Ontology-Driven Conceptual Modeling: A Systematic Literature Mapping and Review

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Abstract. Ontology-driven conceptual modeling (ODCM) is still a relatively new research domain in the field of information systems and there is still much discussion on how the research in ODCM should be performed and what the focus of this research should be. Therefore, this article aims to critically survey the existing literature in order to assess the kind of research that has been performed over the years, analyze the nature of the research contributions and establish its current state of the art by positioning, evaluating and interpreting relevant research to date that is related to ODCM. To understand and identify any gaps and research opportunities, our literature study is composed of both a systematic mapping study and a systematic review study. The mapping study aims at structuring and classifying the area that is being investigated in order to give a general overview of the research that has been performed in the field. A review study on the other hand is a more thorough and rigorous inquiry and provides recommendations based on the strength of the found evidence. Our results indicate that there are several research gaps that should be addressed and we further composed several research opportunities that are possible areas for future research.

1 Introduction

Conceptual models were introduced to increase understanding and communication of a system or domain among stakeholders. According to Stachowiak (1973), a conceptual model possesses three features: (1) a *mapping feature*, meaning that a model can be seen as a representation of the 'original' system, which is expressed through a modeling language; (2) a *reduction feature*, characterizing the model as only a subset of the original system and (3) the *pragmatics* of a model which describes its intended purpose or objective. Conceptual modeling is the activity of representing aspects of the physical and social world for the purpose of communication, learning and problem solving among human users (Mylopoulos, 1992). Conceptual modeling has gained much attention especially in the field of information systems, for design, analysis and development purposes. Their importance was understood in the 1960s, since they facilitate detection and correction of system development errors (Wand & Weber, 2002). The higher the quality of conceptual models, the earlier the detection and correction of these errors occurs. This increase in attention and importance attributed to conceptual modeling led to the development and introduction of a wide range of various conceptual modeling approaches and techniques. Criticism however arose, stating that these approaches and techniques still lacked a comprehensive and generally acknowledged understanding (Moody, 2005). In addition, many conceptual models lacked an adequate specification of the semantics of the terminology of the underlying models, which led to inconsistent interpretations and uses of knowledge (Grüninger, Atefi, & Fox, 2000). In order to provide a foundation for conceptual modeling, ontologies were introduced. As mentioned in (Gruninger, Bodenreider, Olken, Obrst, & Yim, 2008), the appellation of "ontology" encompasses many different types of artifacts created and used in different communities. For keeping a broad interpretation, we adopt the characterization of ontologies as described by Honderich (2006), which describes ontology as "the set of things whose existence is acknowledged by a particular theory or system of thought". Research on ontologies has become increasingly widespread in the computer science community, gaining importance in research fields such as knowledge engineering (Uschold & Gruninger, 1996), knowledge representation (Sowa, 1999) and information modeling (Ashenhurst, 1996). This resulted in the development of different types of ontologies of which some are also used for conceptual modeling.

With respect to the evaluation of conceptual modeling languages and more specifically the evaluation of their conceptual grammars, ontologies proved quite useful in assessing whether different conceptual modeling procedures are likely to lead to good representations of real-world phenomena. Therefore, ontologies quickly became introduced in the field of conceptual modeling originally as a way to evaluate the ontological soundness of a conceptual modeling language and its corresponding concepts and grammars. For instance ontological theories, such as those of Heller & Herre (2004), Chisholm (1996) and Bunge (1977), have been successfully used for the evaluation of conceptual modeling languages or frameworks (e.g. UML, ORM, ER, REA, OWL) (Guizzardi & Halpin, 2008). The usage of ontologies goes further than only evaluating conceptual modeling, in the sense that an ontology would express the fundamental elements of a domain, and therefore becoming the theoretical foundations of a conceptual model (Guarino, 1998). This way of applying ontologies led to a growing interest in the role that they can fulfill in improving the quality of conceptual models. For example, ontologies were used for the development of new conceptual modeling languages (Opdahl, Berio, Harzallah, & Matulevičius, 2012), for adding structuring rules to existing languages (Evermann & Wand, 2005), and for proposing conceptual modeling patterns and anti-patterns (Falbo, Barcellos, Nardi, & Guizzardi, 2013). Additionally, ontology can also be applied as a way to improve (semantic) interoperability. Or, in other words, ontologies can be used as means of translating or interchanging information. This is achieved, for example, by applying an ontology to attain semantic integration for translating between different models, methods, languages or paradigms. (Bittner, Donnelly, & Winter, 2005; Green, Rosemann, Indulska, & Manning, 2007).

In this paper all these techniques are called *ontology-driven conceptual modeling* (ODCM) approaches. We define ontology-driven conceptual modeling as the utilization of ontological theories, coming from areas such as formal ontology, cognitive science and philosophical logics, to develop engineering artifacts (e.g. modeling languages, methodologies, design patterns and simulators) for improving the theory and practice of conceptual modeling (Guizzardi, 2012). Hence, all of these techniques have in common that ontologies are used (e.g. evaluation, analysis, theoretical foundation or interoperability) to improve the mapping, reduction or pragmatic feature of either the conceptual modeling process or the output of this process, the conceptual model. A summary of the definitions related to ODCM can be found in table 1.

Since ODCM is still a relatively new research domain in the field of information systems, there is still much discussion on how the research in ODCM should be performed and what the focus of this research should be (Guizzardi & Halpin, 2008; Saghafi & Wand, 2014). Therefore, this article aims to critically survey the existing literature in order to assess the kind of research that has been performed over the years, analyze the nature of the research contributions and establish its current state of the art by positioning, evaluating and interpreting relevant research to date that is related to ODCM. In order to systematically identify and aggregate evidence of the past trends in ODCM, we present in this paper a systematic mapping review (SMR) and a systematic literature review (SLR) of papers dealing with ODCM. We can distinguish both methods according to the goal they aim to achieve (Rowe, 2014). The purpose of a SMR is to summarize prior research and to describe and classify what has been produced by the literature. The SLR aims at critically examining contributions of past research, to explain the results of prior research and to clarify alternative views of past research. The SMR and the SLR make the following contributions to the research field of ODCM:

- Provide a classification scheme founded on previously developed research dimensions that deal with ontologies and conceptual modeling. These dimensions can also be applied to position and describe future research activities.
- Analyze how the research in ODCM is performed and how it is being applied in the field
- Analyze the past focus and the change of research trends over time.
- Identify any gaps and opportunities that could be areas for further research or improvement.

