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AN INTEGRATED DESCRIPTIVE MODEL OF KNOWLEDGE CREATION IN INTERDISCIPLINARY PRODUCT DEVELOPMENT

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ABSTRACT

Above all, interdisciplinary product development is perceived as interplay of individual and collective activities. Starting from this perception, the paper focuses on analysing the utilized and gained information and knowledge objects within such development processes, whereby individual and collective development activities have to be considered. As a theoretical basis for this analysis, the article introduces an integrated descriptive model of knowledge creation that allows a description of the interaction between individual and collective processes in product development and the sources of knowledge applied within these activities.

It employs a model of cognitive activities in design for explaining the patterns of knowledge application and creation within individuals, whereas it adopts a model of organizational knowledge creation to describe collective processes. For the integration of these distinct models, the integrated descriptive model of knowledge creation is created following an approach that merges the two models based on their common conceptual elements.

Furthermore, an analysis and modelling method is proposed that captures the various knowledge conversion activities described within the integrated descriptive model of knowledge creation. In combination, the integrated descriptive model and the analysis and modelling method constitute a research framework dedicated to the analysis of knowledge characteristics of interdisciplinary product development.

1 INTRODUCTION

Over the last few decades, product development has been perceived as increasingly multidisciplinary due to a higher contribution of electronics and software to the implemented product functions [NEUM12]. This statement could suggest interpreting multidisciplinarity as a recent phenomenon of product development. If we take, however, a closer look at the engineering design for classical products targeted by mechanical engineering (e.g. combustion engine, gear box, asynchronous motor), it appears that the engineering of such machine involves the knowledge from multiple scientific fields and disciplines (e.g. mechanics, thermodynamics, fluid dynamics, material science, and electro-technics). In this context, Tomiyama introduces the term *knowledge structure* to describe the relationships of theories (each of them adhering to disciplines) involved in the product development process [TOMI06].

Today, however, the multidisciplinary character of the design problems for such classical products of mechanical engineering is in many cases not obvious anymore: Firstly, the specialists conducting these design activities do not need to interact with experts from other disciplines especially for products with a moderate degree of innovation. Secondly, new fields of engineering emerged that provide an integrated body of knowledge, as well as design methods and modelling approaches specifically adapted to the targeted products. In addition, these new fields of engineering take care of educating students for the targeted types of products.

By extending this line of thought, we observe that our perception of the multidisciplinary character of engineering design changes over time as specialized fields of engineering emerge that reduce the need for cross-disciplinary interactions.

The initially discussed transformation of formerly mechanical products in the automotive, machinery and equipment industries towards a higher contribution of electronics and software to the implemented product functions and added value provides a compelling example for complex products needing a multidisciplinary product development process. The development of mechatronic products requires tight cooperation, integration, and synchronization of the three mainly involved engineering disciplines (mechanical engineering, electrical engineering, and computer science), which are of roughly equal importance for the development process [NEUM12]. The term *Mechatronics* designates the technology and the products emerging from this ongoing transformation of formerly mechanical products through the addition of electrical components, electronics, and information processing [NEUM12]. Typically, the interaction between the involved disciplines crosses the line from multidisciplinarity to interdisciplinarity, once an extensive collaboration between the disciplines is required to cope with the challenges associated with e.g. spatial integration [NEUM12].

In particular, *Mechatronics* provides a compelling example for the previously discussed forming of a new engineering discipline with its own body of theories, concepts and models. It emerged as an interdiscipline[1] from mechanical engineering, electrical engineering, computer science, and control engineering through the long-term interdisciplinary fusion of their theories, concepts, methods, and tools within the area of the development of heterogeneous technical systems. Accordingly, Tomiyama characterizes the knowledge structure of MPD as *"an integrated knowledge system"* [TOMI06].

Overall, the present paper focuses on the characteristics of similar kinds of product development processes conducted in an interdisciplinary context. Here, the knowledge provided by a single person will commonly not be sufficient to cover the full width and depth of knowledge required in the design process [NEUM14]. In these scenarios, multiple team members with knowledge from different domains and several organizational units typically contribute to the overall knowledge applied during the development process.

