010) and Meier et al. (2013) offer a list of indicators that focus on economic (cost, duration, number of km, …) and ecological (CO_2, energy consumption, ...) aspects

of planning. The optimisation models used for vehicle routing problems often aim to minimise one of these indicators such as delivery cost, comprising the transportation cost, total duration of the rounds or carbon footprint (Vidal et al., 2020; Liu et al., 2018; Konstantakopoulos et al., 2020).

Unlike optimisation algorithms, our aim is not to produce the best schedule but to provide complementary indicators to help the planner to select a schedule compliant with the planner's daily objectives. Our work focuses on the robustness evaluation of the solutions. In addition to classical indicators such as the cost or the duration of a schedule, our model provides robustness indicators measuring the possible influence on the delivery time of disturbances that could occur during the delivery process.

This paper is organised as follows. Section 2 describes our general approach to generate plan's tour and to assess the robustness. Section 3 focuses on the robustness evaluating step of our general approach and describes the model proposed to assess the robustness of a daily schedule. In Section 4, we illustrate the proposed approach and the developed models with a case study and discuss the results. Finally, Section 5 provides a conclusion and some suggestions for future work.

2 Approach overview

This holistic approach aims to help planners choose the best plan based on the company's goals. The overall process of the proposed approach is presented in Figure 1. It is composed by two steps briefly detailed in this section:

- step identifying and modelling dangers
- step evaluating daily schedules robustness.

2.1 Step identifying and modelling dangers

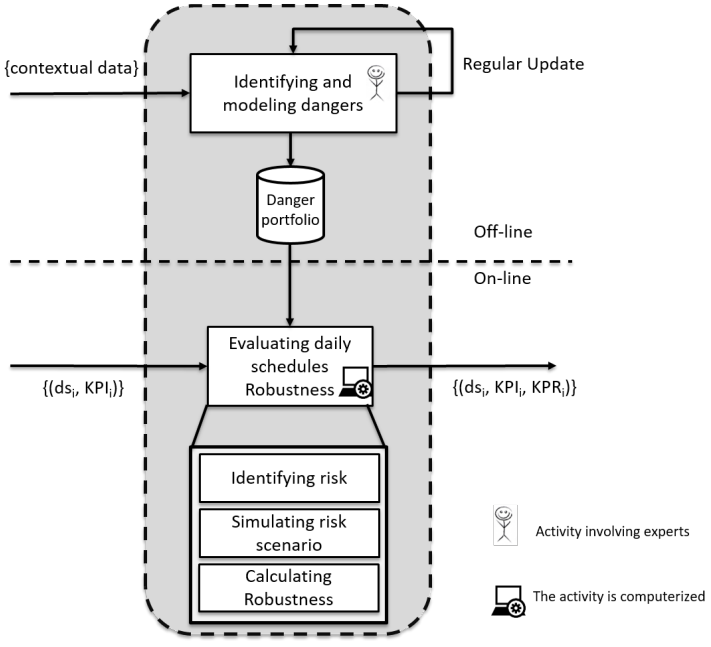
This step is carried by human expertise. It consists of manually identifying the various dangers that may be present and modelling them in a danger portfolios. A portfolio corresponds to a structured list of hazards to be described on a model of danger dedicated. This model, as structured description of a hazard, is part of the contributions of this paper which is presented in Subsection 3.1. It makes possible to identify risks and evaluate their impacts on road freight transport plans. In addition, this step is a data collection step, the frequency of realisation is low compared to the realisation of a daily schedule. The off-line and on-line activities are asynchronous, the off-line activity is performed once and then updates are performed, while on-line activity is daily.

2.2 Step evaluating daily schedules robustness

When selecting a schedule, the planner seeks to compare a number of schedules (ds) using different indicators (KPI). The indicators are mainly economic or environmental. The objective of this step is to provide a schedules' robustness indicator (KPR) to aid the planner to select a daily schedule. This step is done in three parts. First, there is the identification of risks. From the danger portfolio and the different schedules selected, this step generates the risks that will impact the schedules. The second part simulates

risk scenario by simulating all possible risk combinations. The last part corresponds to the implementation of the robustness KPI.

Figure 1 Proposal of approach to assess the robustness of planning



A specific and original simulation approach based on multiple scenario simulator permits to assess the impact of potential risks on the characteristics of the tour. Our contribution on robustness indicator, the elementary characteristics used and the formulation of the aggregated robustness indicator, is detailed in Subsection 3.2.

3 Assessing the robustness of daily schedule with danger

First, in Subsection 3.1, we develop our model of danger dedicated to identifying risks and evaluating risk impacts on road freight transport plans. The proposed model underlies the danger modelling devoted to the activity 'identifying and modelling danger' as presented in Figure 1. Then, in Subsection 3.2, we detailed the evaluation step of the approach, presented in Figure 1, with the robustness KPI proposed.

3.1 Modelling of the concept of danger

Before presenting in detail the danger model, we define the basics of the planning model in the road freight transport and the activities that compose it.

3.1.1 *Model of planning in road freight transport*

To set up the danger model, the planning model studied is essential. A schedule corresponds to a set of tours carried out by resources (vehicle and driver). A couple, vehicle-driver, will realised a set of activities to satisfy all customer requests.