Table 1: Definitions of concepts

Term	Definition
Conceptual model	A conceptual model is composed of (1) a mapping feature, meaning that a model can be seen as a representation of the 'original' system, which is expressed through a modeling language; (2) a reduction feature, characterizing the model as only a subset of the original system and (3) the pragmatics of a model, which describes its intended purpose or objective. (Stachowiak, 1973)
Ontology	Ontology can be defined as the set of things whose existence is acknowledged by a particular theory or system of thought (Ted Honderich, 2005).
Conceptual modeling	Conceptual modeling is the activity of representing aspects of the physical and social world for the purpose of communication, learning and problem solving among human users (Mylopoulos, 1992).
Ontology-driven conceptual modeling	Ontology-driven conceptual modeling is the utilization of ontological theories, coming from areas such as formal ontology, cognitive science and philosophical logics, to develop engineering artifacts (e.g. modeling languages, methodologies, design patterns and simulators) for improving the theory and practice of conceptual modeling (Guizzardi, 2012).

2 Research methodology

In order to achieve a rigorous literature study, we based our method of conducting this literature mapping and review on the systematic literature review methods described in (Dybå, Dingsøyr, & Hanssen, 2007; Kitchenham & Charters, 2007; Petersen, 2011). Mapping and review studies have different purposes. The SMR aims at structuring the area that is being investigated and displays how the work is distributed within this structure. The aim of the SLR on the other hand is to provide recommendations based on the strength of evidence. Hence, the mapping study is concerned with the structure of the research area, while the review study is concerned with the evidence (Petersen, Feldt, Mujtaba, & Mattsson, 2008). In order to properly distinguish the followed approach during the SMR and SLR, this section first describes the general methodology that was being followed in both studies. Section 3 and 4 then go into more detail, each discussing respectively how both studies were performed. To collect the articles for this literature study, we adopted the guidelines of (Kitchenham & Charters, 2007): (1) definition of the research questions; (2) formulation of a search strategy and the paper selection criteria; (3) construction of the classification scheme; (4) extraction of data and (5) synthesis of the results. Figure 1 displays the steps we have followed for conducting this literature study.

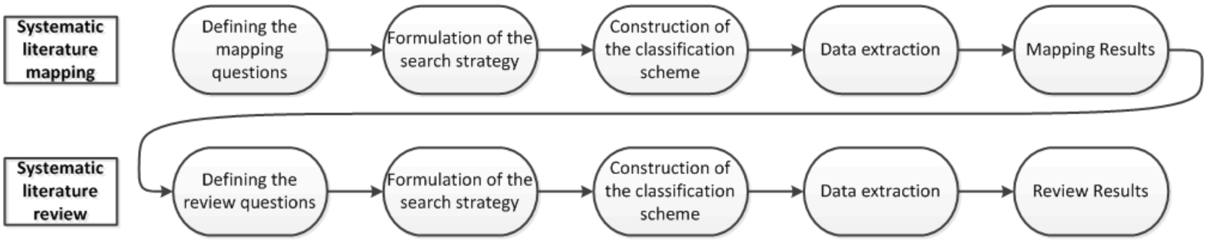

Figure 1: Steps undertaken while conducting the literature study

The research questions act as the foundation for all further steps of the literature study. The research questions should be formulated in such a way that they represent the objectives of the literature study. First, we defined a set of research questions for performing the mapping study, which we refer to now as mapping questions. The underlying reason for the mapping questions was to determine how research has been performed in ODCM, the kind of research that has been performed and how ODCM has evolved over the years. Based upon these mapping questions, we then formulated a search strategy based on the different phases from (Dybå et al., 2007) to collect our initial set of papers. The first phase defines a search string to search relevant databases and proceedings for articles related to the classification questions. The second and third phases define the inclusion and exclusion criteria. In the mapping study, we evaluate the inclusion and exclusion of articles based upon their titles and abstracts. After having collected and selected the papers in the search strategy, we constructed a classification scheme in order to categorize the papers. This classification scheme was based upon our pre-defined mapping questions and can be seen as a structure of research studies performed in the domain of ODCM. A good classification/taxonomy is characterized by certain quality attributes (Petersen, 2011). We have adopted these attributes by first performing a literature search to identify useful classifications for this literature review and by selecting classifications that are generally well-accepted in the domain of ODCM. The next step is the extraction of data according to the classification scheme that we have constructed.

To extract the data, we followed an approach similar to (Bandara, Miskon, & Fielt, 2011), as a reference of how to best extract relevant content from identified papers and how to synthesize and analyze the findings of a literature review. We first gathered all the collected literature from our search strategy into the reference manager Mendeley[1], to organize the general demographic information such as title, author, publication year etc. Next, the extraction was performed through the qualitative analysis tool Nvivo[2] to analyze and structure our data through the means of nodes and classifications. A node can be described as a collection of references dealing

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[1] https://www.mendeley.com/

[2] http://www.qsrinternational.com/products_nvivo.aspx

with a specific topic and is used to group articles and papers. In our research, each node represents a classification linked to one mapping question for categorizing the data. Both the data from Mendeley and Nvivo were then merged in the statistical software tool SPSS[3] to conduct some additional qualitative analyses. After all the data was extracted, we could commence with the analysis and synthesis of the results from the mapping study and present the mapping results.

The results and implications of the mapping study serve as the basis for our review study. The followed methodology runs parallel with the methodology from the SMR. First, our mapping results generated some new questions about ODCM, which we defined as review questions. We then defined a search strategy based on these review questions, where we further distilled the papers of the SLR based upon new defined inclusion and exclusion criteria. We then created a classification scheme based upon existing literature, which was used to structure and categorize the articles. In our data extraction, we collected the papers in Mendeley, structured and classified these papers in Nvivo in order to ultimately analyze the papers in SPSS. Finally, the analysis and synthesis of the results were presented. To conclude this section, all articles, classifications and other data of both the SMR and SLR can be found at http://www.mis.ugent.be/AppliedOntology2015/.

