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Lifecycle's Processes-Based Categories for the Risk Analysis in the Development of Engineering Solutions: An Application to Civil Structures Development

Olga Eugenia URREGO- GIRALDO [a,b] Luis-Emilio VELÁSQUEZ-RESTREPO [a] and Germán URREGO-GIRALDO [a,1]
[a] *Universidad de Antioquia*
[b] *ÁREA Ingenieros Consultores S.A.S*

Abstract. Process concept gathers agents' action and interaction on objects and their associated knowledge, belonging to one of several domains, supported on Transdisciplinary Engineering concepts. An engineering solution is a tangible or intangible object able to satisfy the solution requirements. A solution incorporates knowledge and develops capacities and functionalities in processes of its lifecycle phases. The risk analysis in engineering solutions development is, in general, treated with particular risks frameworks selected or adapted to each project development. Damage risks of an object (solution) correspond to troubles in processes of its life cycle. Our research introduces a framework of generic capacities and another of functionalities of a solution and it uses generic functionalities as risk categories for classifying risks of damages of a solution. The use of knowledge expressed as object's capacities involving the recognized purposes of each lifecycle's phase, and object's functionalities derivate from object's capacities, constitute a contribution of this paper. In this process-based approach, the disaggregation of risk categories in specific risks aspects coincides with the disaggregation of risks categories in a product-based approach using a cause-effect model for the definition of risk categories. This mutual confirmation of both approaches enables their enhancement and use in any engineering field. The proposed risk analysis model supports the ex-post risk analysis of a collapsed tower of a pre-stressed stayed bridge in the field of civil structures development.

Keywords. Transdisciplinary Engineering, Risk Analysis, Civil Structures Risks

Introduction

A problem perceived by agents interested in a domain constitutes a demand of agents' interventions on material or immaterial objects of this and other domains. In the field Requirements Engineering, fundamental concepts of Domain Engineering are proposed [1], an introduction to Domain Analysis is the subject in [2], and a metamodel of domain is explained in [3]. An agent is responsible of an individual action or an interaction with other agents. An agent's intervention is an action of an autonomous agent or an activity or a process or mega-process involving the interactions of several agents. Thus, a domain is a field of knowledge and work, composed by interrelated tangible and intangible objects, where agents intervene in order to satisfy their goals. Context concept, as environment affecting a solution along its lifecycle, may have diverse representations, treated among others by [4], adds interactions capacities to solutions, in [5] and aids to construction and use of families of solutions, in [6]. This context concept supports in [7], [8] mobile and ubiquitous solutions incorporating context-awareness facilities. Other concept of context based on interested agents, characterized as agent's intervention context, is the central aspect in the requirements engineering approach presented in [9]. Agents intervene on domains' objects or knowledge related to these objects. Agents' interventions constitute contexts, where domains' knowledge acquire meaning and value. An Agents Interventions Context considers a set of agents, their interventions, circumstances that determine these interventions, the used means and methods, context's objectives and agents' goals and decisions. Context and domain concepts constitute a knowledge partition, in [9], [10]. The process concept delimits context and domain knowledge in [9].

In terms of context and domain, a process is a set of action and interactions of agents, which work on tangible and/or intangible objects belonging to one or several domains, progressing from initial or delayed supplies or contributions, using proper means, methods, and resource; and aiming at the obtaining of results, which satisfy individual and/or collective agents' objectives. In this sense, a process is an operative context, that is, a context applied on one or several domains looking for specific results. It is the application of a context on one or several domains in order to create value.

The development of a solution in engineering fields is a sequence of processes from the recognition of a problem and the first idea of a solution, to its elaboration, use, evolution, evaluation and end of its life. Project concept, in [11] guides the achievement of solution. The probability of an undesirable effect, coming from different causes, constitutes a risk. Risks in the development of an engineering solution are associated with its sequence of processes. Risk analysis in processes of a product innovation chain is introduced in [12]. Experiences of risks analysis in process of the Civil Engineering projects development are condensed in [13], [14], [15].

