Evaluation of Intellectual Capital in R&D-intensive Companies: an Ontology-based Approach

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Abstract

This paper presents an ontology for assessing the intellectual capital of R&D-intensive companies. The obtained results are based on numerous studies of the intellectual capital as the complex phenomenon as well as on the analysis of information uncertainty in research and development process as the basis for innovations. The paper examines the essence of intellectual capital components from the perspective of managerial tasks. The proposed ontology incorporates sub-ontologies of innovation, human, organizational (structural) and relational (social) capital, as well as the mechanism of knowledge extraction. For each sub-ontology there is a description of classes, properties of these classes and relationships (object properties) that form a model of knowledge to support the evaluation of the intellectual capital in R&D-intensive companies. The result can be useful for specialists engaged in the creation of formalized methods and tools for intellectual capital management, as the presented ontology has wide potential for expansion and scaling.

Keywords

Ontological model, intellectual capital, research and development, evaluation

1. Introduction

Despite the changes in approaches to business functioning, in particular the rapid development of business ecosystems, innovation remains the main way to ensure the competitiveness of a modern manufacturing company. Traditionally, Russian companies are actively engaged in creating technological innovations. Thus, in the Global Innovation Index for 2020, Russia ranks 17th by the number of patents for inventions and 5th by the number of patents for utility models [1]. According to the report of the World Intellectual Property Organization (World Intellectual Property Indicators 2020) [2], in 2020 Russia ranked 8th in the world by the number of applications for registration of patents (35511 thousand applications were filed). At the same time, during the period from 2015 to 2020, our country dropped from a low 49th place to 58th place according to the subindex of innovation results in the Global Innovation Index [1]. These facts indicate existence of the problems with R&D management in Russian companies, and the paper is aimed at finding ways to solve them. The object of the study: R&D intensive manufacturing companies. Since one of the key resources for innovation activities is the intellectual capital of the company, the paper attempts to formally describe this complex phenomenon in the form of an ontology. The results of the intellectual capital measuring can further serve as the basis for building an R&D management system. All the above defines the goal of the study: to create an ontological model for the evaluation of intellectual capital in R&D-intensive manufacturing companies.

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2. Literature review

The phenomenon of the intellectual capital is very complex one, and researchers have not yet reached a consensus on its definition. Intellectual capital is closely related to knowledge and is generally recognized as one of the key intangible assets of a company for knowledge generation [3]. Intellectual capital is a dynamic system of elements that produces knowledge and is fueled by knowledge, evolving over time [4]. From a strategic point of view, intellectual capital helps to realize the knowledge management strategy, and is used to create and use knowledge for the development of the firm [5], [6]. Different definitions of intellectual capital found in the literature can be divided into two groups: knowledge-based and holistic. The first group includes definitions of intellectual capital as a knowledge resource used by a company to gain competitive advantage. The definitions of the second group include the consideration of intellectual capital as the sum of resources and other intangible assets that a company manages [7]. Different approaches to the interpretation and allocation of components of intellectual capital are summarized in Table 1.

Table 1

Components of intellectual capital according to different authors

Components of intellectual capital	Authors
Three-component structure: human, structural and relational capital	Paoloni et al., 2020 [6], Cabello-Medina et al., 2011 [8]; Delgado-Verde et al., 2011 [9]; Aramburu et al., 2015 [10]
human, structural capital and customer capital	Bontis, 1998 [11]
human, social and organizational capital	Subramaniam et al., 2005 [12]
human, organizational/structural capital and social capital	Reed et al., 2006 [13]
Four-component structure: human, structural, social/customer and innovation capital	Zang et al., 2011 [14]; Chen et al., 2004 [15]
Five-component structure: human, structural, organizational, process, and customer (relational or social) capital	Wiig, 1997 [16]; van Dijk et al., 2016 [17]

Human capital, organizational/structural capital and social capital are usually considered as traditional components of intellectual capital [7]. In [14], [15] a four-component structure of intellectual capital, including human capital, structural capital, social (or customer) capital and innovation capital is described. Human capital is the competences and knowledge of employees. Structural capital consists of organizational culture, development strategy and business processes. Social capital includes the relationships between companies and their external stakeholders. Innovation capital is the result of aggregate knowledge and includes the results of R&D, the results of technological-innovation activities and policies to stimulate innovation. In [16], [17] described the five-component structure of intellectual capital, including human capital, structural capital, organizational capital, process capital and consumer (relational or social) capital.