3 Mapping Study

3.1 Mapping questions

In the SLM existing ODCM literature will be structured from a design science perspective. Strictly defined design science research creates and evaluates IT artifacts intended to solve identified organizational problems (Hevner 2014). In this paper the broader interpretation of (Hevner, 2007) is followed. According to Hevner (2007), design science research must be considered as an embodiment of three closely related cycles of activities: (1) The Relevance Cycle, which inputs requirements from the contextual environment into the research and introduces the research artifacts into environmental field testing; (2) The Rigor Cycle, providing grounding theories and methods along with domain experience and expertise from the foundations knowledge base into the research, therefore adding new knowledge generated by the research to the growing knowledge base; (3) the central Design Cycle, which supports a tighter loop of research activity for the construction and evaluation of design artifacts and processes.

Based on the definition of ODCM by Guizzardi provided in the introduction, ODCM can be classified as a design science project that has as general goal improving the theory and practice of conceptual modeling. This

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[3] http://www-01.ibm.com/software/be/analytics/spss/

goal is realized by developing different engineering artifacts, which ideally should be evaluated with respect to this goal. In line with both Hevner (2007) and Baskerville et al. (2015), we also recognize that besides the artifact development goal, design science projects can also have a knowledge production goal. A lot of OCDM design science projects focus on generating knowledge which is needed for the development of these artifacts or which might be the result of the design cycle. Important to notice is that we assume a 'helicopter view' over the research performed in ODCM. This means that ODCM is considered as a covering design science project and that different ODCM studies are interpreted as a part of one of these three closely related cycles. An example of a similar approach for analyzing design science research can be found in (Geerts, 2011). He integrates different papers' contributions and artifacts, and displays the performed research as part of the REA artifact research network. This allows a better understanding of each paper's contribution, of how the research area evolves and illustrates the different types of research interactions. Similarly, we will assess different paper's contributions and artifacts and examine which research approaches have been followed.

Below, we have displayed the questions related to the structuring of the research. The mapping questions serve two purposes: the first question aims to gain more insight into the kind of design science research that has been performed in ODCM. Or more specifically, we would answer questions such as: what type of artifact did the research produce, develop or improve? What kinds of contributions have been made to the research field? And what kind of research method was being followed? The second mapping question aims to discover the application or function of ODCM. This latter mapping question inquires for more specific content related to ontologies and conceptual modeling. We would like to assess the context and setting in which conceptual modeling takes place and discover the intended purpose of the conceptual model and the ontology. Thus, while the first mapping question aims to discover information about how the process of research in ODCM is conducted, the second question aims to explore how the final model or the research result has been applied.

- MQ1: How is design science research performed in ontology-driven conceptual modeling?
- MQ2: How is research in ontology-driven conceptual modeling applied?

3.2 Search strategy and paper selection criteria

As mentioned in section two, we perform three phases to define a comprehensive search strategy. The first phase defines a search string to search relevant databases and proceedings for articles related to the mapping questions. The second and third phases define the inclusion and exclusion criteria. We evaluated articles based upon their titles and abstracts.

Phase 1 – Search articles in relevant databases based upon title and keywords

Our choice of electronic collections was determined by the variety of computer science and management information systems journals: Science@Direct, IEEE digital library, ACM digital library, Springer database, Web of Science and AIS electronic library. The search terms which we used to extract literature from the electronic collections, were constructed using the following steps, as described in (Brereton, Kitchenham, Budgen, Turner, & Khalil, 2007): (1) Define the major terms; (2) Identification of alternative spelling, synonyms or related terms for the major terms and (3) Use the Boolean AND for linking the major terms.

As major terms we selected 'Ontology-driven' and 'conceptual modeling' with alternative terms 'ontological analysis' and 'conceptual analysis'. For the search in titles and keywords the terms were reformulated using Boolean algebra, so that the terms were connected with the AND operator. Our search strings were therefore: "Ontology driven" AND "Conceptual modeling", "Ontological analysis" AND "Conceptual modeling", "Ontology driven" AND "Conceptual analysis". We used the term 'Ontology driven' without the hyphen since this term generated more results. In our search, we specified that papers needed to be written in English and that they were published from 1993 to 2014. Since the paper of (Wand & Weber, 1993) can be seen as the first that introduces ontologies in evaluating conceptual modeling languages, we did not search for papers written before 1993.

Phases 2 and 3 - Inclusion and exclusion of articles based upon title and abstract reading

In these phases, we evaluated the titles and abstracts of the returned articles of phase one. For the inclusion of an article, the following topics were to be explicitly mentioned in the abstract:

- *Ontology*: one or multiple ontologies were a crucial aspect in the research performed in the paper. An ontology could have been the topic of the paper or could be used as a means to, for example improve a model, but had to be an integral part in the development of the paper.
- *Conceptual modeling*: as with ontologies, one or multiple conceptual models needed to be an essential aspect of the article. A conceptual model needed to be the topic of the paper or had to be a deciding factor in the development of the paper. By conceptual modeling, we refer to the framework of (Wand & Weber, 2002), where research on conceptual modeling is composed of: (1) a conceptual modeling grammar, i.e. a set of constructs and rules to combine the constructs to model real-world domains, (2) a conceptual-modeling method that provides procedures by which a grammar can be

used, (3) a conceptual-modeling script, which is the product of the conceptual modeling process and finally (4) the context, being the setting in which the conceptual modeling occurs.

- *Type of literature*: As part of our search strategy, we considered only peer-reviewed journals, workshops and conferences. Although there is a great deal of additional literature in books, web pages, magazine articles and working papers, their content has not been revised by peer review and therefore the quality cannot be reliably determined.

From the search results we excluded those studies were *Ontology-driven conceptual modeling is not the main focus*. If an article focused only on ontologies or only on conceptual modeling, it was excluded. Also if ODCM was only used as a means of general introduction it was not included in the search results. Finally we also applied a limited form of snowballing. More specifically, we restricted the search of papers to the first level, meaning that the references of the selected papers were not automatically included to obtain more papers on ODCM. We did however search the references of the selected papers for any often-occurring references that were not included in our initial dataset. In total, we have added six papers that were often cited in the references of our selected papers but that were not captured by our search strings. The added papers were (Green & Rosemann, 2000; Milton, Kazmierczak, & Keen, 2001; Opdahl & Henderson-Sellers, 2001; Wand & Weber, 1993, 1995; Wand, 1996).