Risk analysis has had ample deployment in engineering projects, as it is condensed in the PERIL database, English acronymous for Project Experience Risk Information Library, in [16]. These projects use, in general, particular frameworks, representatives for each project, with approaches ranging in the Cross-engineering concept. We pursue now integrating methods of requirement engineering with methods of other knowledge disciplines in projects of these ones, reaching the field of Transdisciplinary Engineering, which concepts are considered in [17], [18]. The Transdisciplinarity as a research form is developed in [19]. This research is extended to sustainability in [20]. Transdisciplinarity in urban megaprojects is treated in [20]. The diversity of projects aiming to solutions in any activity field suggest generalizing a model of phases for project development in any knowledge area. Each phase represents a big process with particular results. Thus, a project development constitutes a set of big processes with a specific product of each one. Each specific product represents the capacities acquired by the solution in a particular phase. The solution, as a result of a project, incorporates all capacities acquired in each development phase. Acquired capacities, in each phase, are associated with the knowledge assimilated by the solution in this phase, in a similar way as human beings develop capacities in each development phase during their life. Going from living beings to engineering products, the lifecycle concept makes sense as a sequence of phases for incorporating and experiencing new knowledge. Based on capacities acquired, a solution can answer questions related to its real and potential functionalities. Models based in these questions in each phase of the life cycle extends the concept of project and its development methods beyond the knowledge disciplines limits. Engineering as knowledge for creating and applying methods and developing processes may cover all fields of knowledge and science.

The analysis of risks in the development of civil structures is a big concern for all involved agents. Many probable causes of fails, coming from a diversity of natural, human, and technological agents, may appear in the development processes of a engineering civil structural solution. The development of a civil structural element consists in a set of processes classified in phases framed in the following categories: pre-construction, construction, post construction, and functioning or use. These categories are high-level processes containing disaggregated processes associated with each phase.

We propose, in our process-based risks analysis model approach, a framework of object's capacities and functionalities associated with each recognized phase in the mentioned categories, for the identification of risks. This framework, based on processes, guides the identification of risks in the phases of life cycle of solutions in any knowledge field. Here, we apply this framework in pre-construction and post-construction phases in the lifecycle of a support tower of a pre-stressed suspended bridge, in Colombia. This experience allows us to compare the risk analysis effectuated with a framework of causes applied in a cause-effect model, which is a product-based approach. This comparison constitutes a mutual validation of processes-based and causes-based frameworks used for the risks analysis and offers specific and pertinent concepts to the use of risk models covering the identification, classification, and treatment of risks in civil structures solutions.

After the Introduction, this article presents in Section 1 the concepts of lifecycle and its processes, used in the identification of Risk Categories, and explains the construction of the Process-Based Risk Categories Model. The application of the Process-Based Risks Categories Model in the risk analysis of a support tower of a suspended prestressed bridge belongs to Section 2. Conclusion and future work constitute Section 3. Bibliography appears in the last Section.

1. Risk Analysis Model for the Engineering Project Lifecycle

The existence and behaviour of a tangible or intangible object representing an Engineering solution may be followed throughout its presence in processes along its life. These processes are gathered in phases of the Object-lifecycle supporting a process-based knowledge and functionalities acquisition. Failures of and object are experienced in excising it functionalities. Object's generic functionalities constructed along its lifecycle phases are expressive risk categories useful for the risk analysis of an Engineering solution.

1.1 Lifecycle Processes Used in the Identification of Risks Categories

The concept of lifecycle characterizes in an expressive way the development of living and inanimate objects, considering meaningful phases between their birth and death. An engineering solution is a tangible or intangible object able to satisfy the solution requirements. The sequence of processes that constitutes the existence of an object defines the lifecycle's phases. These represent big processes with specific and consolidated results, and conform stages referred to macro processes, which involve new agents, methods, means and circumstances.