These activities can be classified according to four types:

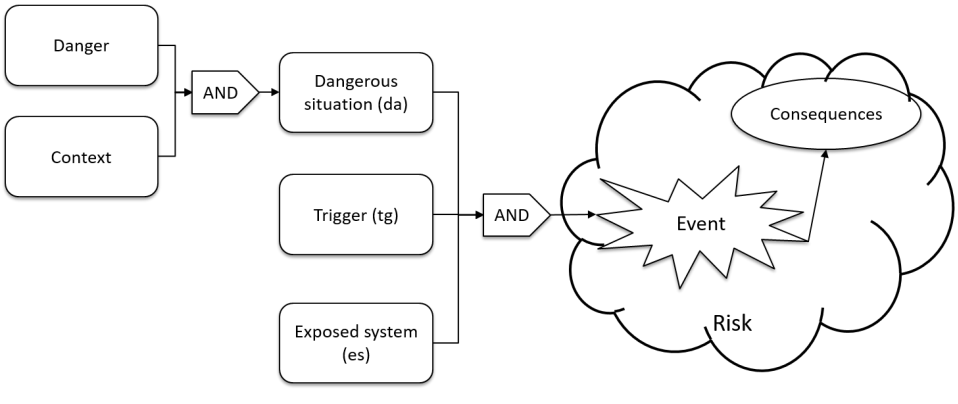
- *Moving activity* that represents the driving phase between two sites/places.
- *Activity on site* (loading/unloading) that illustrates the manipulation of goods.
- *Starting activity* and *ending activity* that takes into account the preparation of the vehicle before starting the tour and for closing the tour.
- *Waiting activity* that materialises a buffer of time when a driver arrives at the deliver site before the required hour. This buffer is necessary because sometimes clients do not accept to get the goods before the hour of the appointment. In these cases, the driver has to wait for the hour of appointment.

Each activity is characterised by a start time, a duration, a location and a type presented above. The planning model being described, it is possible to recommend the danger model

3.1.2 *The model of danger in road freight transport*

Based on the definitions identified in the literature review and inspired by the work of Desroches (2015), we define the danger (see Figure 2) in road freight transport planning' system as any source of potential damage, harm or adverse effects on an element, which can be something or someone, of the system under study. The exposure of an element to a danger combined with a trigger induces a risk, which is characterised by a probability of occurrence and potential effects on the system or elements of the system. Risk concept is a central point of our approach for assessing the robustness indicator, detailed risk definition is given in Marmier et al. (2012), Nguyen et al. (2013) and Marmier et al. (2014b).

Figure 2 The risk design scenario, inspired from Desroches (2013, 2015)



As presented in Figure 2, a dangerous situation da is generated by two concepts:

- danger, corresponding to the overall description of a hazard
- context, corresponding to the environment description which is characterised by a danger zone (dz) and a time window (tw).

A danger zone (dz) defines "any space within and/or around machinery in which a person can be exposed to a hazard".[1] We propose to specify the danger zone with a Geographic Information System (GIS) by zoning the area where the danger is identified.

A time window (tw) represents the period where the danger could be present and where elements or systems staying in the danger zone could be impacted by a risk induced by this danger. The time window can be expressed by temporal expressions with days and hours. For example, every Monday between 7h30 and 8h30. As proposed by Gani et al. (2014) and Bastide et al. (2014), a user centred specification language tailored to express RFT plans using high level abstractions was implemented.

A risk, characterised by an event and its consequences on the RFT system, is modelled by three concepts: a dangerous situation (da), a trigger (tg) and the exposed system (es).

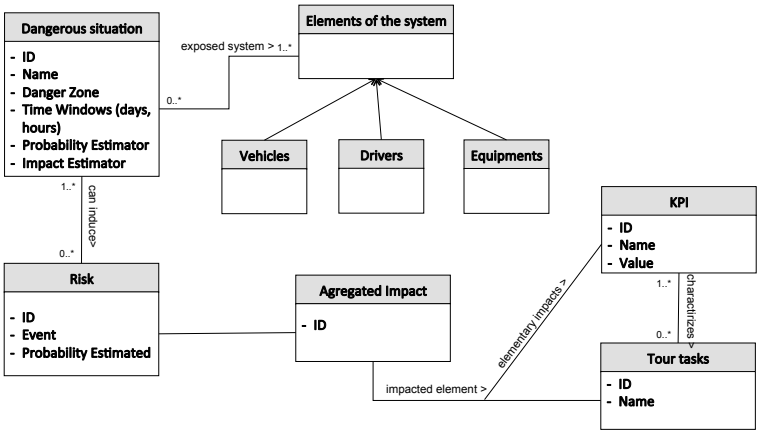
The trigger (tg) lists the triggering factors that could initiate the transformation of a danger to a risk. The exposed system (es) able to list the elements of the system, something or someone that may be concerned by risks induced by this danger. In the context of tour plan, this attribute allows to specify which type of activity of a tour may be impacted by this risk. For example, the risk of traffic jam may, induced by the danger 'intensification of road traffic', occurs during a drive activity between two sites and can impact the same driving activity. Occurring of risk can be observed during the execution of a task (for example, during a driving activity) and the impacts could modify the execution of the same or another task. Modifications could concern, for example, the delay of the activity.

The combination of three concepts (a dangerous situation da, a trigger (tg) and the exposed system (es)) generate new risk attributes such as: probability estimator and impact estimator. Probability estimator (pe) is an expression, or a function, that defines the probability value of the risk induced by this danger for a specific situation. So, this expression is based on the elements of the danger's context in order to generate the specific probability value of the risk. For example, on a road connection, the probability to meet a traffic jam depends on the day (holidays period versus work period, Monday versus Tuesday, ...) and on the hour (hour in the morning when workers are going to their office versus middle of the morning, ...).

Impact estimator (ie) is an expression dedicated to specify the level of impacts of the risk induced by this danger for a specific situation. As the probability estimator, the impact estimator is based on context' elements. Fertier et al. (2017) indicate that a danger brings risks on each stake in its perimeter. Several expressions can be developed according to the diversity of impact' types: delay, cost, tiredness, safety, CO2 emissions, ... For the same example that above, the value of the impact 'delay' depends on the hour the vehicle cross the road connection.

