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Kinematic Model of Project Scheduling with Resource Constrained under Uncertainties

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Abstract. Projects represent the principal means of materialization of products. The inherent complexity of product projects is treated through the techniques and approaches project management. Throughout products life cycle the techniques and approaches project management are mainly involved in the planning, programming and control of project activities conducted in context of resource constrained under uncertainties. In addition of scenarios the complexity of the projects, there are some classes of products, typical of industries of the defense, aerospace, telecommunication, software, and biomedicine, which are problematic for current methods of resource constrained project planning and scheduling under uncertainty. The existing methods fail because they suffer from one or more of the following limitations: focused mainly on the basic RCPSP (Resource Constrained Project Scheduling Problem) model; dealing with only one source of uncertainty, mostly in duration of activities; and do not model uncertainties.

This paper presents the kinematic model of projects scheduling which considering the inherent restrictions in nature of the projects: precedence among project activities; uncertainties of the duration of project activities; and uncertainties in availability of resources for execution of project activities. The kinematic model of projects scheduling provides a graph and mathematical model with the advantages: estimation of the project duration and resources due to uncertainties; estimation of the uncertainties due to project duration and resources; improvement of the outcomes of planning and scheduling of project activities; and assists the dynamics of projects providing information for collaboration policy of the durations and resources between project activities and between different projects. This article describes the Resource Constrained Project Scheduling Problem under uncertainties, discuss previous work on planning under uncertainty, and presentation of the kinematic model of projects scheduling with resource constrained under uncertainties along with a small example of implementation.

Keywords. Project scheduling, product project, resource constrained under uncertainties, project management, kinematic model.

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Introduction

The research on project scheduling problem was intensified from the recognition that network models CPM (Critical Path Method), PERT (Project Evaluation Review Technique) and PDM (Precedence Diagram Method) are based on the assumption that all needed resources will be available [1]. The importance of project scheduling and control is bolstered with many examples where the inadequate scheduling and control are often identified as the most common causes of project failure [2].

This paper presents the kinematic model for projects scheduling with resource constrained under uncertainties which considering the inherent restrictions in nature of the projects: precedence of project activities; uncertainties of the duration of project activities; and uncertainties in availability of resources for execution of project activities. The project scheduling may be considered as an open kinematic chain, which is formed by: a set of rigid links (precedence of activities) that are connected by joints (activities of project) with one fixed extremity (activity that represents the beginning of the project) and one free extremity (activity that represents the end of the project).

The methods for resource constrained project scheduling problem are aimed the project scheduling under uncertainties to minimize the expected total time of project, but these methods, however, these methods present some limitations [3, 4, 5]: The proactive or reactive methods dealing with uncertainty. Proactive methods work better in cases when the uncertainty is quantifiable. Reactive methods work better in cases when the degree of uncertainty is too great. Researches indicate the perspective in combining proactive and reactive methods. The necessity for new models of scheduling which account for production environment conditions. Most of the research up to date has dealt with only one source of uncertainty, mostly in duration of activities. The methods are focused mainly on the basic RCPSP model. The methods do not model the uncertainties.

This paper is divided into 5 sections, being: section 1 presents an introduction for the paper; section 2 presents a literature review on resource constrained project scheduling problem under uncertainties; section 3 presents the kinematic model concepts as well as the mathematical fundaments; section 4 presents the application of the equations of direct and indirect kinematics for a simple schedule with uncertainties in durations and resources of activities; and section 5 presents some conclusions over the implementation of the kinematic model for projects scheduling with resources constrained under uncertainties.

1. Literature Review on Project Scheduling Problem

The literature review states that the project scheduling is the main cause of failure of the projects, only 30% of the projects are completed on schedule and budget [6]. The project scheduling may be defined as the arrangement, leveling and allocation of these activities regarding the duration and resources required for performing each activity [7].

The project scheduling must to consider the present constraints in nature of the projects: precedence of project activities; uncertainties of the duration of project activities; and uncertainties in availability of resources for execution of project activities [8].