3.3 Classification scheme

The classification scheme that is based upon the mapping questions consists of six facets: (1) design artifact, (2) research contribution and (3) design method, which are related to MQ1, while (4) purpose of the conceptual model, (5) purpose of the ontology and (6) type of ontology relate to MQ2. Each of these classifications is discussed in more detail below.

Design Science Artifact

The creation of a purposeful artifact should be the result of any design science research in order to address an important problem. It should be described effectively, enabling its implementation and application in an appropriate domain. (Hevner, March, Park, & Ram, 2004) indicate that design science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation.

- *Constructs* provide the vocabulary and symbols used to define problems and solutions. They have a significant impact on the way in which tasks and problems are conceived and enable the construction of models or representations of the problem domain. In our mapping study, we added any analysis or discussion on conceptual modeling grammars and/or any ontological constructs to this category. For example, an analysis of the relationship construct, the description of mutual properties instead of association properties or an evaluation of ontological rules for developing UML diagrams would fall in this category.

- *Models* are made up from these constructs in order to generalize specific situations into patterns for application in similar domains. We included any abstractions, representations, conceptual models and/or meta-models in this category. Thus, a conceptual model constructed for the analysis of a specific information system or research that investigates the potential of a meta-model for software engineering would be included in this category. Meta-models can be distinguished from ontologies since the latter are acknowledged by a particular theory or system of thought (Ted Honderich, 2005), which is not the case for a meta-model.
- *Methods* can be seen as the blueprints for building models of specific situations. Therefore, frameworks, modeling approaches and/or modeling guidelines and best practices can be seen as methods for building models or guiding the process of constructing models. Examples are the description of a three-stage approach to develop a certain ontology-based system or the development of a methodology for ontological analysis.
- *Instantiations* demonstrate the feasibility of both the design process and of the designed product. Instantiations may occur in the form of intellectual, prototype systems or software tools aimed at improving the process of information systems development. For example, a plug-in tool that supports designers in developing design solutions in the conceptual design phase would be counted as an instantiation.

Again, since we see research performed in ODCM as part of one of the three closely related design science cycles, we would like to emphasize that papers will also be assigned to one of the above categories even if they did not actually construct or originally develop the specific artifact.

Design Science Contribution

Having classified the artifacts that were constructed in the papers, it is useful to further clarify the relationship between the kind of artifact that was created in a paper and the research contribution that was made. For classifying the design science contributions, we adopt the design science research knowledge contribution framework of (Gregor & Hevner, 2013). Their framework distinguishes four kinds of contributions: improvement, invention, exaptation and routine design. Each of these contributions are discussed in more detail below:

- *Improvement*: the contribution aims to develop better solutions in the form of more efficient and effective products, processes, services, technologies, or ideas. Researchers must contend with a known application context for which useful solution artifacts either do not exist or are clearly suboptimal. They draw from a deep understanding of the problem environment to build innovative artifacts as solutions to important problems.
- *Invention* is a radical breakthrough, a clear departure from the accepted ways of thinking and doing. The invention process can be described as an exploratory search over a complex problem space that requires cognitive skills of curiosity, imagination, creativity, insight, and knowledge of multiple realms of inquiry to find a feasible solution. The result is an artifact that can be applied and evaluated in a real-world context and where substantial new knowledge is contributed.
- *Exaptation* contributions can be described as known solutions that extend to new problems. This often occurs in a research situation in which artifacts required in a field are not available or are suboptimal but where effective artifacts may exist in related problem areas that may be adapted or, more accurately, exapted, to the new problem context. In other words, contributions in this category are design knowledge that already exists in one field and is extended or refined so that it can be used in some new application area.
- *Routine design* occurs when existing knowledge for the problem area is well understood and when existing artifacts are used to address the opportunity or question. Research opportunities are less obvious, and these situations rarely require research methods to solve the given problem.

Since both inventions and exaptations are rather rare and often are not easy to distinguish, we merge these two categories into one. For example, the paper of (Wand & Weber, 1993), where the Bunge ontology was first introduced to give a foundation for conceptual modeling, would be classified in the category Exaptation & Invention. Thus, a paper can be classified as an improvement, as exaptation & invention or as routine design.

Design Science Evaluation Method

The utility, quality, and efficacy of a design artifact are demonstrated through well-executed evaluation methods. As mentioned above, a design artifact is constructed to address a specific problem, and therefore the artifact can only be considered complete and effective when it satisfies the requirements and constraints of the problem it was meant to solve. The development and evaluation of designed artifacts are often performed through the use of different kinds of methodologies. For classifying these various evaluations methods, we adopt the design evaluation methods classification of (Hevner et al., 2004). They distinguish five different methods for evaluating a design artifact: observational, analytical, experimental, testing and descriptive. The differences between these methods are explained below:

- *Observational*: Can be in the form of a case study or field study. A case study explores the artifact in depth in its environment while a field study monitors the use of the artifact in multiple projects.
- *Analytical*: Consists of an analysis of the artifact in, for example an IS architecture or in the form of a study of the structure and qualities of the artifact. Hevner et al. (2004) distinguish further between static, architecture and dynamic analyses. In order not to fragment our classification scheme, we generalized the different analyses described above into just one category.
- *Experimental*: This can be a controlled experiment where the artifact is studied in a controlled environment for qualities (e.g. usability) or simulation, where the artifact is executed with artificial data.
- *Testing*: We distinguish between functional (black box) testing and structural (white box) testing. The former executes the artifact interfaces to discover failures and identify defects while the latter performs coverage testing of some metric in the artifact implementation.
- *Descriptive*: This can be done through scenarios, where the utility of the artifact is demonstrated through detailed scenarios, or through informed arguments, where information is used from the knowledge base (e.g. relevant research) to build a convincing argument for the artifact's utility.

Conceptual modeling purpose

As mentioned above, one of the main features of a model is its purpose or objective (Stachowiak, 1973). We will therefore investigate the different purposes of the models in the field of ODCM. (Wand & Weber, 2002) classify conceptual models into four generic purposes. We have adopted this classification because of our diverse set of papers, which require a more general classification scheme. The four purposes are: (1) supporting communication between developers and users; (2) helping analysts understand a domain; (3) providing input for the design process and (4) documenting the original requirements for future reference. As an example, if the purpose of a conceptual model was to maximize expressivity, clarity and truthfulness of the concepts, we categorized this as a communication purpose. If the purpose of the model however would be described as modeling requirements engineering for software configuration, we would classify this model as providing input for the design process. If a paper would describe the purpose of the model as a means for problem-solving analysis, we interpret this as an implicit purpose of understandability. Finally, if a paper gives a rather vague description such as 'conceptual models are often used as a basis for the construction and integration of information systems or to gain process knowledge' or mention multiple purposes such as 'models represent the application domains and are created for the purpose of analyzing, understanding, and communicating about the application domain and are input to the requirements specification phase for IS development', we leave this category blank. This means that this paper does not fall into one of the specified categories.