There are many models and methodologies in the literature that present different approaches to measuring intellectual capital [11], [18]. While some models address only financial indicators, others are more comprehensive and involve the calculation of a composite index for objective comparisons. Many articles [19], [20], [21] mention the following methods as the most popular non-financial ones used to evaluate intellectual capital: «Intangible Assets Monitor» [18], «Balanced Scorecard», Skandia Navigator.

Intangible Assets Monitor methodology [18] is based on quantitative and qualitative indicators to assess intellectual capital and divides intangible assets into three groups: individual competences, internal structure and external structure. The «Balanced Scorecard» methodology includes four groups of measures: Financial measures, Customer measures, Internal process measures, Learning and growth measures. The «Skandia Navigator» model reflects four key aspects of activity: Financial focus, Customer focus, Process focus, Renewal and development focus. The advantages and disadvantages of using each of these methods are analyzed in [21].

Some authors [11], [15], [22] propose their models for the evaluation of the intellectual capital and offer the specific indicators. In [22] there are examples of indicators to measure the intellectual capital in four categories: Human resources, Customers, Technology, Processes. The authors evaluate the category «Human resources» with such indicators as employee satisfaction, human resource turnover, number of development days per employee. The second category «Customers» offers to evaluate with the help of customer satisfaction, repeat purchase, customers with long-term relations, customers per employee, reputation of the company. For the «Technology» category it is suggested to evaluate total IT investments, IT expenses per employee, IT literacy. «Processes» can be assessed with the help of indicators of human resource distribution by processes, product development time, lead time, error rate, waiting time, quality, investments in R&D and infrastructure.

The authors [15] in their study propose to evaluate «Human capital» the authors propose to evaluate with such indicators as employees` competence, employees` attitude and employees` creativity. To evaluate «Structural capital» the authors propose to evaluate corporate culture, organizational structure, organizational learning, operation process and information system. To assess «Customer capital» it is proposed to use basic marketing capability, market intensity, customer loyalty indices. «Innovation capital» can be assessed with the help of indicators of innovation achievements, innovation mechanism, innovation culture. Also examples of indicators for the assessment of «Human capital», «Customer capital», «Structural capital» and «Performance» are given in the article [11].

Thus, intellectual capital is a complex object of research, the components of which differ in the composition of the possible characteristics and form numerous interrelationships. Based on this, we chose the ontological approach to obtain a formal description of intellectual capital. According to the definition from [23], «ontology» is «a specification of the subject area or its formal representation, which includes a dictionary of pointers to the terms of the subject area and logical expressions describing what these terms mean, how they relate to each other and how they can be related or unrelated».

In researches of domestic and foreign authors there are various ontological models describing these or those components of intellectual capital. For example, the work [24] describes an ontological model for the storage, accumulation and presentation of scientific and technical capital. The article proposes an ontology of scientific and technological stock and analyzes the possibilities of its use to ensure the integration of information resources, effective search and analysis of data on the state of various technologies and scientific problems in the aviation industry.

The model of subject domain ontology as a tool for analyzing scientific activities is proposed in the article [25]. However, the authors of this article consider the possibility of constructing an ontology only for R&D results without connection with the processes of obtaining these results. An example of the ontology of social capital as a network interaction between enterprises and their external stakeholders is presented in [26]. One possible approach to automating the collection of ontological information about Internet resources for a scientific knowledge portal serving to support scientific research is described in [27].

For the formalized representation of various subject areas and the extraction of dependencies, methods of case-based reasoning (Case-Based Reasoning) using ontologies are currently widespread. The article [28] considers the task of monitoring and adapting databases of project precedents in the management of innovative projects at all stages of the life cycle based on a fuzzy ontological approach. The model of knowledge management in research and innovation organization based on ontology is proposed in [29]. The proposed model allows to describe such aspects as intellectual capital of the organization, business model and its processes, dynamic behavior of research and innovation processes, but the model is high-level and is not designed to solve practical problems of research and development management.