- Activities: represented as a network in a discrete and finite set of activities [9].
- Durations: the scheduling depends of the duration estimation modeling, may be probabilistic or possibilistic [9].
- Resources: may be grouped into three types of categories [9]:
  - Renewable: there is a certain amount of resource available for each activity, for example, hours of employees, facilities and others.
  - No Renewable: there is a certain amount of resource available for entire project, for example, raw materials, financial resource, and others.
  - Doubly restricted: resources are considered renewable and no renewable.

The challenge of the project scheduling is related with allocation of resource constrained in a multiple projects environment with different sources of uncertainty, for example, duration of activities, resource availability, among others [9]. The formal research for the project scheduling problems began after second world war, until the 1950 decade, the challenge of project management was to determine a detailed graphical representation for the project scheduling problem, which was solved through of the approaches and techniques [10]: Gantt diagram, and project network diagram.

In 1960 and 1970 decades there was the need of approaches and techniques for project scheduling problem driven by duration of activities was solved through approaches and techniques for the project scheduling problem with activities on node [10]: Critical Path Method (CPM) and Precedence Diagram Method (PDM) assuming deterministic activity duration, and Program Evaluation and Review Technique (PERT) assuming probabilistic activities duration.

The 1980 and 1990 decades treated of the problem related with the omission of required resources for the execution of activities that is known as Resource Constrained Project Scheduling Problem (RCPSP) which is represented by a CPM deterministic problem with addition of resources as constraints [11]. The RCPSP problems are treated by algorithms, the exact methods are applied to projects with small instances (until 30 activities), for the case of projects with large amounts of instances must be used the heuristic methods [12].

From 2000 decade the project scheduling problem considering the uncertainties is known as Stochastic Resource Constrained Project Scheduling Problem (SRCPSP) which is a stochastic variant of the RCPSP and it can involve many sources of uncertainty like: activity durations, renewable resource availability, task insertion, resource consumption, and others. In general, there are four approaches to dealing with uncertainty in a scheduling environment [13]: reactive scheduling, stochastic project scheduling, fuzzy project scheduling, and proactive methods.

2. Kinematic Model of Project Scheduling with Resource Constrained under Uncertainties

The kinematic model of project scheduling with resource constrained under uncertainties deals the movements of the schedule activities without to consider the causes of movement origin. The kinematic model of project scheduling presents two types of variables:

- Project variables: precedence, duration of activities, resources to perform the activities.

- Parameters of project activities:
  - Activities variables: estimation of duration of activities, estimation of resources to perform the activities, estimation of precedence of activities, critical factor of activities.
  - Uncertainties of activities: uncertainties of duration of activities, uncertainties of resources to perform the activities.

In kinematic model of project scheduling the activities are represented as vector into coordination system through project variables and parameters of project activities. Thereby, from parameters of project activities (activities variables and uncertainties of activities) may be determined the project variables with direct kinematic model of project scheduling, as well as, from project activities variables may be determined the uncertainties of activities with inverse kinematic model of project scheduling.

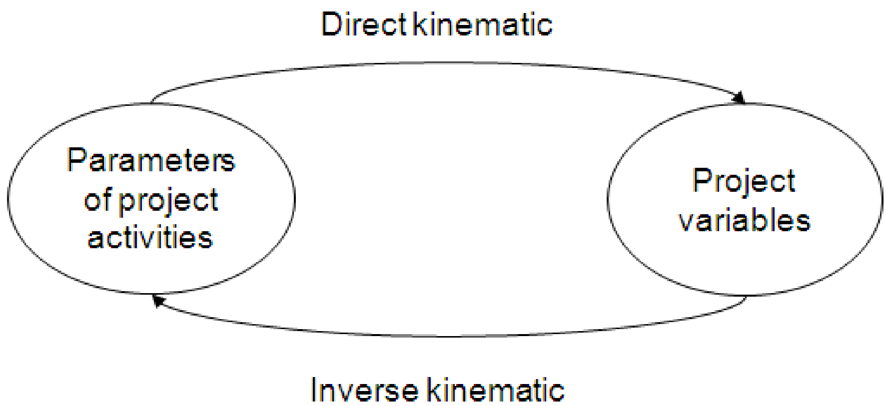

Figure 1. Kinematic model of project scheduling.