Type of ontology

This classification distinguishes the kind of ontology that has been applied in ODCM. To categorize different types of ontologies, we adopted the classification of (Guarino, 1998), where ontologies are being distinguished based upon their level of dependence of a particular task or point of view:

- *Top-level ontologies* describe very general concepts like space, time, matter, object, event, action, etc., which are independent of a particular problem or domain;
- *Domain ontologies* and *task ontologies* describe, respectively, the vocabulary related to a generic domain (like medicine or automobiles) or a generic task or activity (like diagnosing or selling), by specializing the concepts introduced in a top-level ontology;
- *Application ontologies* describe concepts that depend both on a particular domain and task, and often combine specializations of both the corresponding domain and task ontologies. These concepts often correspond to roles played by domain entities while performing a certain task, like replaceable unit or spare component.

Purpose of the ontology

Since this literature research is conducted to investigate the performed research in ODCM, it would be interesting to discover in which ways ontologies have been applied in this context. For classifying the purpose of applying an ontology, we adopted the classification of (Uschold & Jasper, 1999). They classified ontologies more specifically according to the purpose they fulfill: to assist in communication between human agents, to achieve interoperability, or to improve the process and/or quality of engineering software systems.

To explain these purposes more specifically in the context of ODCM, we will classify an ontology in the category of communication if the purpose is described as: 'providing real-world semantics for language constructs'; 'clarifying the structure of knowledge' or 'ontological theory is well-suited for benchmarking the adequacy and sufficiency of modeling constructs for representing concrete problem domains'. Thus if the purpose of an ontology is described rather generic (i.e. for the purpose of a clear representation of a domain), then we classify the ontology in the category of communication. However, when the purpose of the ontology is mentioned to improve or support system development, the ontology is classified in system engineering benefits. Examples are: ‘for the purpose of constructing a flexible and configurable software environment, ontology is built to organize and utilize resources dynamically’ or ‘ontology is applied to support the retrieval and the re-use of project information’. Finally, an ontology is classified in the category of interoperability if the purpose is described as: ‘ontologies facilitate the establishment of a common understanding of the semantics of context elements and their associated metadata and therefore boost interoperability’ or ‘a task ontology was developed to be used for addressing semantic interoperability problems’.

3.4 Data Extraction

Figure 2 displays the number of included articles after each phase of the article selection process. We conducted our search of articles at the end of January 2015. In total, we identified 749 articles, of which we reduced the number of articles to 707 due to duplicates and papers that were not written in English. Thereafter, articles were selected based on the inclusion and exclusion criteria, leaving 180 articles for review. The reason for the high number of excluded papers is that many articles focused only on either conceptual modeling or ontologies.

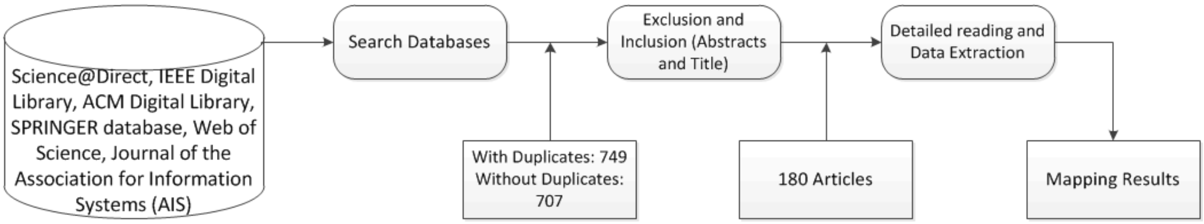

Figure 2: Mapping study selection procedure

After carrying out the inclusion and exclusion of all the papers, we applied our classification scheme. Nvivo allows the classification of data through the means of nodes. A node can be described as a collection of references dealing with a specific topic and therefore is particularly useful to group articles and papers according to this topic. Our node structure was as follows: we created six parent nodes, each bearing the overall classification facets: design artifact, research contribution, design evaluation method, purpose of the conceptual modeling, type of ontology and purpose of the ontology. Next, we created for every main aspect of the classification scheme different sub-categories, each also represented by a node. Thus in Nvivo, we can assign certain fragments of an article to a specific node. As a consequence, this reference is then classified according to classification facet that this node represents. For example, in the parent node type of ontology, there are four child nodes: top-level ontology, domain ontology, task ontology and application ontology. When a certain paper for example dealt with a foundational ontology, we could select and highlight the text in the paper that refers to this foundational ontology and assign it to the child node 'top-level ontology'. This piece of text could then be found in the contents of the specific child node. Also, when a child node was selected, the parent node was also automatically assigned to that specific paper. After having classified all papers according to the classification scheme, we exported all the obtained data from Nvivo to the quantitative analysis tool SPSS for a more thorough analysis of the data. The results of this analysis can be found in the section below.

3.5 Mapping results

MQ1: How is design science research performed in ontology-driven conceptual modeling?

In order to answer our first mapping question, we take a look at the developed design science artifacts over time in the upper panel of Figure 3. We can clearly see that constructs and methods have a decisive share in the kind of artifacts that have been developed. Especially in the 1990s, most of the papers dealt with only constructs while the development of methods started several years later, around the years 2000s. The construction of models and instantiations only really started around the period 2005-2009. This evolution seems logical, the focus in the 1990s and beginning of 2000s being on developing theoretical bases and foundations while over time artifacts such as models and instantiations were derived from these theories and foundations. However, the share of more applied artifacts such as models and instantiations remains much lower compared to the share of the more theoretical developments such as constructs and methods. Of all design artifacts, 43.3% were constructs, 37.6% methods, 14.6% models and 4.5% were instantiations. We thus identify a gap in the research of ODCM, where theoretical developments take a much larger share compared to empirical developments. The figure also clearly displays the growth of the number of papers dealing with ODCM. This observed increase in the number of papers indicates that ODCM is a fast growing research domain.