The results of the analysis of the current state of research have shown that despite the existing scientific groundwork, the task of system description of intellectual capital in the form of an ontological model designed for R&D-intensive companies remains relevant. The proposed version of such a model is presented below.

3. Ontology of Intellectual Capital for a R&D-intensive company

3.1. General overview of the ontology

The developed ontological model should provide knowledge extraction that reduces information uncertainty in the process of intellectual capital evaluation. Based on the purpose of the ontology and existing interpretations of the concept of intellectual capital, the structure presented below has been proposed. The ontology of intellectual capital (O^{IC}) for a R&D-intensive company incorporates four sub-ontologies and knowledge extraction mechanism:

$$O^{IC} = < O^{Tech}, O^{HR}, O^{Org}, O^{Rel}, M>,$$

where O^{Tech} – innovation capital ontology, O^{HR} – human capital ontology, O^{Org} – organizational (structural) capital ontology, O^{Rel} – relational (social) capital ontology, M – knowledge extraction mechanism (logical inference machine model).

Figure 1 illustrates the high-level ontology of intellectual capital. In this ontology the relations between O^{Org} and O^{HR} are modelled by object properties of classes Creator and Activity. The connection between O^{Org} and O^{Tech} is realized at the level of classes Activity and Result, O^{Rel} and O^{HR} - at the level of classes Company and Creator, O^{Rel} and O^{Tech} - at the level of classes Communication and Result.

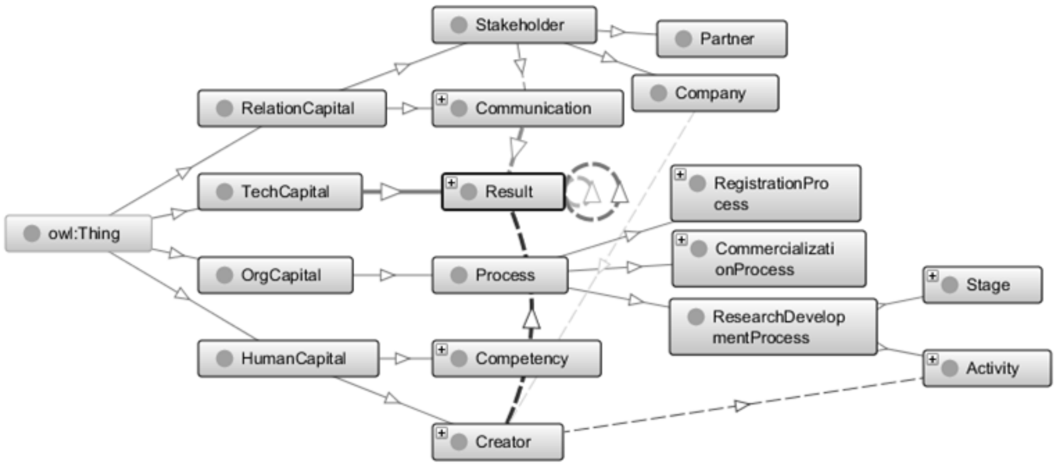

Figure 1: Graphic illustration of the Intellectual Capital ontology

The main classes of the ontology (Result, Process, Creator, Competency and Communication) correspond to the objects of IC evaluation.

The Intellectual Capital ontology components, objects of evaluation and their characteristics, and corresponding R&D management tasks are summarized in Table 2.