It is important to note that a risk can modify a task of a tour, and potentially modify its attributes. The meta model, presented in Figure 3, gives a global view of all these concepts and their relationships.

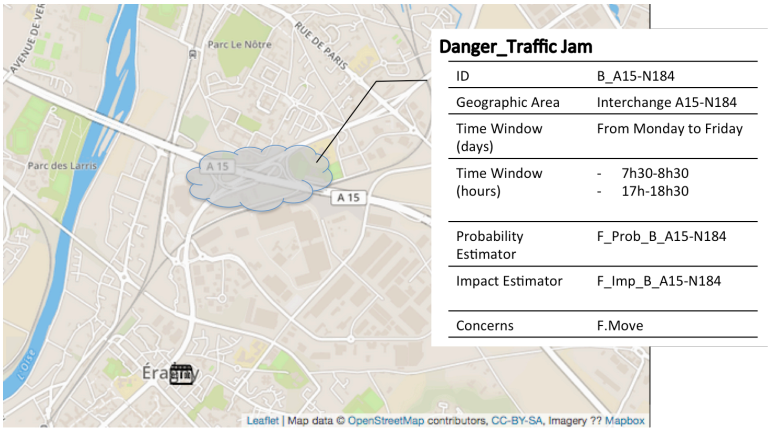
Figure 3 The danger and risk meta model



We focus our study on the dangers that are relied to the road freight planning system. For this, we express the fact that the dangers we study involve at least one element of the road freight planning system.

In Figure 4, an illustrative example for danger modelling is proposed. It concerns the description of the danger 'traffic jam' which is related to a road connection between the road A15 and N184. The attributes are fulfilled and specify that this danger could occur each day of the working days (from Monday to Friday) specially on the periods 7h30-8h30 and 17h-18h30. The probability estimator (F_Prob_B_A15-N184) is illustrated in Table 2. In each cell of this table (couple day-hour period), a level of probability for the risk 'traffic jam' is given according to a 4-level intensity scale (no risk, moderate, high, very high). These estimations are performed by planners with the help of drivers that are in charge of the deliveries in these zones. A similar table is proposed to specify the impact in delay.

Figure 4 Illustration of the danger 'traffic jam' (see online version for colours)



Danger_Traffic Jam

ID	B_A15-N184
Geographic Area	Interchange A15-N184
Time Window (days)	From Monday to Friday
Time Window (hours)	- 7h30-8h30 - 17h-18h30
Probability Estimator	F_Prob_B_A15-N184
Impact Estimator	F_Imp_B_A15-N184
Concerns	F.Move

Table 2 Illustrative example of the probability estimator F_Prob_B_A15-N184

	7h30–8h30	*17h–18h30*	*other hours*
Monday	Very high	Very high	No risk
Tuesday	High	High	No risk
Wednesday	High	High	No risk
Thursday	High	High	No risk
Friday	Very high	Very high	No risk
Other days	No risk	Moderate	Moderate

Finally, this danger impacts only the driving activity from one site to the next because it concerns moving activities (F_move). Thus, for each driving activity crossing this geographical zone during one of the periods mentioned, an induced risk must be created and assigned to that driving activity with the specified characteristics. We explicit this risk instantiating mechanism in the next subsection.

3.2 Daily schedules robustness assessment

This section aims to present the approach proposed to assess robustness indicator of daily schedules selected by the planner. The process, used to realise the step 'evaluating delay schedules robustness' of the global approach, is composed of three stages. Based on the dangers identified and modelled, the first stage consists in automatically identifying and generating risks that will disturb the execution of the daily schedules (Subsection 3.2.1). The second stage aims to simulate the whole scenarios of risks and to measure the impacts of the risks on the deliveries plan (Subsection 3.2.2). And then, in the third stage, the robustness indicators are calculated to help planners choosing the daily schedule to execute (Subsection 3.2.3).

3.2.1 Risk identification based on the dangers' definition

Based on the portfolio of dangers and the plan activities, which are part of the daily schedule definition, we propose an instantiating mechanism to create the tour' risks and to assign them to the inherent activities. In this work, we adopt the risk definition presented in Nguyen et al. (2013). Risk is defined as an event, which has occurrence characteristics (for example, the probability of occurrence) and consequence characteristics on the schedule objectives (for an example, the impacts if the event occurs). The increase of the duration of the task impacted is an illustration of a risk impact.

The instantiating mechanisms, including the identification of risks and then the creation of associated risks, are specified respectively in Algorithms 1 and 2. Algorithm 1 develops the mechanism enabling the identification of a risk. When an activity a is performed inside a context of danger (i.e., inside the danger zone, the period where the danger is present, ...) an associated risk must be created. So, this process able to identify a list ER of risks $R_i, (i = 0, ..., n)$, where n is the number of risks.

Algorithm 2 gives details of the risk creating process and information used to fulfil the risk attributes. A risk R_i is characterised by several attributes, the two first able to define the activity where the risk can occur $task\_source$ and the task that is impacted

by the occurrence of the risk $task\_impacted$. The probability of the risk, designed by $proba(R_i)$, is the probability that the event related to R_i happens. The impact of the risk is measured on two dimensions, respectively cost $CI(R_i)$ and duration $DI(R_i)$.

These probabilities and impacts are also named initial probability and initial impact. Their valuation is obtained by the use of the estimators pe and ie that are modelled in the dedicated danger.

At the end of this stage, all dangers of the portfolio, identified during humane activity, has been analysed and the induced risks are assigned to activities of the daily schedules.