When we analyzed the research contribution of our papers (see middle panel figure 3), we noticed that contributions in the early years of ODCM were mainly improvements, with a minor share of exaptations and inventions. After a couple of years we noticed a rise of more routine design in the domain of ODCM. This trend makes sense that, after certain theoretical foundations have been established and improvements have been made, more routine design is developed to the already existing research. In total, it is however clear that the research field of ODCM consists of mostly improvements (62.1%), routine design (34.5%) followed by exaptations and inventions (3.4%). There are multiple reasons why there are fewer inventions and exaptations. First, inventions and exaptations are generally more rare than improvements and routine design. Second, many inventions or exaptations on which much research in ODCM is founded, were written in papers that did not belong to the topic of this literature study. With this we mean that, for example ontologies (e.g. Chisholm's ontology (Chisholm, 1989)) or conceptual modeling languages (UML, BPMN etc.), were introduced in papers that focused only on either ontology or conceptual modeling, therefore not meeting the inclusion criteria of this literature study. Finally, certain inventions or exaptations that did belong to the field of ontology-driven conceptual modeling could neither be included in this study since they were published in a type of literature that did not meet our inclusion criteria, such as a PhD thesis. For example the thesis of Guizzardi (Guizzardi, 2005) introduced both the ontology UFO and the extension of UFO, OntoUML, which can definitely be classified in the category exaptation & invention.

To gain more insight in the evaluation methods that have been applied on the design artifacts, we constructed another line graph in the lower panel of figure 3 that displays the applied method of every article over the years. As the graph demonstrates, there was more analytical research performed in the 90s compared to any other design science evaluation method. However, starting from 2000, more descriptive research was being applied. After the year 2005, descriptive research methods were then most applied in ODCM. Analytical research however did increase in a rather linear trend.

As for experimental, observational and testing methods, they were being applied around the years 2000–2005. However, as we can see from the graph, the number of experimental, observational and testing methods is reasonably lower than the number of analytical and descriptive research methods. Therefore, we consider this lack as our second research gap of ODCM. These observed trends in figure 3 align with our design science artifact and design science contribution observations above, indicating that first, theoretical and foundational theory was being performed, applying mostly analytical and descriptive design science methods.

After several years, more empirical research was performed, applying these theoretical and foundational theories and evaluating them with experimental, observational and testing design science methods. It would be interesting to compare these results to the publication of studies on research methodologies in information systems or papers that for example introduce a new paradigm. Determining the influence of such studies and papers on the overall research trends in the domain could be an interesting area for further research.

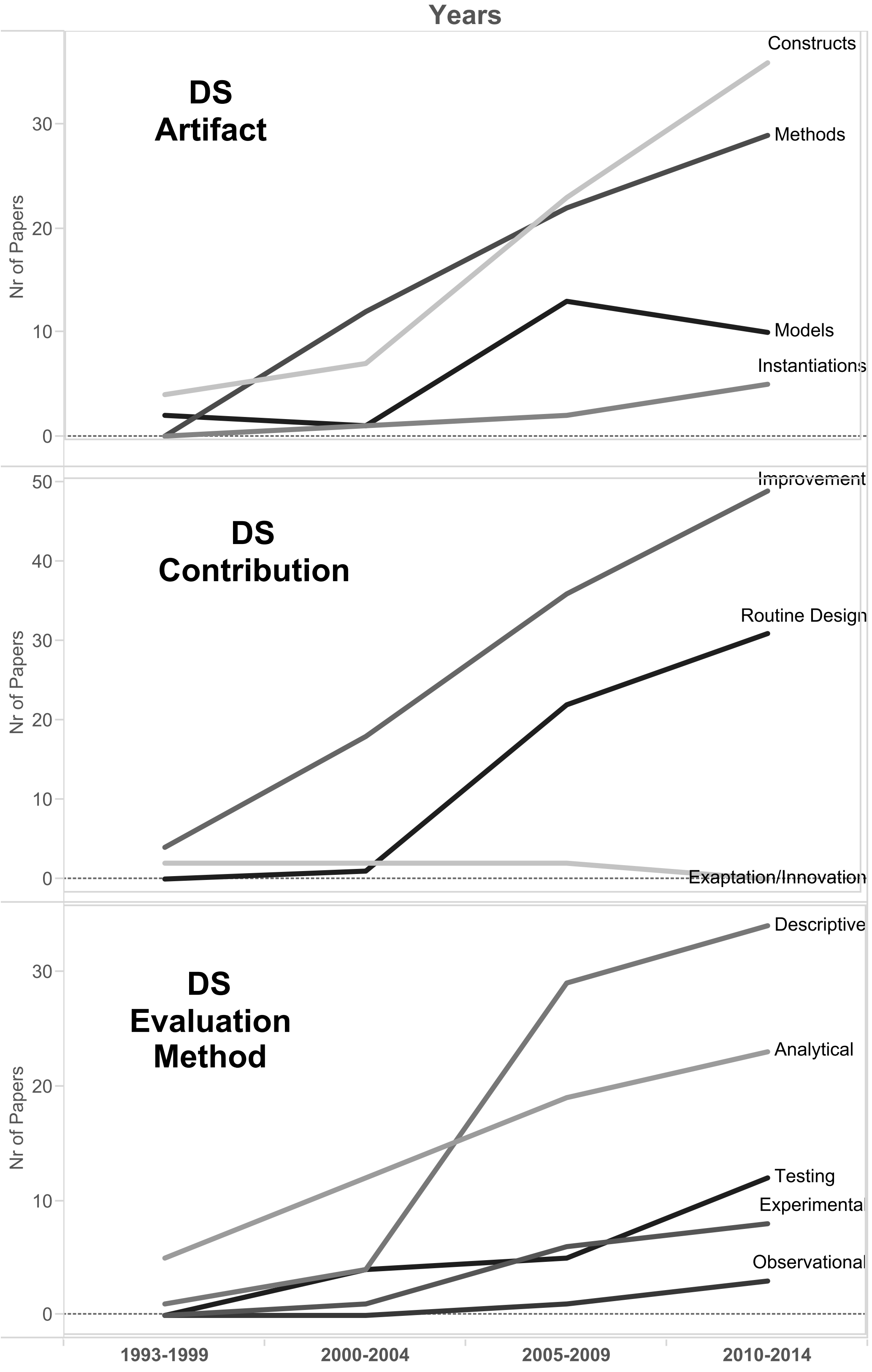

Figure 3: Design science artifact, contribution and evaluation method over time

In order to gain more insight between the design science evaluation methods that were applied according to the design science artifact, we composed this relation in figure 4. As we can see from the size of the circles, most analytical research was performed for constructs while most descriptive research was performed for methods. Another interesting observation is that most experiments can be associated with constructs while most testing is applied to methods.