Lifecycle Phases	Knowledge-Based Object Capacities	Object's Generic Functionalities (Risk categories)
Stage 1: Pre-construction		
Definition	What **it must** potentially do	What a tangible or intangible object does with the knowledge that it requires, takes, rejects, or receives, determining or affecting its nature, functioning or evolution.
Analysis: Requirements Study	What **it expects** potentially do	What an object can do with it knows and according to its nature (essential characteristics or proprieties, structure, shape, components) and its environment.
Analysis: Logical Model	What **it could** potentially do	What an object does with that it knows and enhances.
Design	What **it will** potentially do	What an object does with that it knows and proposes (its function).
Stage 2: Construction		
Planning	What **it must** do when concretized or implemented	What an object does with that it knows and diversifies (as a means. method, input, resource, component, or other uses).
Construction	What **it expects** to do when concretized or implemented	What an object does with that it knows and reaches to learn and adopts.
Testing	What **it could** do when concretized or implemented	What an object does with that it knows, when revised, verified, validated, correct, and rectified.
Operation	What **it will** do when concretized or implemented	What a tangible or intangible, produced or derivate object does with that it knows, keeps, enables, and offers according to its nature, functioning, or evolution.
Stage 3: Post-construction		
Programming and preparing the distribution	What **it must** do when put into practice or delivered	What an object does with that it knows, configurates, shows and differentiates (as a means. method, input, resource, component, or other uses).
Distribution	What **it expects** do when put into practice or delivered	What an object does with that it knows and reaches to recognizes and delimits.
Post-production Service	What **it could** do when put into practice or delivered	What an object does with that it knows, when reconfigured, recuperated, isolated and particularized.
Impact evaluation	What **it will** do when put into practice or delivered	What a tangible or intangible, produced or derivate object does with that it knows, influences, determines and stablishes according to its nature, functioning, or evolution.
Stage 4: Functionning or use		
Change identification	What **it must** do when functioning, used, and changed	What an object does with that it knows, identifies, affronts and discovers (as a means. method, input, resource, component, or other uses).
Application of Evolution Categories	What **it expects** to do when functioning, used, and changed	What an object does with that it knows and reaches to aggregate, substitute, eliminate, repair adapt, strength, review, conserve, adjust, provide, support, assay, modify, correct, update and receive.
Interaction with other agents	What **it could** do when functioning, used, and changed	What an object, intervening as mean, object, method or agent does together with other agents on other objects, with that it knows, integrates, isolates, interferes, activates, stops, and stimulates.
Mantainning of integrity, correction, consistency, and technical conditions	What **it will** do when functioning, used, and changed	What a tangible or intangible, produced or derivate object does with that it knows, conserves, retakes, adopts, ensures and protects as technical conditions and uses according to its nature, uses, risks and challenges.
Solution's uses as a means, method, ressource, component, input, and other uses		

Figure 1. Capacities, Processes of Solution and Risk categories.

The lifecycle, Figure 1, contains, in line 1, 6, 11, and 16, four stages (macroprocesses): Pre-construction, Construction, Post-construction, and Functioning or Use. Thinking in one whole process for the development project of a solution, the four stages constitute, in the same order, in column 5 of Figure 1, the four steps of a process: Input, Evolution, Evaluation and Decision, and Output.

Each stage, Figure 1, lines 1, 6, 11, and 16, in turn, contains four lifecycle's phases, Figure 1, column 1, according to the four steps of the respective macro-process in Figure 1, column 2, associated to this stage: Input, Evolution, Evaluation and Decision, and Output. In each one of the sixteen phases listed in column 2, the solution incorporates knowledge, expressed then, in capacities acquired and offered by the solution in this particular phase. These capacities denominated Knowledge-Based Object's Capacities appear in Figure 1, column 3.

1.2 Construction of the Process-Based Risks Categories Model

Object's functionalities are practical uses of object's capacities in order to satisfy requirements or goals of agents involved in processes of the object's lifecycle. Object's problems, which are risks materialization, occur in the exercise of object's functionalities. Object's generic functionalities derivate from object's generic capacities, listed in Figure 1, column 4, constitutes the risk categories of the proposed risk analysis model.

Requirements Engineering searches to find solutions, which resolve a problem satisfying defined requirements. As matter of knowledge and sensitivity solutions are tangible or intangible objects, whose existence, development, use, and roles are important in all fields of knowledge. In Engineering, by example, the amplitude of concepts such as object, process and method allow the apparition of Interdisciplinary, Multidisciplinary, Transdisciplinary and Supra-disciplinary Engineering and the intervention of these expressions of Engineering in all fields of the science. Supra-disciplinary looks for solutions assuming processes of human, and social sciences, cooperating in the creation, development, and application of methods of these sciences.