Algorithm 1 Identifying and creating risks associated to a daily schedule ds

for all $da \in \mathcal{D}$ **do** ▷ For all the dangers identified
  for all $a \in ds$ **do** ▷ For all the activities in ds
    if $Context\_of\_Realisation(a) \cap Context(da) \neq \varnothing$ **then**
      $Create\_Risk(da, a)$
    end if
  end for
end for

Algorithm 2 Create a new risk

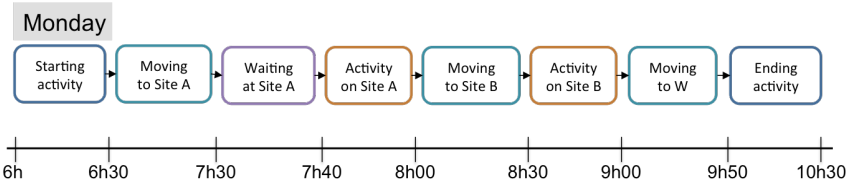
procedure CREATE_RISK(da, a) ▷ da is the danger that induces a risk on task a
Ensure: Risk r
  $r \leftarrow newRisk$
  $r.name \leftarrow string(da, a)$
  $r.task\_source \leftarrow a$
  $r.task\_impacted \leftarrow a$ ▷ this risk could occur on task a
  $r.probability \leftarrow l.pe(a)$ ▷ Use of the probability estimator pe
  $r.impact \leftarrow l.ie(a)$ ▷ Use of the impact estimator ie
end procedure

As an example, we illustrate in Figure 5 a projected schedule with estimated hours which is programmed for Monday. Based on the danger specified in Figure 4 and Table 2, the instantiating process generates a specific risk that is illustrated in Table 3. This risk relates to the task 'moving to site B' because this driving activity passes through the road link A15-N184 during a period of heavy traffic. The probability of occurrence of this risk is very high and, if it occurs, the consequences will be materialised by an increase of 25 minutes in the duration of the activity 'moving to site B'.

Table 3 Extract of the risk description

Name	*Traffic_jam_Moving to site B*
Task concerned	Moving to site B
Probability	Very high
Task impacted	Moving to site B
Impact on duration	+25 mn

Figure 5 Illustration of a projected schedule with estimated hours (see online version for colours)



3.2.2 Simulating risk scenario in daily schedules

Nguyen et al. (2013) proposed the method ProRisk, supported by a software tool that assists in modelling and evaluating the impact of risks on project activities and project KPI. In this work, dedicated to a project context, the KPI's proposed concerns cost and duration of the activities. The authors define the concepts of risk scenario, treatment scenario and project scenario. This method has been applied in several domains for aiding decision makers dealing with uncertainty: satellites design projects (Marmier et al., 2014b), new product development projects (Deniaud et al., 2016; Marmier et al., 2013, 2012), construction projects (Marmier et al., 2014a). ProRisk is now integral part of the platform RIOSUITE.[2]

The ProRisk methodology aims to generate all the possible combinations of identified risks to assess the global impacts on the whole process. The assessment framework is based on the evaluation of risk scenario. A risk scenario ScR for a specific process corresponds to the combination of s, with $s = 0, ..., n$ risks occurring during the daily schedule studied and $n - s$ risks no occurring. It exists several possible combinations. For example, a process with k risks leads to 2^k risk scenarios. ScR_s, $(s = 1, ..., 2^n)$ is one possible implementation with k risks $(0 \leq k \leq n)$. We consider a particular risk scenario noted $\emptyset$. It corresponds to the situation where there is no risk occurring, all the hazards have been avoided. The total number of risk scenarios, presenting k risks is equal to $n!/k(n-k)!$.

We have chosen to implement and upgrade this framework in the domain of RFT robustness assessment. So, we extended it to make possible to consider the assessment of daily schedules. For this, a first stage simulates risk impacts on a tour level t, i.e., a process, and then, an aggregated phase calculates indicators on the daily schedule level ds. A daily schedule ds is composed of r tours.

A risk can have an impact on the strong constraints and thus make a scenario become not feasible but it also simply affect the indicators without modifying its feasibility. Based on these appraisals, we implement an analysis process allowing to generate all possible scenarios and calculate the indicators characterising each scenario. The aim is, first, to determine the probability of occurrence of risk scenario s in the tour j noted $proba_j(ScR_s) = p_j^s$. This probability of the scenario depends on the combination of risks in this scenario. The probability of this risk scenario represents the probability that the events related to this risk scenario occur and other risks do not occur, the expression is developed equation (1).

$$proba_j(ScR_s) = \prod_{i=1} \begin{cases} proba(R_i), & \text{if } R_i \in ScR_s \\ 1 - proba(R_i), & \text{if } R_i \notin ScR_s \end{cases} \quad (1)$$

Beside the occurrence probability of a scenario, we characterise each scenario by other indicators. Very typically, the time and cost indicators are mobilised to effect this characterisation. Thus, for each identified scenario, its duration and its cost are calculated. The expression of the cost calculation for a tour level is shown in equation (2). The cost of the project scenario j considered under the risk scenario ScR_s is named $CI_j(ScR_s) = CI_j^s$. It includes the cost of tasks $C(T_a)$ which constitute the initial planning process, impacts of occurrence risks, i.e., risks present in ScR_s, on the process tasks and the global cost $GC^{initial}(R_s)$ of occurring risks. $GC^{initial}(R_s)$ is the aggregation of risk impacts on the cost criterion. This includes a fixed portion of the total cost (materials, tools, parts, etc.) and indirect costs depending on the duration of action of each possible impact of risk.

$$CI_j(ScR_s) = \sum_{i=1}^{t} CI(T_i) + \sum_{R_i \in ScR_s} GC^{initial}(R_i) \quad (2)$$

Similar functions have been developed to calculate the values of the other indicators, as those concerning duration characteristics. Calculation of the tour's duration ($DI_j(ScR_s) = DI_j^s$) characteristics compels to take into account the graph structure of activities and the PERT algorithm.