Table 2

The characteristics of intellectual capital and R&D management tasks

Intellectual capital components	Evaluated objects	Characteristics of evaluated objects	R&D management tasks
Innovation capital	Results obtained	Applicability, Value, Patentability, Completeness	Management of intellectual property, stimulation of innovations, selection of R&D projects for implementation
Human capital	Creators	Competence, Engagement, Productivity	Allocation of resources to R&D tasks, formation of resource pools, stimulation of creators

Organizational (structural) capital	Processes and activities	Organization of R&D, Efficiency	Organizational and information support for R&D, planning of R&D processes and activities
Relational (social) capital	Communications in the research and development process	Exchange of expertise, Information integrity of communications	Selection of forms and methods of networking for the implementation of R&D projects

3.2. Ontology of Innovation Capital

The main class in the ontology of Innovation Capital (O^{Tech}) is the Result. This class implements a faceted classification of R&D results and has four major subclasses. The structural components of the Result class are detailed in Table 3, as well as the characteristics of Intellectual Capital that can be evaluated via object and data properties of the corresponding classes.

Table 3
The elements of the Innovation Capital ontology and Intellectual Capital characteristics

Basis for classification	Subclass of Result	Second tier subclasses	Characteristic of Intellectual Capital
The type of obtained artifact	ResultInProgress	Idea, Concept, Model, Prototype, Scheme, Sample, etc.	Completeness
The application of the result	Application	Product, Method, Service	Applicability
The impact of the result on company processes	Impact	ImpactOnProcessCharacteristics, ImpactOnProcessStructure, EmergenceNewProcesses	Value
The peculiarities of intellectual property rights	IntellectualProperty	Copyright, Patent	Patentability

Note, that the composition of the second tier subclasses is universal, except for the subclasses of ResultInProgress class, where the list of subclasses is determined by the company sector.

3.3. Ontology of Human Capital

The main classes in the ontology of Human Capital (O^{HR}) are the Creator and the Competency.

The ontograph with the description of object relations, illustrating the high-level ontology OHR and its connection with the classes Result (O^{Tech} ontology) and Activity (O^{Org} ontology) is presented in Figure 2.

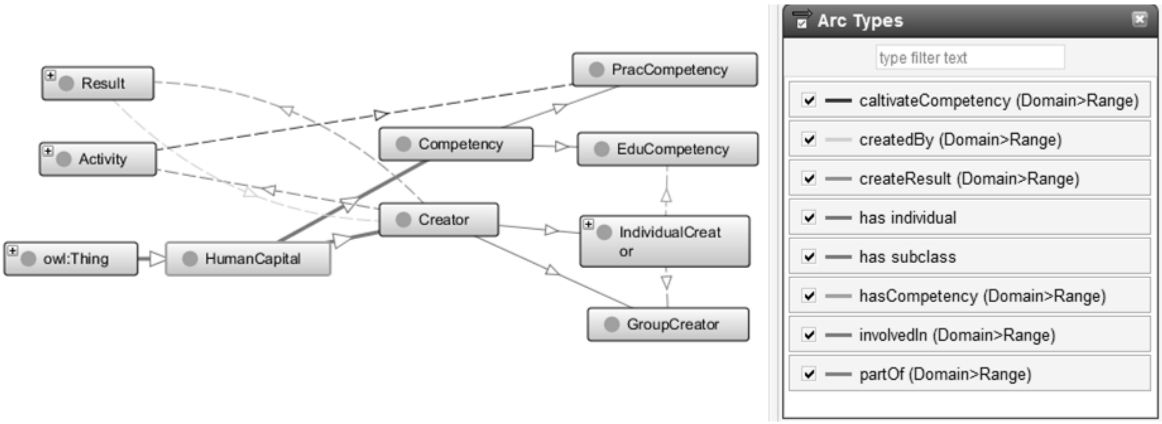

Figure 2: Graphic illustration of the Human Capital ontology

The Human Capital ontology takes into account that the creator of R&D result is often not an individual creator (IndividualCreator), but a collective one (GroupCreator). The collective can be either permanent or temporary. The GroupCreator is not a formal organizational unit (department, laboratory, etc.), but a collective of authors, since in the task of R&D planning it is the pool of resources assigned to tasks.

The IndividualCreator has competencies modeled by the class Competency with two subclasses:

- competencies acquired in the process of learning – EduCompetency;
- competencies acquired while working on R&D projects – PracCompetency.