2 RESEARCH FOCUS

The extensive collaboration between team members and organizational units leads to widespread and complex networks of information and knowledge exchange spanning across disciplinary and organizational boundaries [NEUM12]. If we want to gain an overview on the different pieces of information and knowledge applied and transformed by the various proponents, we need to consider both individual and collective processes in product development and their interactions. Here, individuals create knowledge by their creativity, skills, and experience, whereas this knowledge is subsequently amplified at the various organizational levels [NEUM14].

Typically, the product development process debuts with a vast lack of knowledge about the end product and sometimes even on the development approach to be adopted. Whereas design methodology provides support to cope with the latter problem, the designers' skills, experiences, creativity, and ability to learn are the key factors to fill the gaps in knowledge during the development process [NEUM14]. Consequently, the product development process belongs to the category of *knowledge-intensive business processes* which Gronau et al. characterize by the following set of attributes [GRON04]:

(a) High contribution of knowledge to the added value of the process
(b) Business processes consist of many creative parts
(c) Strong emphasis on communication
(d) Applied knowledge may have a short life-time; nevertheless the build-up of new knowledge is time and resource intensive

[1] An interdiscipline designates a scientific field that starts in-between the bodies of knowledge of established disciplines and may later on become an academic discipline in its own right [REPK08].

Departing from the above mentioned assumptions on the nature of interdisciplinary product development, the research described in this paper is directed towards the following objectives:

1. Clarification of the nature of cognitive activities
2. Identification of the most-suitable approach for the description of (individual) cognitive activities in product development
3. Identification of the most-suitable approach for the description of the provisioning and amplification of knowledge at the various organizational levels
4. Conception of an integrated model describing the individual and organizational knowledge creation activities and their interactions in interdisciplinary product development

3 INDIVIDUAL KNOWLEDGE CREATION WITHIN PRODUCT DEVELOPMENT

Building on empirical evidence, *cognitive psychology* develops theories explaining the processes of lower-level cognition (perception, attention, and memory) and higher-level cognition (thinking and reasoning). For the understanding of the knowledge creation in individuals in the context of product development, two types of cognitive processes are of major interest [NEUM14]: Firstly, an individual may acquire new insights by means of *reasoning* when applying for instance deductive inferences, or by *creative thinking* that applies abductive inferences and strategies for problem solving. Secondly, *learning* permits the extension of an individual's long-term memory by the previously gained insights. Consequently, the present paper adopts the following definition of individual knowledge creation:

In the targeted context of product development, the modelling of these cognitive activities may remain at a relatively coarse level. Accordingly, the model for a cognitive activity depicted in Figure 1 captures the characteristics of (a) the information and knowledge artefacts used as input and transformed in this cognitive activity, (b) the utilized background knowledge, and (c) the generated information and knowledge objects at the output.

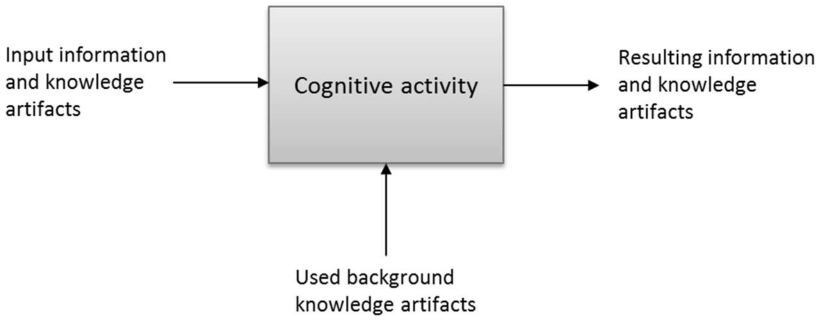

Figure 1: Model for cognitive activity in the context of individual knowledge creation [NEUM14]