It is important to note that 'wait' activities play the role of buffer in planning. That is, if a risk increases the duration of an activity, and the delivery time can not be changed then if there is an activity 'wait' the delay generated by the risk will be absorbed either totally by reducing this activity (if the delay is less than the duration of the activity Wait) or partially by limiting the delay. The other wait activities of the process will decrease the delay if there are any left.

Table 4 Matrix of daily schedule assessment with risk impact

Tours in ds	$\emptyset$	ScR_1	...	ScR_s	...	$ScR_?$
t_1				$CI_1^s; DI_1^s$		
...						
t_j				$CI_j^s; DI_j^s; p_j^s$		
...						
t_r				$CI_r^s; DI_r^s$		

3.2.3 Calculating robustness KPI

In the RFT domain, meeting delivery deadlines is considered as a crucial issue for customer satisfaction. Therefore, we focus our robustness KPI on measuring the ability to deliver goods in accordance with customer requirements. Characterising the

robustness of a daily schedule through a single number may be quite restrictive (Ghezail et al., 2010), therefore we choose to consider several indicators to take into account all the dimensions of the robustness.

Based on the risk scenario assessments, produced by the previous stage, we first characterise robustness dimensions at a tour level. In the second stage, we propose robustness KPI's at a daily schedule level.

At a tour level, we propose to measure three characteristics:

- $TMaxDelay_t$: The maximum delay of the deliveries of the tour t that need to add for comply with the client's requirements [equation (3)]
- $TMinSat_t(x)$: The minimum number of deliveries of the tour t that comply with the client's requirements for all risk scenarios with a margin of x minutes [equation (4)].
- $TProbRespect_t(x)$: Probability of a tour to meet all customer requirements in terms of delivery times with a margin of x minutes [equation (5)].

Clément et al. (2017, 2018a) proposed a robustness indicator based on the calculation of a global probability for a tour to be compliant with all the customer requirements. In this work, we propose a new probability indicator introducing acceptable lateness x for the client in the delivery activity. Thanks to the two measures, presented above ($TMaxDelay_t$, $TMinSat_t$), and the knowledge of risk probabilities, we construct a KPI measuring the probability of meeting customer requirements in terms of delivery times with a margin of x minutes ($TProbRespect_t(x)$). $TNumDel_t$ corresponds to the number of delivery present in the tour t. $TProbRespect_t(x)$ is the robustness indicator, $TMinSat_t(x)$ and $TMaxDelay_t$ are actionable data for the robustness indicator. The activable data are indicators which for us vary according to the delay on a delivery accepted. They are intended to allow the planner to make his schedule more robust to satisfy his customers.

$$TMaxDelay_t = \max_{s \subset 1..2^n} [delay(ScR_s)] \tag{3}$$

$$TMinSat_t(x) = \min_{s \subset 1..2^n} \frac{NumberOfDeliverySatisfied(ScR_s)}{TNumDel_t} \tag{4}$$

$$TProbRespect_t(x) = \sum_{s=1}^{n} proba_t(ScR_s) * \begin{cases} 1, & \text{if } delay(ScR_s) \leq x \\ 0, & \text{else} \end{cases} \tag{5}$$

with 2^n the number of risk scenarios, and $proba_t(ScR_s)$ the probability of the risk scenario s of the tour t.

At a daily schedule, similar measures are proposed:

- $SMaxDelay_{ds}$: The maximum delay of the deliveries of the daily schedule ds that need to add for comply with the client's requirements [equation (6)],
- $SMinSat_{ds}(x)$: The minimum number of deliveries of the daily schedule ds that comply with the client's requirements [equation (7)].
- $SProbRespect_{ds}(x)$: The probability of a daily schedule to meet all customer requirements in terms of delivery times with a margin of x minutes [equation (8)].

$SProbRespect_{ds}(x)$ is the robustness indicator, $SMinSat_{ds}(x)$ and $SMaxDelay_{ds}$ are actionable data for the robustness indicator at daily schedule level.

$$SMaxDelay_{ds} = \max_{t \subset DS} TMaxDelay_t \tag{6}$$

$$SMinSat_{ds}(x) = \frac{\sum_{t \subset DS} TMinSat_t(x) * TNumDel_t}{\sum_{t \subset DS} TNumDel_t} \tag{7}$$

$$SProbRespect_{ds}(x) = \prod_{t \subset DS} TProbRespect_t(x) \tag{8}$$

The use of the robustness indicator and the two actionable data are described during the computational study. These three elements are intended to allow the planner to make a compromise between the various solutions that are proposed. The validation of our model was carried out by a panel of planners during one week of planification. The schedules produced by the planners have been evaluated with the robustness indicators. At the same time the system proposes others schedules qualified by the robustness indicators we proposed. This experiment has allowed planners to validate the pertinence of the indicators. On this basis, they improve their own schedules. In the next section, we pursue the demonstration with a simplified version of a daily schedule of this experiment.

4 Computational study

In this section, we apply the proposed framework to a real-world case. Then, we present the experimental results and discuss the interest of our approach, its limits and the future developments.