The project schedule may be considered as an open kinematic chain, which is formed by a set of rigid links that are connected by joints, with one fixed extremity and one free extremity, making equivalence between the components of open kinematic chain and schedule:

- Fixed extremity: activity that represents the beginning of the project.
- Free extremity: activity that represents the end of the project.
- Rigid links: precedence of activities.
- Revolute joints: activities of project.

In order to model the project scheduling depending on variables and parameters of project, the activities are represented by three dimensional coordinate system and direct:

- Abscissa (x axis): duration of project activities.
- Ordinate (y axis): resources to perform the project activities.
- Cote (z axis): precedence, this value do not have uncertainties.
- Alpha for uncertainties of estimation of activities duration.
- Beta for uncertainties of estimation of resources to perform the activities.

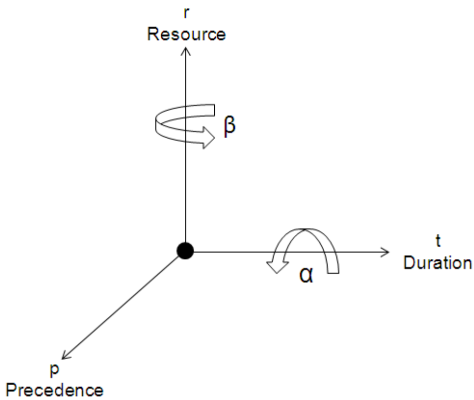

Figure 2. Three dimensional coordinate system for kinematic model.

The representation of (direct and inverse) kinematic model for project scheduling with resource constrained under uncertainties is the outcome of sum of the homogenous transformations matrices between project variables and parameters of project activities. The equations of (direct and indirect) kinematic model for project scheduling with resource constrained under uncertainties must consider the set of activities and resources.

$$A_n^0(j) = \sum_{i=0}^{n} \sum_{j=1}^{m} A_i^{i-1}(j) \tag{1}$$

$$A_i^{i-1}(j) = \{[H_i^{i-1}(\alpha_i^j).H_i^{i-1}(T_i^j;R_i^j)] + [H_i^{i-1}(\beta_i^j).H_i^{i-1}(T_i^j;R_i^j)]\} + H_i^{i-1}(P_i^j) \tag{2}$$

- i - set of activities: i = (0, 1, 2,…, n).
- j - set of resources: j = (1, 2, 3,…, m).
- $A_i^{i-1}(j)$ - homogenous transformation matrix of kinematic model for project scheduling with resource constrained under uncertainties.
- t_i - abscissa axis representing the estimation of duration of project activities.
- r_i - ordinate axis representing the estimation of resources to perform the activities.
- p_i - cote axis representing the precedence of activities.
- T_i^j - estimation of duration of project activities.
- R_i^j - estimation of resources to perform the activities.
- P_i^j - precedence of activities.
- θ_i^j - critical factor of activities, for cases where the durations and resources may be greater than double of estimations.
- α_i^j - uncertainties of duration of project activities, represented through the rotation in the abscissa axis (t).
- β_i^j - uncertainties of resources to perform the activities, represented through the rotation in the ordinate axis (r).

- H_i^{i-1} - basic homogenous transformation matrix.
- $H_i^{i-1}(\alpha_i^j)$ - basic homogenous transformation matrix with rotation α_i^j in the abscissa axis t_i.
- $H_i^{i-1}(\beta_i^j)$ - basic homogenous transformation matrix with rotation β_i^j in the ordinate axis r_i.
- $H_i^{i-1}(T_i^j;R_i^j)$ - basic homogenous transformation matrix with translation $\theta_i^j.T_i^j$ and $\theta_i^j.R_i^j$.
- $H_i^{i-1}(P_i^j)$ - basic homogeneous transformation matrix with translation $P_i^j - [\theta_i^j.(T_i^j.s\beta_i^j - R_i^j.s\alpha_i^j]$ to cancel the effects of uncertainties.