At present, several interrelated fields of cognitive psychology focus on the different phenomena of thinking (e.g. reasoning, decision-making and judgment, and problem solving) and do not yield a coherent body of theory explaining the relevant traits of cognitive activities. These distinct perspectives of cognitive psychology find a distant echo in the multitude of opinions on the nature of the design process highlighted by three prominent directions: Roozenburg and Eekels approach engineering design as a *reasoning process* where different inference patterns are applied for gaining the required knowledge for decision making and the synthesis of design solutions [ROEE95]. Ullman, however, perceives the mechanical design process from the perspective of *problem solving* for ill-structured problems [ULLM03]. Visser comprehends the design process mainly as *construction of representations* (i.e. the different types of design models) [VISS06a]. In addition, she adopts certain aspects of the problem-solving approach by perceiving problems in terms of the representations constructed for these tasks [VISS06a]. She proposes three main types of cognitive activities contributing to the construction or conversion of design artefacts:

(a) *Generation* describes the initial cognitive activity of constructing product representations out of mental models.
(b) *Transformation* comprises cognitive activities modifying an input representation R_i and leading to an output representation R_{i+1}.
(c) *Evaluation* represents cognitive activities for assessing how well a design solution (captured by representations) conforms to a set of requirements.

This conception of the product development process as a sequence of constructions of representations matches well with the specific interest of the described research, as these design artefacts contain embedded information and knowledge to be assessed by the intended analysis of knowledge creation activities. The above mentioned types of *cognitive activities* are visualized in the centre of Figure 2 where they represent the relationship between the involved cognitive systems and the generated, transformed or evaluated states of the product.

The various *representations*, depicted on the right side of Figure 2, describe the product at subsequent states. Here, the arrow leading from Representation_i to $\text{Representation}_{i+1}$ describes the transformation of this design artefact by an associated cognitive activity. In the other direction, the arrow leading back from $\text{Representation}_{i+1}$ to Representation_i describes an evaluation activity that assesses the achieved product characteristics by taking into account elements of the anterior design artefact (e.g. requirements, functions, or constraints).

On the left side of Figure 2, the *tripartite model of mind* introduced by Stanovich, West et al. [STAN11b] describes the involved cognitive systems, their relationships, and the relationships to knowledge. It allows to associate *tacit* and *explicit* knowledge with specific cognitive systems: The *autonomous* mind conducts preattentive, cognitive activities of intuitive thinking (Type 1 processes of dual-process theories) and depends on *tacit* knowledge. The *reflective* and *algorithmic* minds represent cognitive systems conducting deliberative and logical cognitive activities (Type 2 processes of dual-process theories) that rely on *explicit* knowledge.

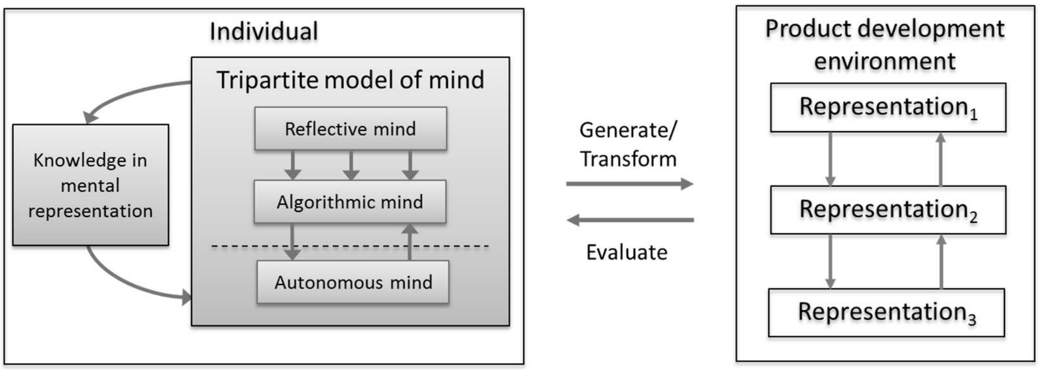

Figure 2: Integration of the tripartite model of mind [STAN11b] with the framework for cognitive design research [VISS06a] for describing the cognitive activities of an individual interacting with the product development environment [NEUM14]

Tacit knowledge refers to knowledge bound to an individual and to a particular context that is difficult to articulate and formalize through means like language or writing [NOTA95]. In contrast, *explicit knowledge* describes knowledge that can be articulated through words, diagrams, formulae, computer programs, and similar means and can be readily transmitted to other people. It can either be represented in the form of mental representations in the human brain or in its physical form by means of language or writing [NEUM14]. Moreover, the reflective mind regulates the algorithmic mind according to individual and epistemic goals and hereby employs knowledge and strategies [STAN11b]. The algorithmic mind, however, utilizes micro-strategies for steering the cognitive activities and rules for the sequencing of behaviours and thoughts [STAN11b].