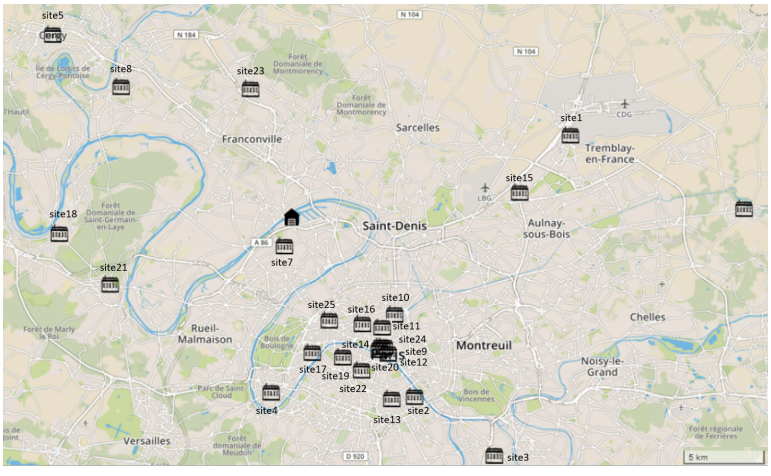
4.1 Data

The use case presented corresponds to the half-day planning of a real company. All data have been anonymised for reasons of confidentiality. The planner must plan 25 orders, and own 15 vehicles and 15 drivers. An order is described by the site where it must be delivered, the quantity of pallet to be delivered as well as the delivery time. The delivery time is a fixed hour. The delivery points are presented on the map Figure 6. Other attributes describing the site or the order are used to calculate financial, economic and health and safety indicators. A vehicle is described by its type of energy, its pallet capacity (4, 6, 8, 10 pallets), its CO_2 emission... Drivers are described for example by their type of driving license, the number of hours worked...

Table 5 List of orders

Order Id.	*Delivery site*	*Delivery time*	*Quantity (pallets)*
Order 1	Site 1	7h15	3
Order 2	Site 2	7h00	2
Order 3	Site 3	8h00	3
Order 4	Site 4	7h15	3
Order 5	Site 5	5h30	2
Order 6	Site 6	8h15	3
Order 7	Site 7	7h30	2
Order 8	Site 8	7h15	2
Order 9	Site 9	6h30	3
Order 10	Site 10	6h00	3
Order 11	Site 11	6h00	2
Order 12	Site 12	7h00	3
Order 13	Site 13	6h30	2
Order 14	Site 14	7h30	3
Order 15	Site 15	5h00	3
Order 16	Site 16	6h45	3
Order 17	Site 17	6h45	3
Order 18	Site 18	8h30	2
Order 19	Site 19	5h00	2
Order 20	Site 20	6h45	2
Order 21	Site 21	7h30	2
Order 22	Site 22	7h30	2
Order 23	Site 23	8h00	3
Order 24	Site 24	7h30	2
Order 25	Site 25	6h30	2

Figure 6 Map of the delivery points (see online version for colours)



In the identification step, the experts identified three hazards described in Table 6. Road 1 is the axis between site 1 and site 6. Route 10 is the axis allowing to leave the site 10 caused by a one-way street. Period in the journey are identified to distinguish specific values of probabilities and impacts of the potential risks according the phase of the day. For example, the probability to have a high circulation on road 1 is more important between 5h and 10h (40%) than between 0h and 5h (5%). In a similar manner, the impact of this perturbation is more important between 10h and 16h (+15 minutes) than between 21h and 24h (+5 minutes). The detailed values are presented in Table 7. In order to illustrate our proposition, risks used in this use case are independent. This means that the presence of one risk on a schedule does not affect the probability or impact of others risks.

Table 6 Description of dangers

Id	*Name of danger*	*Task concerned*	*Localisation*
d1	High circulation road 1	Move	Road 1
d2	Absence of customer 13	Act. site	Site 13
d3	High circulation road 10	Move	Road 10

4.2 Results and discussion

Once the data set is complete, for this use case, 56 schedules are produced by an external planning module. This module generates solutions respecting a list of constraints imposed by the planner such as for example the respect of the delivery time or the use of specific vehicles (vehicle with tailgate, electric vehicle, ...). They are labelled ds_1 to ds_{56}. These schedules are then evaluated according the three indicators financial, environment and H&S. The results are presented in Figure 7. Each bullet corresponds to a schedule.

A first comparison is made by the planner to select a smaller number of schedules. It can exclude schedules that do not meet his financial goals using a threshold. In this example, the planner fixed the financial threshold at €4,000. In the same way, he put a threshold on the indicators environment and H&S so as to preserve only the schedule which seems to him to satisfy its objectives. The environment indicator is between 20,500 and 21,700 gram of carbon dioxide and for the health and safety indicator it is between 100 and 135 for this example.

After this analysis only five daily schedules are kept for the study of robustness ($ds_{27}, ds_{32}, ds_{34}, ds_{46}, ds_{48}$). The evaluation of these schedules is presented in Table 8.

Subsequently, the robustness indicators will be calculated on the different schedules selected. Tables 9 and 10 correspond to the details of the calculations carried out for the three robustness indicators on the whole tour of the planning ds27 and by aggregation of the schedule ds27. Table 9 corresponds to the robustness value for a delay accepted of 0 minute (x = 0) and Table 10 corresponds to the robustness value for a delay accepted of 10 minutes (x = 10). The schedule ds27 is composed of 11 tours (t1 to t11). The three dangers (d1, d2 and d3) generated risks (R1, R2 and R3) on the schedule. The risk R1 impacts the tour t8, R2 impacts t5 and R3 impacts t2.