The next Section illustrates the application of the risk analysis model, using risk categories with their specific risk aspects, to the collapse analysis of a suspended bridge tower.

While in [15], authors introduced the Knowledge-Based Generic Functionalities of an object. Here, we establish the relationship between lifecycle's phases and Knowledge-Based Capacities and their derivate generic functionalities. In both approaches acquired knowledge expressed object's capacities is the same and the corresponding knowledge-based functionalities coincide too. The risk categories headed by objects' functionalities or limitations to the exercise of these functionalities involve the same risks subcategories.

2. Risks Analysis of a support tower of a suspended prestressed bridge

We apply the framework of risk categories for the ex-post analysis of the collapse of a stayed bridge tower, in the construction period of the Chirajara bridge superstructure, in Colombia. This bridge of 450 meters long was suspended by cables crossing over two towers with a central span of 300 meters. When events occur, the risk of damage to an object derives from problems. In the case referred to in this research, a support tower collapsed and we with designers together use the risk model for establishing and explaining events, risk concepts, and how problems materializing risks happened. The tower was constructed, and was being used in the elaboration process of the bridge superstructure. Only the processes of pre-construction and construction stages intervened in the tower, from the definition phase to the operation phase of its lifecycle. Under these circumstances, the analysis of the tower collapse considers the following elements extracted from Figure 1, column 4: the eight first risks categories, and the category 15th, named "Interaction with other Objects", corresponding to the third process of the stage 4, denominated "Functioning and Use". In fact, the bridge was in the construction stage and the tower was not ready, neither submitted to processes of the stage 3, nor other processes of stage 4, except the third process.

The next paragraphs present the involved risk categories and their subordinated specific risk concepts. A preliminary analysis allowed us together with designers and constructors to take the possible risk subcategories affecting the tower, according to its development state. Then, our research group, designers and constructor selected, based on specialized technical studies, the risks concepts more directly influencing the tower behaviour at the time of its collapse. These concepts are highlighted in bold italic type. R1, R2, R3, R4, R5, R6, R7, R8, and R15 are the involved risk categories, disaggregated in their specific risk subcategories until the second level.

R1 What a tangible or intangible object does with the knowledge that it requires, takes, rejects, or receives, determining or affecting its nature, functioning or evolution.

a) Deficiencies in previously built works. b) Deficiencies in geology and soils. c) Deficiencies in hydrological studies. d) Inconsistency or incompleteness of technical standards used. e) Inconvenient access conditions for people, equipment, materials. f) Spaces and infrastructure inadequate for the construction of the works and for the operations on the site. g) Adverse environmental conditions. h) Deficiencies in the identification of the agents interested in the realization of the bridge and the actions and interactions that they must carry out in the processes of the phases of the bridge life cycle. i) Deficiencies in obtaining knowledge from studies, research and other sources, which must incorporate and use the bridge (as a solution). This knowledge is treated in the actions and interactions of the interested agents so that individually and collectively they satisfy their objectives in relation to the construction and use of the bridge. j) Deficiencies regarding the suitability, capacity, and experience of those who must intervene in the execution of the works. k) Failures in the scheduling of activities. l) Unreliable Suppliers and Supply Scheduling. m) Non-availability of machinery, equipment and adequate technical resources n) Non-availability of adequate human resources. o) Poor construction methods. p) Deficiencies in the management model of the work on the site (planning, organization, direction, execution, review and control). q) Deficiencies in the construction plans. ***r) Deficiencies in the supervision of construction***. s) Insufficiency of advice in Construction.

These first causes affect the bridge and the tower as one of its constituent elements.
The following categories focus on the tower as the object of study that interests us.
R2 What an object can do with it knows and according to its nature (essential characteristics or proprieties, structure, shape, components) and its environment.

a) Insufficiencies in the definition of the requirements that the work must satisfy in terms of its operation and quality. b) Deficiencies in the operationalization of the requirements. c) Deficiencies in the logical structural model. c1) Structure (constituent elements and their relationships) not adequate. c2) Inappropriate form.

c3) Inadequate allocation of forces. c4) Inadequate consideration of the application of forces. c5) Inadequate structural analysis method.