Therefore, the representation of kinematic model for project scheduling with resource constrained under uncertainties must be determined through developing of homogenous transformation matrix of kinematic model for project scheduling with resource constrained under uncertainties.

$$- c\alpha_i^j = \cos(\alpha_i^j); - s\alpha_i^j = sen(\alpha_i^j); - c\beta_i^j = \cos(\beta_i^j); - s\beta_i^j = sen(\beta_i^j) \quad (3)$$

$$A_i^{i-1}(j) = \begin{vmatrix} 1 & 0 & 0 & a_i^{i-1}t_i(j) \\ 0 & 1 & 0 & a_i^{i-1}r_i(j) \\ 0 & 0 & 1 & a_i^{i-1}p_i(j) \\ 0 & 0 & 0 & 1 \end{vmatrix} = \begin{vmatrix} 2+c\beta_i^j & 0 & 0 & \theta_i^j.T_i^j.(1+c\beta_i^j) \\ 0 & c\alpha_i^j+2 & s\alpha_i^j & \theta_i^j.R_i^j.(c\alpha_i^j+1) \\ s\beta_i^j & s\alpha_i^j & c\alpha_i^j+c\beta_i^j+1 & P_i^j \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (4)$$

3. Implementation of Kinematic Model of Project Scheduling with Resource Constrained under Uncertainties

This section presents the implementation of kinematic model for project scheduling with resource constrained under uncertainties. The equations of direct kinematic model for project scheduling with resource constrained under uncertainties must be implemented from work breakdown structure (WBS) and execution of project time management processes: define activities, sequence activities, estimate activity resources, estimate activity durations, develop schedule (arrangement, leveling and allocation of activities).

To illustrate the implementation of kinematic model for project scheduling with resource constrained under uncertainties must be done some observations over the schedule diagram precedence illustrated in Fig. 3:

- The example presents a small schedule with activities of project critical path.
- The criterion for determination of the resources must be part of organization policies.
- The criterion for determination of the uncertainties must be part of organization policies.
- The uncertainties must range between 0° (highest degree of uncertainty) and 89° (lowest degree of uncertainty). When alpha and beta equal 90°, there are

not uncertainties or certainties. The certainties must range between 91° (lowest degree of certainty) and 180° (highest degree of certainty).

- A0: beginning of the project.
- A1: with uncertainties of duration and uncertainties of resources (j = 1 and j = 2).
- A2: with uncertainties of duration and uncertainties of resources (j = 1 and j = 2).
- A3: end of project.

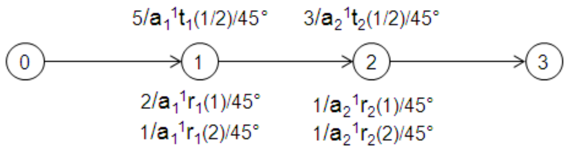

Figure 3. Schedule diagram precedence of direct kinematic model.

Eq (5) represents of project variables and parameters of project activities in regarding to resources of direct kinematic model.

$$A_i(j) = (T_i^j \; ; R_i^j \; ;P_i^j \,) \, , [\theta_i^j ; \alpha_1^j ;\beta_i^j \,] \, , \{a_i^{i\text{-}1} t_i(j);\; a_i^{i\text{-}1} r_i(j);\; a_i^{i\text{-}1} p_i(j)\} \qquad (5)$$

$$A_0(1) = (0;\;\; 0;\;\; 0), \; [\theta_0^1 \;=\; \text{-};\; \alpha_0^1 = -;\beta_0^1 = -]$$

$$A_1(1) = (5;\;\; 2;\;\; 1), \; [\theta_1^1 \;=\; 1;\; \alpha_1^1 = 45^\circ;\beta_1^1 = 45^\circ]$$

$$A_1(2) = (5;\;\; 1;\;\; 1), \; [\theta_1^2 \;=\; 1;\; \alpha_1^2 = 45^\circ;\beta_1^2 = 45^\circ]$$

$$A_2(1) = (3;\;\; 1;\;\; 1), \; [\theta_2^1 \;=\; 1\;;\; \alpha_2^1 = 45^\circ;\beta_2^1 = 45^\circ]$$

$$A_2(2) = (3;\;\; 1;\;\; 1), \; [\theta_2^2 \;=\; 1\;;\; \alpha_2^2 = 45^\circ;\beta_2^2 = 45^\circ]$$

$$A_3(1) = (0;\;\; 0;\;\; 1), \; [\theta_3^1 \;=\; \text{-};\; \alpha_3^1 = -;\beta_3^1 = -]$$

For direct kinematic model the Figure 4 presents the project variables and parameters of project activities.