Table 7 Characterisation of the probability and impact of the dangers

Id	*Probability*					*Impact*				
	[0h–5h]	*[5h–10h]*	*[10h–16h]*	*[16h–21h]*	*[21h–24h]*	*[0h–5h]*	*[5h–10h]*	*[10h–16h]*	*[16h–21h]*	*[21h–24h]*
d1	0.05	0.4	0.25	0.4	0.05	+1 min	+10 min	+15 min	+10 min	+5 min
d2	0.05	0.5	0.3	0.4	0	+5 min	+10 min	+15 min	+10 min	+2 min
d3	0.1	0.3	0.3	0.4	0	+1 min	+15 min	+10 min	+10 min	+2 min

Figure 7 Three-axis representation of evaluation of daily schedules (KPI) (see online version for colours)

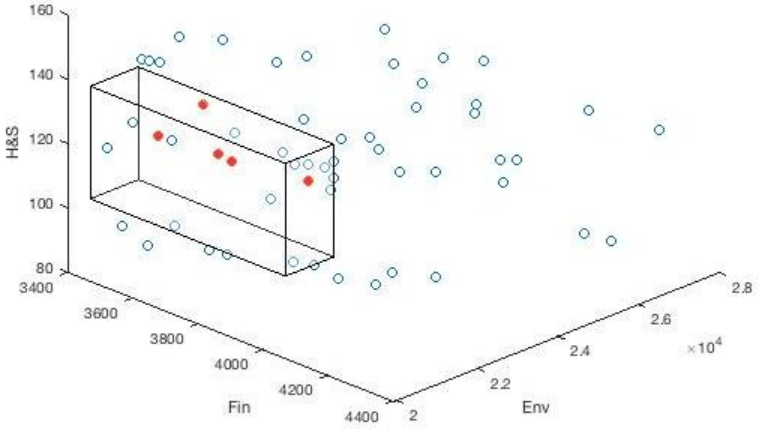


Table 8 Evaluation of planning

Daily schedule	*Fin. (€)*	*Env. (gCO2)*	*H&S*
ds27	3,601	21,684	131
ds32	3,961	21,397	123
ds34	3,702	21,558	119
ds46	3,589	20,655	126
ds48	3,712	21,145	123

Table 9 Robustness indicators (for $x = 0$) detailed for each tour of ds27

	$TNumDel$	$TProbRespect(0)$	$TMinSat(0)$	$TMaxDelay(min)$
t1	3	1	1	0
t2	4	0.7	0.5	12.77
t3	2	1	1	0
t4	2	1	1	0
t5	3	0.5	0.5	1.8
t6	2	1	1	0
t7	2	1	1	0
t8	2	0.6	0.5	8.1
t9	1	1	1	0
t10	2	1	1	0
t11	2	1	1	0
	$SNumDel$	$SProbRespect(0)$	$SMinSat(0)$	$SMaxDelay(min)$
ds27	25	0.21	0.84	12.77

Table 10 Robustness indicators (for $x = 10$) detailed for each tour of ds27

	$TNumDel$	$TProbRespect(10)$	$TMinSat(10)$	$TMaxDelay(min)$
t1	3	1	1	0
t2	4	0.7	0.75	12.77
t3	2	1	1	0
t4	2	1	1	0
t5	3	1	1	1.8
t6	2	1	1	0
t7	2	1	1	0
t8	2	1	1	8.1
t9	1	1	1	0
t10	2	1	1	0
t11	2	1	1	0
	$SNumDel$	$SProbRespect(10)$	$SMinSat(10)$	$SMaxDelay(min)$
ds27	25	0.7	0.96	12.77

Tables 11 and 12 present the values of robustness indicators for each daily schedule. Table 11 considers a margin x equal to 0 and Table 12 considers a margin x equals to 10.

Table 11 Robustness indicators with $x = 0$

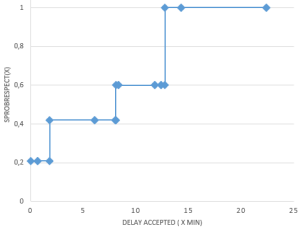
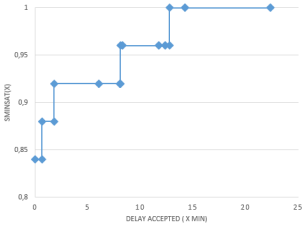
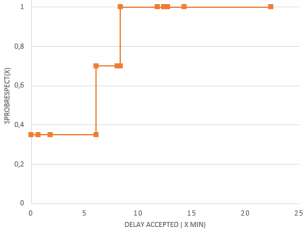
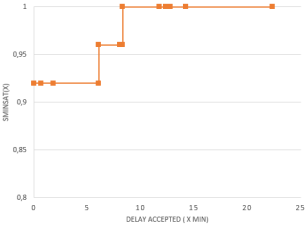
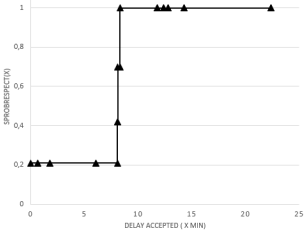
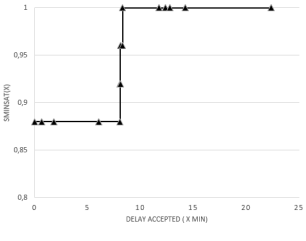
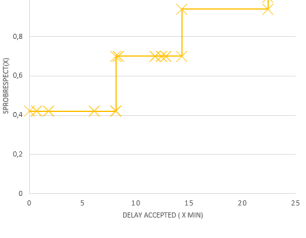
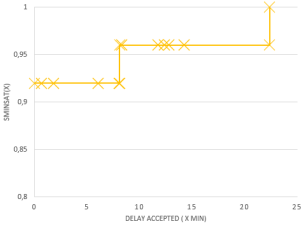
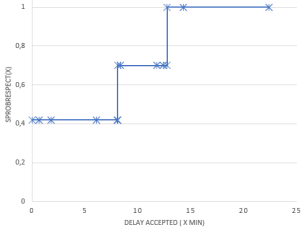
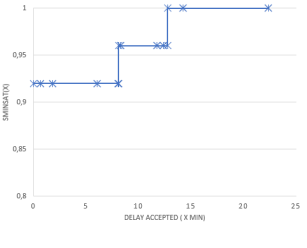
Daily schedule	$SProbRespect(0)$	$SMinSat(0)$	$SMaxDelay(min)$
ds27	0.21	0.84	12.77
ds32	0.35	0.92	8.32
ds34	0.21	0.88	8.32
ds46	0.42	0.92	22.37
ds48	0.42	0.92	12.77