Overall, the tripartite model of mind enables explaining the interaction of the three cognitive systems in order to obtain the desired rational behaviour. In particular, it offers a promising perspective to better explain research problems as for instance the dichotomy of rational thinking and expert intuition, or the importance of hypothetical reasoning and cognitive simulations for creativity in design [NEUM14].

4 ORGANIZATIONAL KNOWLEDGE CREATION IN PRODUCT DEVELOPMENT

To date, the model of organizational knowledge creation [NTK00] has found only limited attention in the context of product development where this model is often perceived as directly linked to knowledge management. Nonaka and Takeuchi [NOTA95] explain the process of organization knowledge creation as a two-dimensional interplay of (a) tacit and explicit knowledge (*explicitness* dimension) at (b) different organizational levels (*organizational reach* dimension). Figure 3 depicts the knowledge creation process consisting of the four modes of conversion between tacit and explicit knowledge: *socialization*, *externalization*, *combination*, and *internalization* (SECI).

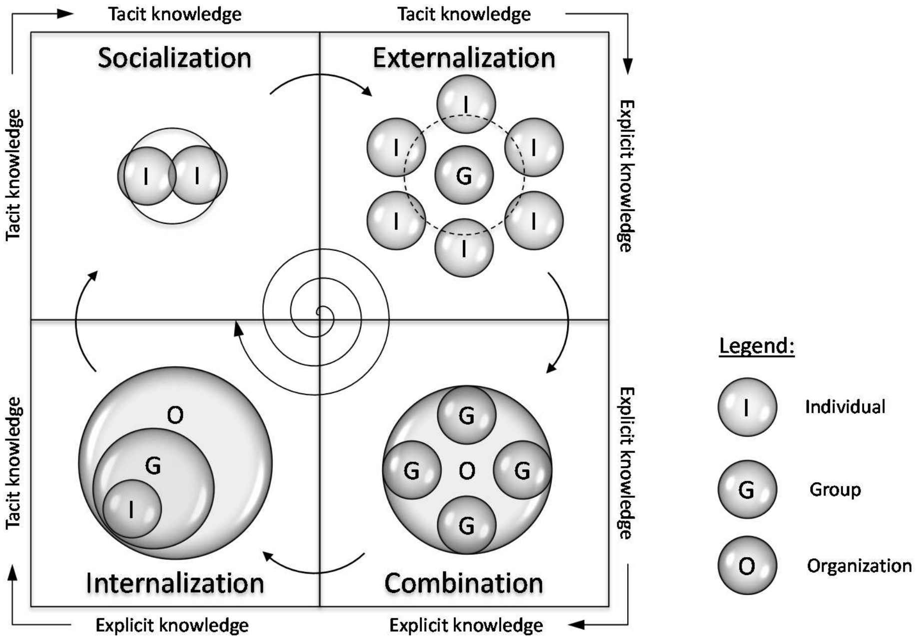

Figure 3: The SECI process of organizational knowledge creation, according to [NOKO98]

Socialization describes the sharing of tacit knowledge between individuals as typically occurring through joint activities in combination with physical proximity, e.g. during an apprenticeship or pair programming [NOKO98]. Within the *externalization* transformation, tacit knowledge is translated into explicit concepts, which are comprehensible to a larger group. *Combination* describes the process of converting existing explicit knowledge into new and more complex sets of explicit knowledge by methods like editing, sorting, classifying, and structuring. *Internalization* describes the embodiment of parts of a company's explicit knowledge within the shared tacit knowledge resources of an organization at various levels.