R3 What an object does with that it knows and enhances.

a) Effect of the earthquake in the construction period***. b) Changes in geology, soils and hydrology after their studies, before and during the construction period***. c) Electric shock, winds and temperature changes in the construction period. d) Manipulation of the built tower.

R4 What an object does with that it knows and proposes (its function).

a) Deficiencies in sections. a1) Insufficient dimensions. a2) Insufficiency of the steel area. a3) Insufficient cable area. a4) Insufficiency of the concrete area. a5) Coating deficiencies (compression reinforcement depth). a6) Deficiencies in surface treatments. b) Deficiencies in materials. b1) Insufficient quantity or proportions of materials (concrete, steel rods, steel cable, precast elements, plastic elements and other materials). b2) Deficiencies in the mechanical properties of materials (Ductility, flexibility, adherence, compressive strength, modulus of elasticity, yield point, yield strength). b3) Deficiencies in the behaviour of materials (elastic, plastic). b4) Deficiencies in treatments and their management. c) Deficiencies in design methods.

R5 What an object does with that it knows and diversifies (as a means. method, input, resource, component, or other uses).

a) Use of the tower or its components as support during construction. b) Changes in the logical model of the structure caused in the construction. ***c) Submit the tower or its components to unforeseen loads in terms of intensity or location during the construction period of the tower or of the bridge.***

R6 What an object does with that it knows and reaches to learn and adopts.

a) Changes in the mechanical properties of materials. b) Changes in the quantity and proportion of materials. c) Changes in the internal structure of the tower. d) Changes in its components and in its organization.

R7 Inadequacy in what an object does with that it knows, when revised, verified, validated, corrected, and rectified.

The deficiencies on different elements can appear simultaneously giving rise to a coincidence and chain of deficiencies in multiple elements of the tower.

Reasons that demand radical interventions:

a) Insufficiency (Lack) of one or more elements of the tower. ***b) Loss of validity of one or more elements of the tower***. c) Intrusion or obstruction of one or more elements in the operation of the tower as a whole.

Reasons that demand moderate interventions:

a) Damage, deficiency, deterioration of one or more elements of the tower. ***b) Incapacity of one or more elements of the tower to fulfil some functions, assimilate changes in a context or behave within it***. c) Saturation or limit requirement of the capacities of one or more elements of the tower. d) Deterioration, mismatch, lag of one various elements of the tower as a whole that limit its operation and capabilities. e) Existence, expansion or inappropriate behaviour of one or more elements of the tower. f) Wrong or abnormal behaviour of one or more elements of the tower. g) Loss of significance or validity of one or more elements of the tower. h) Loss of capacity, resources, or efficiency of one of several elements of the tower to achieve the results.

The two types of reasons detailed above, in turn, constitute problems that call for radical or moderate interventions (solutions), such as:

Radical interventions: aggregation, substitution, elimination

Moderate interventions: repair, adaptation, strengthening, maintenance (review, conservation, adjustment, provision, support, attention), modification, correction, update, recovery

The above reasons are deficiencies that have in turn a possible set of reasons, such as:

a) Changes in the location of other works of the project. b) Changes in the design of the set of works of the project. c) Changes in geology, in the soil in hydrology after its construction. d) Changes in pre-existing works. e) Changes in the earthquake regime after their construction. f) Changes in environmental conditions. g) Changes in the spaces and infrastructure to carry out the other works of the project. h) Changes or alterations of the construction processes of the other works of the project. i) Changes in the means and methods used for the other works of the project. j) Accidental or malicious actions on the processes, materials, the tower and its constituent elements.

R8 What a tangible or intangible, produced or derivate object does with that it knows, keeps, enables, and offers according to its nature, functioning, or evolution.

a) Insufficiency of a constituent of the constructed tower. ***b) Deficiency in objects, which behaviour affects the tower, during or after the construction time.*** c*)* Deficiencies in the consideration of stresses and elastic deformation. d) Accumulated tension losses in cables. e) Deficiencies in the consideration of the yield point and the breaking moment. f) Deficiencies in the consideration of behaviour of cracked sections. g) Deficiencies in the consideration of the maximum moment and the ultimate resistance. h) Deficiencies in the consideration of the collapse of the structure and memento-curvature. i) Incorporation of cracks, alterations of the sections, modifications in the quality of the materials, and changes in the arrangement and treatment of the constituent elements, affecting the behaviour of the tower during its construction and in the construction period of other works of the project.