The IndividualCreator is also characterized by productivity, which is determined by the number of obtained results of different types. The productivity of an individual creator consists of two components: individual productivity and productivity as a part of group. These two estimates are considered independently in the planning of R&D projects. The first one is used to calculate the time parameters of the project when assigning individual resources to tasks, the second one when assigning a pool of resources. The task of identification the contributions of team members to the R&D result is complex and its solution serves as the subject of a separate study.

Table 4 contains the data properties of Human Capital ontology classes that are used to estimate intellectual capital characteristics.

Table 4
The elements of the Human Capital ontology and Intellectual Capital characteristics

Class	Data property (type)	Characteristic of Intellectual Capital
IndividualCreator	IndividualProductivity InGroupProductivity	Productivity
GroupCreator	Permanent	Engagement
EduCompetency PracCompetency	Level	Competence

The values of individualProductivity and inGroupProductivity can be obtained from the proposed ontology of Intellectual Capital. An example is given further.

3.4. Ontology of Organizational and Relational Capital

The formation of practical competencies is associated with the Organizational Capital of the company. The basic class in the ontology of Organizational Capital (O^{Org}) is Process, subclasses of which are: the R&D process, the intellectual property registration process, the intellectual property commercialization process. The composition of the stages of the R&D process, logical and temporal relationships between them are determined by regulations or established practice in the company. In this work, within the framework of O^{Org} ontology construction, the typical models of business processes of manufacturing companies are taken as a basis. As an example, Figure 3 shows the IDEF0 diagram of the Theoretical research stage. The UoB (Units of Behavior) elements of process diagrams are implemented in the ontology in the form of Class type elements. Elements of links (information and object flows) are implemented in the form of classes (Class), or object properties (Object Property).