In the first presentations of the organizational model of knowledge creation, Nonaka and Takeuchi did not fully clarify the relationship of individual and collective knowledge creation [NEUM14]. In a later publication, however, Nonaka, von Krogh and Voelpel stated more precisely the scope of the model of organizational knowledge creation and considered individual knowledge creation as outside of their model [NvKK06]. The following definition reflects their understanding of organizational knowledge creation:

5 SYNTHESIS OF THE DESCRIPTIVE MODEL FOR KNOWLEDGE CREATION IN INTERDISCIPLINARY PRODUCT DEVELOPMENT

Each of the two previously introduced approaches for describing knowledge creation in product development captures only certain aspects of the complete range of thinking, learning and decision-making processes in product development. Both modes of knowledge creation, however, have to be understood in their interaction to assess the complete range of sources of knowledge as well as the interplay of individual and collective processes in product development [NEUM14]. For this purpose, the two approaches need to be incorporated into an integrated descriptive model of knowledge creation.

For the integration of the models, it is conceivable to generalize the approach of one of the models for the integrated model. A first attempt could consist in extending the use of the cognitive model of individual knowledge creation towards the organizational side. This approach, however, presupposes acknowledging that social groups possess the characteristics of cognitive entities. In this regard, Cook and Yanow uncovered three substantial problems that impede a simple transfer of the cognition-based model to organizations [COYA93]. The second approach proposes employing the socio-cultural model of organizational knowledge creation to individuals. This line of thought, however, has already been dismissed by the previously cited statement of Nonaka, von Krogh and Voelpel who considered individual knowledge creation as outside of the model of organizational knowledge creation [NvKK06].

Therefore, a third integration approach is required. It proposes to integrate the two models at the level of their common conceptual elements. The cognitive model of individual knowledge creation and the model of organizational knowledge creation have several concepts in common that can be employed as integration points:

(a) Knowledge conversion activities
(b) *Information and knowledge objects* involved in such conversion activities
(c) The *actors* of individual knowledge creation appearing in the organizational activities directly or as *members of teams* and other *organizational units*

Figure 4 depicts the resulting integrated descriptive model of knowledge creation in interdisciplinary product development. In the centre of Figure 4, the involved individuals apply their cognitive abilities and knowledge resources while interacting with the product development environment. Subsequently, the results caused by these interactions are observed and compared to the anticipations. From these results, the individuals may infer new insights through activities conducted by their cognitive systems in combination with the existing knowledge resources. The gained insights lead to an extension of the individual's knowledge resources. In interdisciplinary product development, however, the individuals involved possess *knowledge profiles*[2] specialized to their respective disciplines. This results in a fragmentation of the knowledge profiles of the involved actors that limits the social knowledge conversion modes to the few participants possessing the required depth of knowledge for the respective activity.

As depicted at the rights side of Figure 4, the *product artefacts* of interdisciplinary products are fragmented into system-level and disciplinary components.

[2] The knowledge profile captures the width and depth of knowledge from an individual, a team, or an organization. It is typically depicted in a two-dimensional diagram, where the horizontal axis captures the width of the knowledge distributed over the various knowledge domains, whereas the vertical axis symbolizes the depth of knowledge, i.e. the achieved level of expertise. The knowledge profile typically visualizes an increased depth of knowledge towards the bottom. This way, it depicts a knowledge profile with large background knowledge in many domains and deepened knowledge in one area as T shape. [NEUM14]