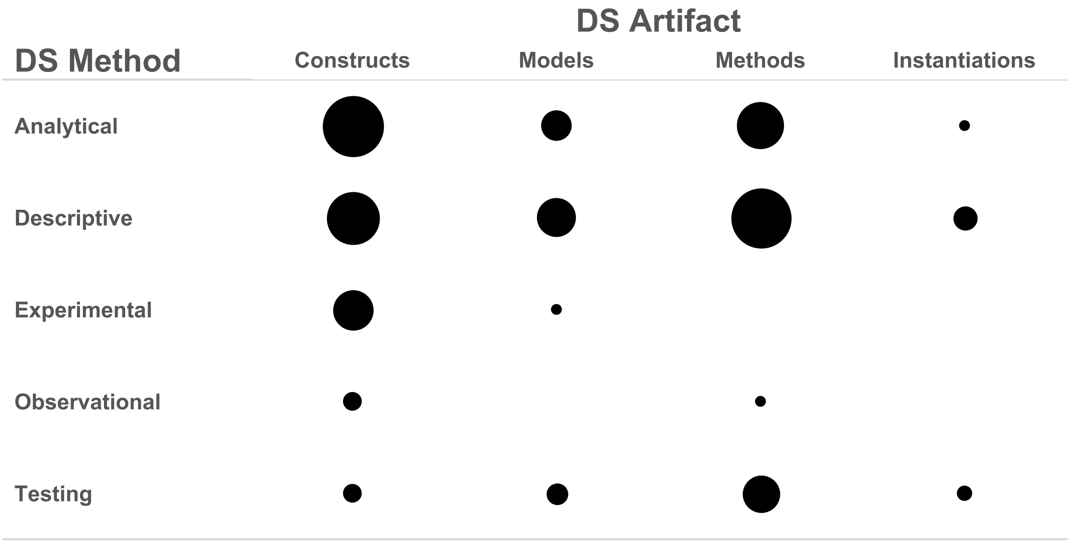

Figure 4: Design science artifact and evaluation method

MQ2: How is research in ontology-driven conceptual modeling applied?

To determine how research is applied in ODCM, we first explore the different purposes of why ontology-driven conceptual models are being developed and to gain a better understanding for which purpose they are applied. In total, 43% of the purposes were classified as understanding, followed by 35% input for the design process, 17% as communication and finally 5% were categorized as documentation purposes. If we refer again to the definition of conceptual modeling, as given by (Mylopoulos, 1992): ‘Conceptual modeling is defined as the activity of representing aspects of the physical and social world for the purpose of communication, learning and problem solving among human users’. Our results are clearly in line with this definition, since 60% of our articles mentioned either the purpose of communication or the purpose of understanding. An interesting observation is that only 145 articles indicated a specific purpose for the conceptual model. This mapping dimension is therefore the dimension with the lowest completeness in terms of assigned articles. We also have to mention that during the classification, we were rather flexible and tolerant when assigning a purpose for a conceptual model. With this we mean that if a paper implicitly mentioned the purpose of the conceptual model, we also categorized this paper. For example, if a paper had constructed a model and tried to assess this model in terms of its problem-solving capabilities, we assigned a purpose of understanding to this article, even though the paper did not explicitly mention this purpose. If we had only assigned purposes to papers that explicitly mentioned a purpose, the total amount of articles for this mapping dimension would have been significantly lower. Thus, we can observe that many articles and papers either do not (explicitly) give a specific purpose for their intended conceptual model or just the opposite, that they assign practically every purpose of a conceptual model to their intended model. Hence, we identify this as our third gap in the domain of ODCM. Clearly mentioning the specific purpose of the intended model or performed research for a specific conceptual model is essential for any further steps in the design science cycle of that particular model or research. If no clear and specific purpose is mentioned for a model, method or any artifact for that matter, how can one evaluate and test this model? Therefore, we believe that the influence of the role and the purpose of a conceptual model is a future research possibility.

To gain more insight into our mapping question, we look at which type of ontology is used in the research on ODCM. We created a line graph that displays the adopted ontology over the years, which can be found in figure 5. We can see that overall, top-level ontologies have been used most in the field of ODCM. Already in the 1990s, top-level ontologies dominated the research field and kept on rising during the years. We can however see that the increase between the years 2005 and 2014 has somehow declined compared to previous years. Another interesting observation is that starting from the years 2000-2004, domain ontologies have been applied increasingly more in research on ODCM, experiencing a relatively stronger increase over the last years compared to top-level ontologies. Overall, a total of 90 articles applied top-level ontologies, 57 used domain ontologies, 16 articles applied task ontologies and finally 8 articles adopted application ontologies. In order to assess how ontologies were applied in combination with conceptual models, we take a closer look at the given purpose for adopting an ontology. In total, we classified 98 articles in the category of System Engineering Benefits, 51 in Communication and 29 in Interoperability. These numbers indicate that most of the ontologies were applied for supporting systems in their development and implementation. In figure 6, we related the purpose of the ontology with the type of ontology that was being applied in the article. We only selected top-level ontologies and domain ontologies since they were the most represented in our articles. The differences in the sizes of the circles clearly show that both domain and top-level ontologies are being applied mostly for system engineering purposes. However, while much top-level ontology can be found in the category of communication, relatively more domain ontologies are being found for the purpose of interoperability.