Table 12 Robustness indicators with $x = 10$

Daily schedule	$SProbRespect(10)$	$SMinSat(10)$	$SMaxDelay(min)$
ds27	0.6	0.96	12.77
ds32	1	1	8.32
ds34	1	1	8.32
ds46	0.7	0.96	22.37
ds48	0.7	0.96	12.77

These table are not enough to be able to make a choice. The planner can look at the evolution of the functions $SProbRespect(x)$ and $SMinSat(x)$ for different values of x. The $SProbRespect(x)$ and $SMinSat(x)$ functions of the schedules (ds27, ds32, ds34, ds46 and ds48) are presented in their respective columns of Table 13. These functions allow him to see according to the delay that he can negotiate with the customer what would be the best planning.

Table 13 Schedules evaluation of ProbRespect(X) and Minsat(X) (see online version for colours)

	$SProbRespect(X)$	$SMinSat(X)$
ds27		
ds32		
ds34		
ds46		
ds48		

For example, if the customer is very demanding and does not accept a single minute late, the planner will be interested in $SProbRespect(0)$ and $SMinSat(0)$. By viewing the graphs present in Table 13, schedules ds27, ds32, ds34, ds46 and ds48 have a probability $SProbRespect(0)$ low (less than 0.42, Table 11). So it is difficult to select these schedules because the planner knows that all deliveries will be not satisfied. If the planner can not negotiate with his customer he will then choose the solution that has the highest probability of respect $SProbRespect(0)$, the highest satisfaction $SMinSat(0)$ and the lowest delay $SMaxDelay$ to satisfy his customer.

For the case of a compliant customer accepting 10 minutes late, schedules ds32 and ds34 can be implemented without any problem because $SMaxDelay$ is less than 10 minutes (Table 12). Other schedules (ds27, ds46 and ds48) can have some deviation. For the values of the ds27 schedule $SProbRespect(10)_{ds27} = 0.6$ and $SMinSat(10)_{ds27} = 0.96$. This schedule shows the planner that despite the 10 minutes delay, all customers are not satisfied only 96% ($SMinSat(10)_{ds27}$) and that the probability that all goes well is 60% ($SProbRespect(10)_{ds27}$) .

Depending on the values of 'x' the schedules will be considered as risk taking acceptable by the planner both on the probability indicator that for the delivery percentage satisfied in the most catastrophic scenario. Because it is difficult to select a scenario with a high probability of success ($SProbRespect(x)$) if the percentage of delivery satisfied can be very low ($SMinSat(x)$). This means that there is a small risk that a lot of customers will be unsatisfied because their delivery is not delivered on time. Conversely, if the probability of success is low ($SProbRespect(x)$) and the percentage of delivery satisfied is high ($SMinSat(x)$) this means that a very small number of customers are likely to not be delivered on time. The indicator $SMaxDelay$ flag allows you to give a quick value of the number of minutes that the planner has to negotiate with the client so that his schedule runs without any worries.

If the delay accepted by the client is not sufficient for a schedule to run correctly, the planner makes either a compromise using the indicator or actionable data presented or he can select other schedules to assess their robustness.

These robustness indicators allow the planner to see the different problems that may impact his schedule and their consequences give him the means to be able to anticipate the negotiations with the customer on possible delay so that his panning can meet both the requirements of his company and that of customers.

5 Conclusions

The road freight transport sector plays a crucial role in the economic balance of a country. Moreover the constraints and the client requirements become more and more important. At the same time, the delivery process frequently encounters many disruptions that make it more difficult for planners to meet customer deliveries. In this context, many research works focused on reactive scheduling methods to aid planners when disturbances occurred. As an alternative way, this paper proposes to take into account disturbances as soon as the design of the tour and to give planners the opportunity to select a solution knowing its capacity to respect clients' requirements despite possible disturbances.

Firstly, this paper proposes a model of danger allowing to model the knowledge of the planners in terms of hazard situations which could impact the delivery process.

Secondly, this paper proposes three indicators to assess RFT plannings. The first one gives the estimated probability that the daily schedule could meet all customers' requirements. The last two, $SMaxDelay$ and $SMinSat$, are actionable data. They give planners information on how to improve the robustness of the planning evaluated ($SProbRespect$). Lastly, this paper provides an original approach to assess these robustness indicators. The approach is based on a dynamic mechanism of risk identification which used a danger instantiating mechanism. Then, the impacts of the identified risks on the activities of the plans are assessed through a risk scenario simulator labelled RIOSUITE.

Our proposal uses as an input a schedule which can be generated either manually or by a commercial tool when it can be exported in a neutral and/or compatible format with the one used by our module. This approach hypothesises that activities' duration are considered without taking into account the potential impacts of risks. However, if the planner has planned extra time on some activities to anticipate the impacts of potential risks, during the robustness evaluation process he can deactivate, from the risk portfolio, the risks that are associated with this extra time. The tool offers the possibility to select which risks the planner wants to consider in the schedule analysis.

For any planner who has little experience (in planning, new delivery area, …), the system makes it possible to give an assessment of the level of robustness of the planning currently being designed and retain expertise on risks that can impact planning.

Further research should be done on finding ways to improve the risk model and the scenario simulator in order to take into account possible dependencies between risk occurrences. Nowadays, the proposal considers all the risks as independent. However, it is also necessary to consider that a specific risk could induce disturbances on two or more tours, as an example a risk of traffic jam that can impact several tours in the same time.

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Notes

1 ISO15442:2012.

2 RIOSUITE is available online at https://research-gi.mines-albi.fr/display/RIOSUITE/Welcome.