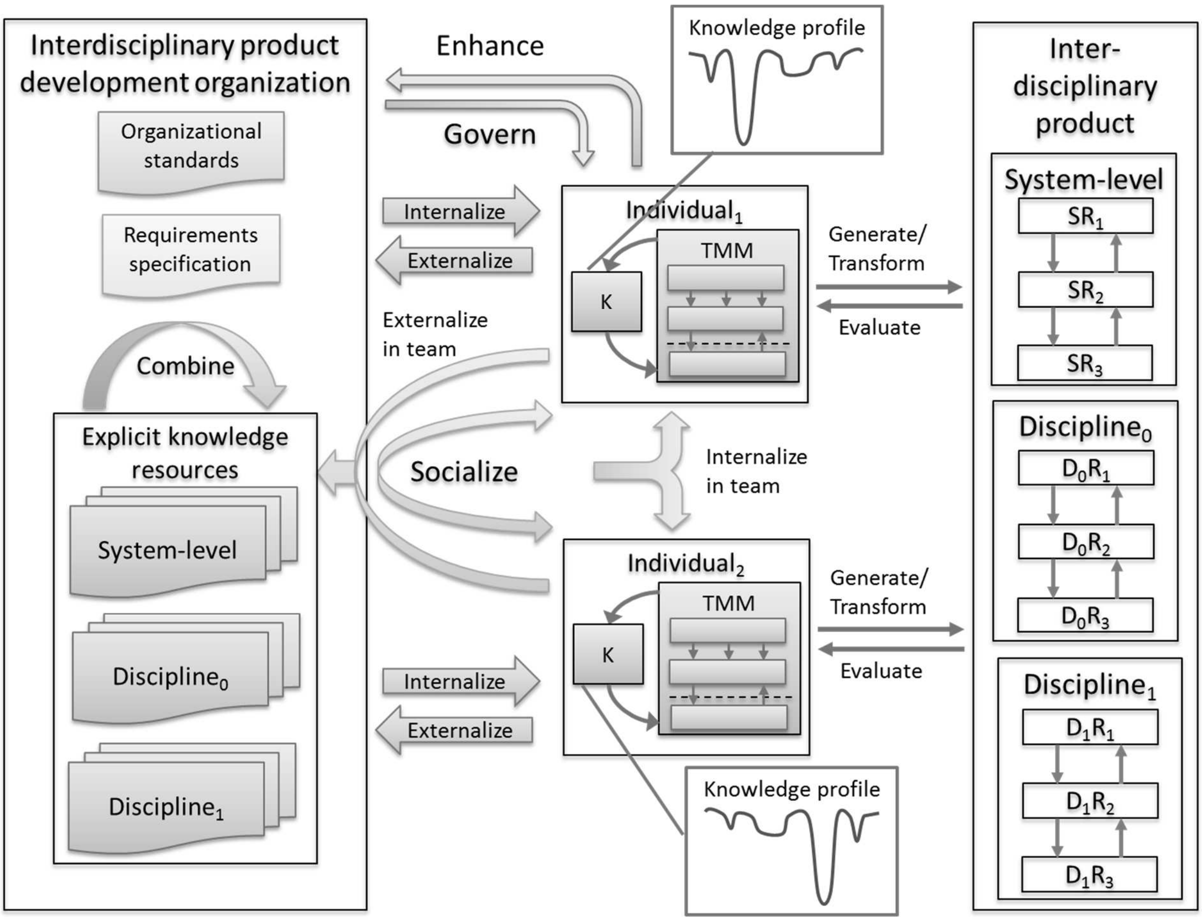

Figure 4: Integrated descriptive model of knowledge creation in interdisciplinary product development [NEUM14]

As shown at the left side of Figure 4, the *product development organization* captures the goals defined by managers of the organization, provides prevailing organizational standards, and possesses explicit knowledge resources. Usually, the stakeholders of a new product compile the problem definition and the business requirements into the requirements specification. Subsequently, the requirements specification will be used to generate the product's function structure, which belongs to the product artefacts. Overall, the organizational standards and goals issued by the management govern the cognitive activities of an individual. In the opposite direction flows feedback given by an individual on the organizational standards and the requirements specification, which may subsequently enhance them. Moreover, the individual may externalize parts of its knowledge resources towards the organization's knowledge resources as well as internalize explicit knowledge resources from the organizational context.

In interdisciplinary product development, the organizational knowledge resources are fragmented into system-level and disciplinary components. Consequently, an individual interacts only with the subset of them he/she is knowledgeable.

In addition to the already introduced types of *individual cognitive activities* (generate, transform, evaluate), the four knowledge conversion modes of the SECI-model (socialization, externalization, combination, internalization) have to be included. Besides externalization and internalization conducted as individual activities, in organizational knowledge creation both conversion modes are performed as social activities. Overall, the interactions involving an individual are indicated in blue and social interactions at the different organizational levels are shown in red.