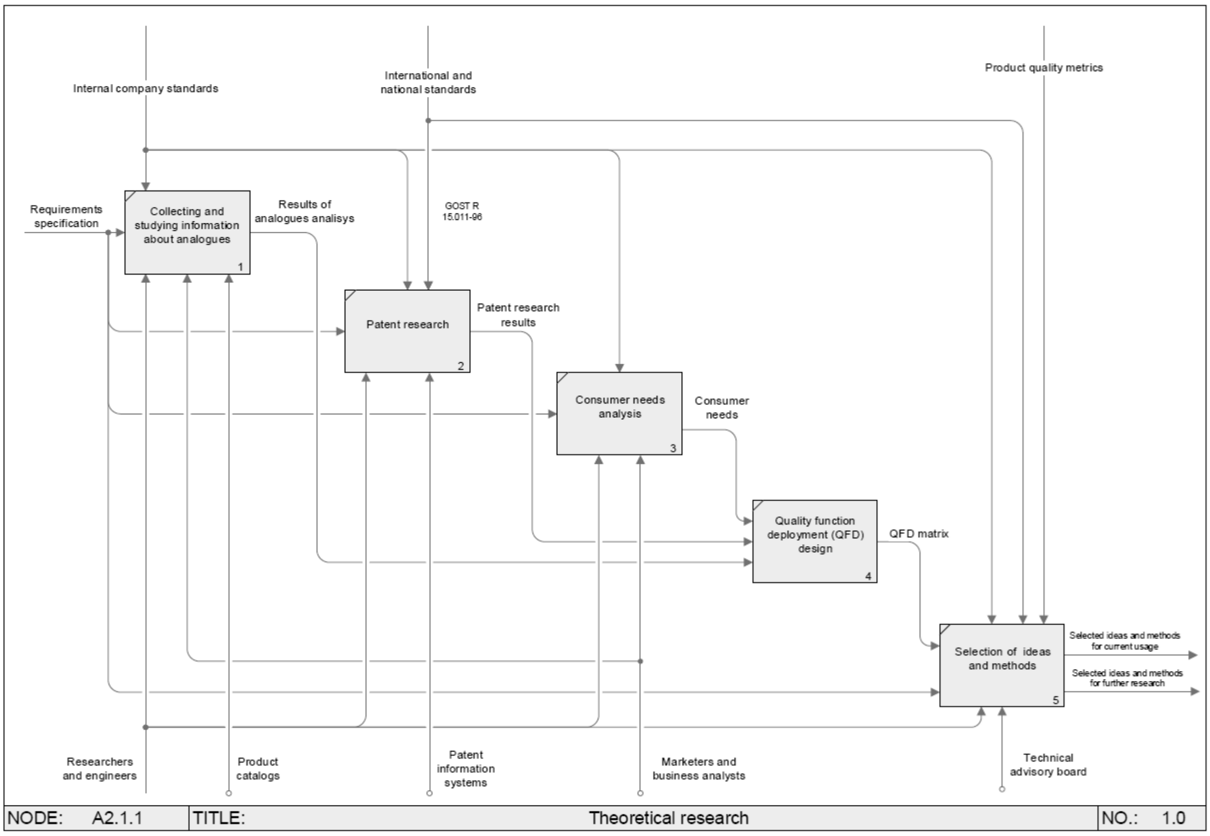

Figure 3: Theoretical research stage diagram

In addition to phases and stages, the process includes various activities, such as brainstorming, working with patent databases, preparing an experiment, observing the results of an experiment, reporting the results, preparing a report for a conference, participating in a conference as a listener, etc. In the O^{Org} ontology activities are associated with process stages (Figure 4).

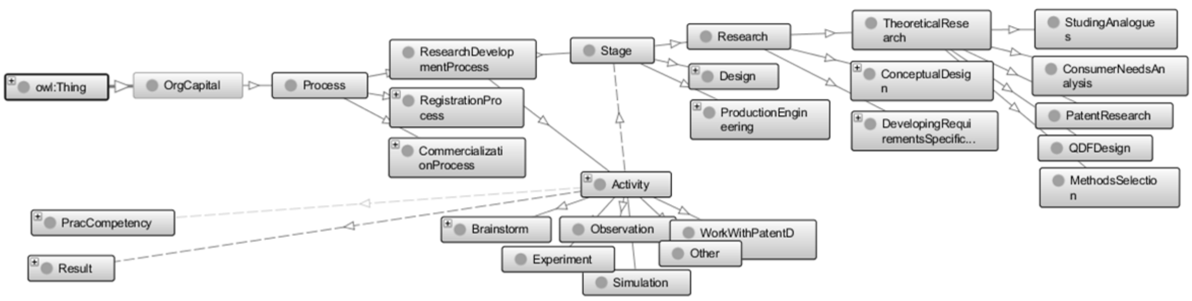

Figure 4: Graphical representation of the Organizational Capital ontology

According to the effectiveness of R&D stages, they have the following characteristics:

- the result obtained/not obtained;
- completeness of the result (final/intermediate);
- deviation of the result (due to low quality/no prospects);
- the existence of a spin-off result.

The listed properties underlie the facet classification, and their values are used in the rules of logical inference to evaluate the effectiveness of R&D stages and activities. Besides, the relations between

Creator and Activity classes allow evaluating the involvement of creators in activities and identify related results. Such estimates can be used for evaluation of engagement and productivity.

Note that all chains of relationships are analyzed by the Protege built-in solver (HermiT was used). Thus, based on the chain of Object properties for the createResult property, the solver identifies the results related with a Creator. Figure 5 shows an example of the identification the results obtained by the Creator (MiddleEngineer) based on his involvement in different activities.