R15 Inadequacy in what an object, intervening as mean, object, method or agent does together with other agents on other objects, with that it knows, integrates, isolates, interferes, activates, stops, and stimulates.

The deficiencies on different components can appear simultaneously giving rise to coincidences and concatenations of deficiencies in multiple elements of the tower.

In its interactions with other objects, the tower and its interacting agent affect other objects, tangible or intangible. These interactions use means and methods, and consider the situations or circumstances of the objects on which they act, as well as, those circumstances affecting the used means and methods.

In these interactions with other objects, the object can act as a whole or some or some of its parts. In these cases, risk categories indicated possible object damages requiring radical or moderated interventions.

Causes that demand radical interventions:

a) Dispersion or divergence of constituent elements of the tower. b) ***Disturbance or loss of connection of a constituent element of the tower due to the presence or actions of other elements or other external objects.*** c) Presence or improper action of a constituent element of the tower in the place or trajectory of others

Causes that demand moderate interventions:

a) Suspension or extinction of functions of one or more constituent elements of the tower in relation to other elements b) Activity, movement or unwanted behaviour of one or more constituent elements of the tower affecting other elements c) Decrease or depletion of the ability to act of one or more constituent elements of the tower in its relationship with other elements.

The causes in turn constitute problems that demand radical or moderate interventions (solutions), such as:
Radical interventions: integration, isolation, interference.
Moderate interventions: activation, stopping, stimulation.

For the risk analysis, the bridge designer used recognized linear and nonlinear structural analysis and design methods, took in account 6 studies contracted by interested parts, an independent structural analysis carried out by a different designer, requested by the bridge constructor, and in situ observations and inspections, as well as, phenomena noticed by workers before the collapse. In fact, these ones perceived movements and sounds before the collapse, although any earthquake was registered. The mentioned technical contributions are condensed in [22], [23]. The critical analysis of the six demanded studies verified the certainty of the bridge design and revealed the existence of extreme forces surpassing the magnitude of predictable limits. The search of these forces considered the settlement of five centimetres of the tower foundation after the tower collapse, constated in situ phenomena there perceived before the collapse, the way as the tower felt down, the state, position and cut surfaces of tower constituents, and the final state of work site and surrounding areas. The evaluation of the tower behaviour and the simulated push down, realized by the world-wide known consultant Cervenka, in [24] [25], confirm the high magnitude of forces required for causing the tower collapse. The sudden settlement of the tower foundation appears as originator of external forces and determinant of the tower collapse. The referred studies, phenomena and detailed analysis presented by the designer and constructors supported the exoneration of the design and designer of responsibilities in the tower collapse, decided by an Arbitration Tribunal convoked by the Constructor and the work Concessionaire.

3. Conclusion and Future Work

The development of a solution in any engineering field involves a set of processes. A solution is a tangible or intangible object developed along its lifecycle. The concept of lifecycle allows to organize processes in lifecycle phases grouped in four stages: Pre-construction, Construction, Post-construction, and Functioning or Use.

Unwished effects on an object constitutes limitations to its capacities and functionalities, coming from troubles in processes of its lifecycle. Risks are classifiable into Generic Functionalities of a solution achieved in processes of its lifecycle phases.

The here proposed process-based risks categories cantered on generic functionalities coincide the product-based risks categories oriented by cause-effect proposed in [21].

The correspondence between generic functionalities of a solution and generic causes of the solution damage unifies the detailed disaggregation of risks aspects in both approaches, cause-effect and process based, applied to an ex-post risks analysis of a stayed bridge tower.

Ex-post risk analysis of the collapsed tower allowed discard the design responsibility and drove the study of soil and geological conditions causing sudden settlement of the tower foundation. The mutual confirmation of useability of product-based cause-effect and process-based functionalities approaches strengthen the capacities of both approaches and support their development and applicability in many engineering fields

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