		Parameters of project activities						Project variables		
		Activities variables				Uncertainties				
Activity (j)		T_i^j	R_i^j	P_i^j	θ_i^j	α_i^j	β_i^j	$a_i^{i-1}t_i(j)$	$a_i^{i-1}r_i(j)$	$a_i^{i-1}p_i(j)$
0		0	0	0	-	-	-	-	-	-
1	(1)	5	2	1	1	45°	45°	?	?	?
	(2)	5	1	1	1	45°	45°	?	?	?
2	(1)	3	1	1	1	45°	45°	?	?	?
	(2)	3	1	1	1	45°	45°	?	?	?
3(1)(2)		0	0	1	-	-	-	?	?	?
Total (1)		8	3	3	-	-	-	?	?	?
Total (2)		8	2	3	-	-	-	?	?	?

Figure 4. Direct kinematic model of the implementation example.

Homogenous transformation matrices for each project activities in regarding to resources applying the Eq. (3, 4) and information of Figure 4 for direct kinematic model.

Direct kinematic model for activity (i = 1) and resource (j = 1).

$$A_1^0(1) = \{[H_1^0(45^\circ, t_1).H_1^0(5;\ 2)] + [H_1^0(45^\circ,\ r_1).H_1^0(5;\ 2)]\} + H_1^0(1) \quad (6)$$

$$A_1^0(1) = \begin{vmatrix} 1 & 0 & 0 & a_1^0 t_1(1) \\ 0 & 1 & 0 & a_1^0 r_1(1) \\ 0 & 0 & 1 & a_1^0 p_1(1) \\ 0 & 0 & 0 & 1 \end{vmatrix} = \begin{vmatrix} 2{,}7 & 0 & 0 & 8{,}5 \\ 0 & 2{,}7 & 0{,}7 & 3{,}4 \\ 0{,}7 & -0{,}7 & 2{,}4 & 1 \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (7)$$

Direct kinematic model for activity (i = 1) and resource (j = 2).

$$A_1^0(2) = \{[H_1^0(45^\circ, t_1).H_1^0(5;\ 1)] + [H_1^0(45^\circ, r_1).H_1^0(5;\ 1)]\} + H_1^0(1) \quad (8)$$

$$A_1^0(2) = \begin{vmatrix} 1 & 0 & 0 & a_1^0 t_1(2) \\ 0 & 1 & 0 & a_1^0 r_1(2) \\ 0 & 0 & 1 & a_1^0 p_1(2) \\ 0 & 0 & 0 & 1 \end{vmatrix} = \begin{vmatrix} 2{,}7 & 0 & 0 & 8{,}5 \\ 0 & 2{,}7 & 0{,}7 & 1{,}7 \\ 0{,}7 & -0{,}7 & 2{,}4 & 1 \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (9)$$

Direct kinematic model for activity (i = 2) and resource (j = 1).

$$A_2^1(1) = \{[H_2^1(45^\circ, t_2).H_2^1(3;\ 1)] + [H_2^1(45^\circ, r_2).H_2^1(3;\ 1)]\} + H_2^1(1) \quad (10)$$

$$A_2^1(1) = \begin{vmatrix} 1 & 0 & 0 & a_2^1 t_2(1) \\ 0 & 1 & 0 & a_2^1 r_2(1) \\ 0 & 0 & 1 & a_2^1 p_2(1) \\ 0 & 0 & 0 & 1 \end{vmatrix} = \begin{vmatrix} 2{,}7 & 0 & 0 & 5{,}1 \\ 0 & 2{,}7 & 0{,}7 & 1{,}7 \\ 0{,}7 & -0{,}7 & 2{,}4 & 1 \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (11)$$

Direct kinematic model for activity (i = 2) and resource (j = 2).