6 RESEARCH FRAMEWORK FOR THE ANALYSIS OF KNOWLEDGE CHARACTERISTICS OF INTERDISCIPLINARY PRODUCT DEVELOPMENT

As a second part of the research framework aiming at the analysis of knowledge characteristics in product development, an analysis and modelling method was proposed that is able to capture the various knowledge conversion activities described by the integrated descriptive model of knowledge creation. As the result of a selection process between six analysis and modelling approaches, the KMDL method [POGO09] was identified as the most suitable approach described in the research literature [NEUM14]. In order to fulfil the complete range of identified requirements, however, the KMDL method had to be extended by the following set of features:

(a) Means for modelling of knowledge resources moderating the knowledge conversion activity
(b) A modified modelling pattern employing knowledge objects to represent tacit and explicit knowledge in its mental representation, whereas information objects are used for describing articulated, explicit knowledge

Moreover, KMDL provides as specific methodology defining the various phases typically conducted in a KMDL-based consulting and analysis project [POGO09]. Out of the nine phases proposed by KMDL, Figure 5 depicts the three phases that will be used in the present research framework. During the first phase, the process view is employed to capture the process model. In the second phase, knowledge-intensive tasks will be identified from the overall set of tasks of the process model. Finally, the activity views for each of these knowledge-intensive tasks needs to be established.

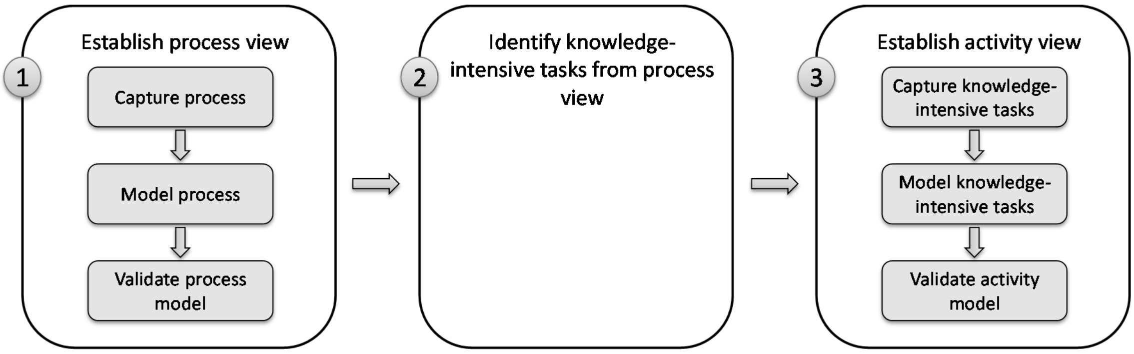

Figure 5: Methodology for analysis of knowledge characteristics, adapted from [POGO09]

7 SUMMARY

As part of a prescriptive study, the presented research framework was applied for the analysis of knowledge characteristics of mechatronic product development (MPD) that is perceived as an example of interdisciplinary product development [NEUM14]. Here, the development process was represented by common process elements compiled from various procedure models of MPD. Following the methodology introduced in the previous section, the KMDL process and activity views were established for a set of representative process elements in a first step. Departing from these views, the knowledge characteristics of the process elements were captured and documented. The presented research framework for the analysis of knowledge characteristics in interdisciplinary product development proved capable for modelling and analysing all knowledge conversion activities of the considered process elements [NEUM14].

Each of the initially described research objectives was elaborated at in the course of the present paper: Visser's framework for cognitive design research perceiving the design process mainly as *construction of representations* (i.e. the different types of design models) was adopted for understanding the nature of cognitive activities. Moreover, the *tripartite model of mind* introduced by Stanovich, West et al. [STAN11b] provides an understanding of the characteristics and relationships of the cognitive systems. The combination of both models was selected for describing the cognitive activities of an individual interacting with the product development environment. Furthermore, the model of organizational knowledge creation introduced by Nonaka and Takeuchi was adopted as the most-suitable approach for the description of the provisioning and amplification of knowledge at the various organizational levels. Finally, the two models were integrated at the level of their common conceptual elements in order to obtain the integrated descriptive model of knowledge creation. It allows describing the fragmented and heterogeneous activities of knowledge creation, its application, sharing, externalization, and internalization in interdisciplinary product development.

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