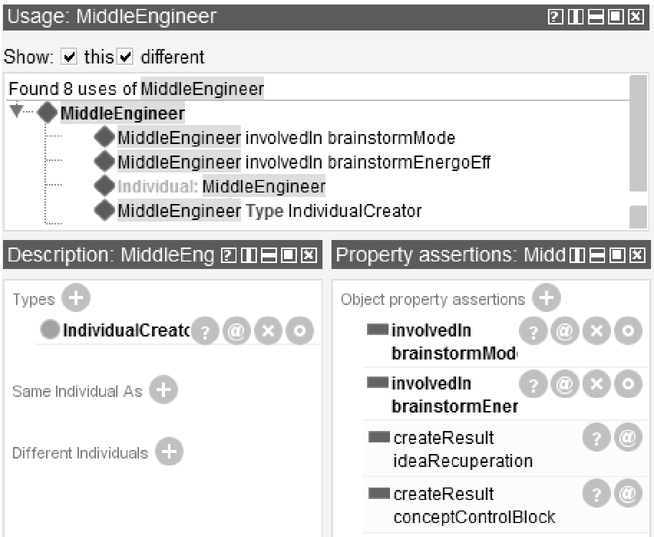

Figure 5: An example of the solver working

The basic classes in the Relational Capital ontology (O^{Rel}) are Stakeholder and Communication (form of interaction). For R&D-intensive companies, the core of Relational Capital is the collaboration between companies involved in value chains. From this perspective, the most important characteristics of Relational Capital are the exchange of expertise and the informational integrity of communications. The approach to evaluating the exchange of expertise is similar to the one used to assess the engagement of employees. As for the informational integrity indicator, initial data for its estimation can be obtained from the models described in the paper [30]. In the ontology, these estimates are used as values of data properties for the Individuals of the Communication class.

4. Mechanism of logical inference for evaluation of intellectual capital characteristics

The mechanism of logical inference M in the ontology of intellectual capital OIC is formed by:

- object properties (links) between the classes of the general ontology that constitute the axiomatics of the model;
- chains of object properties that provide sequential knowledge extraction (e.g., createResult = SuperProperty of (involvedIn o generate), where «Creator involvedIn Activity», «Activity generate Result»);
- possible enumerated data property values (e.g., properties of the R&D process stages) used to generate outputs using DL- and SPARQL queries.

The establishment of relationships between classes in the form of object properties is based on the principles of correspondence of the characteristics of these properties (transitivity, symmetry, reflexivity, etc.) to the logic of the modeled relation and the relevance of the axioms set by the properties to the purpose of the developed ontology. In order to support the consistency of the system of axioms by limiting the number of object properties, complex relations between classes are described by chains of links.

To illustrate the work of the knowledge extraction mechanism, we use an example of identifying progress in R&D in two areas: improving the energy efficiency class of an electric motor to IE3 (start of the process - brainstormEnergoEff), and optimizing the mode of motor operation (start of the process - brainstormMode). The logic of knowledge extraction is illustrated by the SPARQL query in Figure 6.

SPARQL query:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX rd: <http://www.semanticweb.org/ovstoyanova/ontologies/2021/research#>
SELECT ?creator?activity?result?next_result
        WHERE
        {
         ?creator rd:involvedIn ?activity.
         OPTIONAL {?activity rd:generate ?result.}
         OPTIONAL {?activity rd:generate ?result.
                 ?result rd:originateResult ?next_result}

         }
order by ?activity
```

creator	activity	result	next_result
SeniorEngineer	brainstormEnergoEff	ideaRecuperation	conceptControlBlock
MiddleEngineer	brainstormEnergoEff	ideaRecuperation	conceptControlBlock
Intern2	brainstormEnergoEff	ideaRecuperation	conceptControlBlock
MiddleEngineer	brainstormMode		
Intern1	brainstormMode		

Figure 6: Engagement of Creators and R&D progress

The findings presented not only provide an assessment of the progress of a particular R&D project, but also serve as a baseline for evaluating characteristics of the intellectual capital, such as «organization of R&D», «efficiency of R&D».

All of the above elements of the Intellectual Capital ontology create the basis for IC evaluation and R&D management system that uses modern methods of knowledge representation and extraction.

5. Conclusion

The developed ontology of intellectual capital is based on numerous studies of this complex phenomenon. The structure and characteristics of this model derive from its purpose - to assess the intellectual capital of an R&D-intensive company. The axiomatics of the proposed ontological model includes support for temporal and spatial reasoning. The presented result can be useful for specialists engaged in the development of formalized methods and tools of intellectual capital evaluation, as the created ontology is scalable. The main ways to extend an ontology are to include new classes, derived from existing ones, and to integrate it with the specific ontologies of other researchers discussed above. Scalability is provided by the possibility to create new class instances and new data properties tailored to a company's specific context.

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