$$A_2^1(2) = \{[H_2^1(45^\circ, t_2).H_2^1(3;\ 1)] + [H_2^1(45^\circ, r_2).H_2^1(3;\ 1)]\} + H_2^1(1) \quad (12)$$

$$A_2^1(2) = \begin{vmatrix} 1 & 0 & 0 & a_2^1 t_2(2) \\ 0 & 1 & 0 & a_2^1 r_2(2) \\ 0 & 0 & 1 & a_2^1 p_2(2) \\ 0 & 0 & 0 & 1 \end{vmatrix} = \begin{vmatrix} 2{,}7 & 0 & 0 & 5{,}1 \\ 0 & 2{,}7 & 0{,}7 & 1{,}7 \\ 0{,}7 & -0{,}7 & 2{,}4 & 1 \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (13)$$

Direct kinematic model for activity (i = 3) and resources (j = 1 and j = 2).

$$\begin{aligned} A_3^2(1) &= A_3^2(2) = H_3^2(P_3^1) = H_3^2(P_3^2) \\ A_3^2(1) &= A_3^2(2) = H_3^2(1) \end{aligned} \quad (14)$$

$$A_3^2(1) = A_3^2(2) = \begin{vmatrix} 1 & 0 & 0 & a_3^2 t_3(1/2) \\ 0 & 1 & 0 & a_3^2 r_3(1/2) \\ 0 & 0 & 1 & a_3^2 p_3(1/2) \\ 0 & 0 & 0 & 1 \end{vmatrix} = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 \end{vmatrix} \tag{15}$$

The elements of fourth column are analyzed in order to determine the project variables for each activity of direct kinematic model.

Direct kinematic model for activity (i = 1) and resource (j = 1), from Eq. (7).

- Project variable of duration: $a_1^0 t_1(1) = 8{,}5$
- Project variable of resource: $a_1^0 r_1(1) = 3{,}4$
- Project variable of precedence: $a_1^0 p_1(1) = 1$

Direct kinematic model for activity (i = 1) and resource (j = 2), from Eq. (9)

- Project variable of duration: $a_1^0 t_1(2) = 8{,}5$
- Project variable of resource: $a_1^0 r_1(2) = 1{,}7$
- Project variable of precedence: $a_1^0 p_1(2) = 1$

Direct kinematic model for activity (i = 2) and resource (j = 1), from Eq. (11).

- Project variable of duration: $a_2^1 t_2(1) = 5{,}1$
- Project variable of resource: $a_2^1 r_2(1) = 1{,}7$
- Project variable of precedence: $a_2^1 p_2(1) = 1$

Direct kinematic model for activity (i = 2) and resource (j = 2), from Eq. (13).

- Project variable of duration: $a_2^1 t_2(2) = 5{,}1$
- Project variable of resource: $a_2^1 r_2(2) = 1{,}7$
- Project variable of precedence: $a_2^1 p_2(2) = 1$

Direct kinematic model for activity (i = 3) and resource (j = 1 and j = 2), from Eq. (15).

- Project variable of duration: $a_3^2 t_3(1) = a_3^2 t_3(2) = 0$
- Project variable of resource: $a_3^2 r_3(1) = a_3^2 r_3(2) = 0$
- Project variable of precedence: $a_3^2 p_3(1) = a_3^2 p_3(2) = 1$

4. Conclusions and Comments

Analyzing the application of the equations of direct kinematics model for example schedule with uncertainties in durations and resources of, should be highlighted some conclusions: Achievement of robust project scheduling provided by balancing of uncertainties for durations and resources between project activities and between projects. The project activities are modeled as an open kinematic chain which the graphical and mathematical representation different of the RCPSP basic model. The model is driven by multi source of uncertainties for the estimation of durations and resources availabilities. The project variables and parameters of project activities are influenced by sources of uncertainties. Outcomes of direct kinematic model for the implementation example:

- For activity (i = 1): increase in 70% de estimation of duration, increase in 70% de estimation of resource (j = 1) and increase in 70% de estimation of resource (j = 2).
- For activity (i = 2): increase in 70% de estimation of duration, increase in 70% de estimation of resource (j = 1) and increase in 70% de estimation of resource (j = 2).
- For project: increase in 70% de estimation of duration, increase in 70% de estimation of resource (j = 1) and increase in 70% de estimation of resource (j = 2).

For future works, the uncertainties for durations and resources may be modeled through indirect kinematic model. There are some opportunities in regarding to the developing the criterion of identification and categorization for resources, as well as, the criterion of identification and categorization for uncertainties which are treated as indirect risks.

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