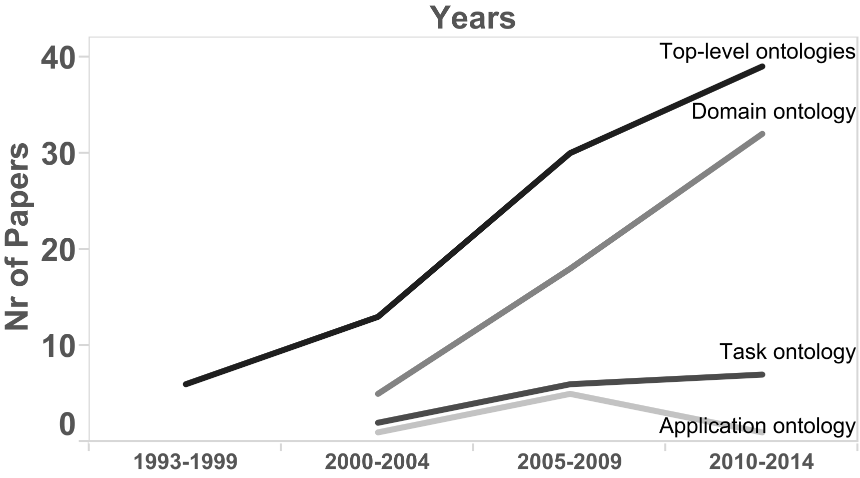

Figure 5: Type of Ontology over time

These results are rather logical, since top-level ontologies are more general descriptions, independent of a particular problem or domain and are thus more convenient for the purpose of communication than a domain ontology. Another interesting observation we could deduce from our data was that top-level ontologies were adopted more often in the early years of ODCM, whereas the adoption of domain ontologies started to increase around the years 2005-2006. When we reconsider the results above concerning the purpose of a conceptual model, most of the articles indicated that the purpose was mainly for either understanding or input for the design process or communication. Therefore we can conclude that the purposes of the model and the purpose of the ontology are aligned. However, we again noticed a similar observation as with the purpose of a conceptual model and, i.e. that many researchers are rather vague in defining the specific application of the ontology and in motivating their choice of ontological theories for the intended purpose. We consider this observation as our fourth research gap. This makes us wonder that if one does not clearly define the intended application of an ontology, how can one then clearly define the meaning of constructs and statements of a representation that must represent the phenomena of the application domain they are intended to describe? Therefore, we believe that the role and purpose of an ontology is an interesting area for future research in the domain of ODCM. Also, relating the role and purpose of an ontology with the role and purpose of a conceptual model is definitely also a future research possibility. For example, research could focus on where the limits of ontology-based theories lie as to the field of conceptual modeling (Recker & Niehaves, 2008).

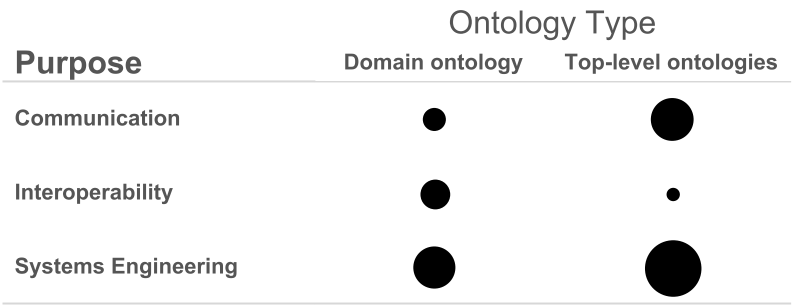

Figure 6: Number of articles according to purpose of the ontology per type of ontology

4 Review Study

4.1 Review Questions

When referring again to the definition of ODCM by (Guizzardi, 2012), ODCM uses ontological theories to develop artifacts in order to improve the theory and practice of conceptual modeling. Our mapping study clearly shed light on the kind of artifacts that were developed and how they were developed for each contribution. However, we still have questions concerning the application of ontological theories and models and concerning the kind of improvements they are intended for. As our second mapping question demonstrated, the intended purpose of both the model and ontology was not always clearly identified. Therefore, we formulate two new review questions to assess: (1) what the research in ODCM intends to improve with the applied ontological theories and models and (2) how ODCM intends to improve the conceptual modeling process and model. The formulation of our review questions can be found below. Thus, while the mapping study assessed the kind of research that has been conducted in papers and aimed to give a comprehensive structure of the domain, the review study aims to provide a more thorough assessment of the papers that significantly improved the research field, created new insights or had a convincing impact on the further directions of ODCM research. The review study aims to analyze the quality of a paper, evaluate its contents and link the research with other research performed in ODCM.

- RQ1: What does the research in ODCM intend to improve?
- RQ2: How does ODCM improve the conceptual modeling process and model?

4.2 Search strategy and paper selection criteria

We again apply the same phases to define a comprehensive search strategy as introduced in section 2. However, since we will derive our papers from the papers selected in the mapping study, it is unnecessary to reproduce every phase identically as in the mapping study. Instead, we selected papers based upon their classification in the mapping study to arrive at a set of papers that made a significant contribution to the field of ODCM. In order to identify the papers that have tackled generic problems and made substantial improvements in the domain of ODCM, we selected a sub-set of papers from the mapping study based upon the following classifications: (1) a paper had to be either classified as ‘improvement’ or ‘exaptation & invention’ concerning the design science contribution and (2) the design science method had to be ‘analytical’, ‘experimental’, ‘observational’ or ‘testing’. The selections of these categories are derived from our search for contributions that make a new and/or significant addition to the field of ODCM. As mentioned in (Hevner et al., 2004), routine design and descriptive evaluation methods apply existing knowledge to organizational problems or to build a convincing argument for the artifact. However, they do not address unsolved problems or fabricate new knowledge. Hence, descriptive evaluation methods and routine design were excluded from the review study. Next, as per our second and third phases, we defined our inclusion and exclusion criteria to apply on our selection of papers from the mapping study. Again, these criteria differ from the inclusion and exclusion criteria as defined in the SMR, since all papers already belong to the domain of ODCM and are of the correct type of literature. We evaluated the articles by their entire content and in order to be included in the review study, they had to fulfill the following criteria:

- *A generic interest of improvement was addressed:* Since it is our goal to identify overall improvements that research has focused upon over time, we will select only papers that deal with general and overall issues of the ODCM domain.
- *Focus on quality improvement:* As we mentioned in our introduction, ODCM approaches either aim to improve the conceptual modeling process or the output of this process, the conceptual model. We thus include papers that explicitly attempt to improve the quality of conceptual models or the quality of the conceptual modeling process.

Since we have already excluded all the papers that do not belong to the topic of this literature review in the SMR, we have formulated no additional exclusion criteria in this section.

4.3 Classification scheme

In order to develop our classification scheme, we derive our classifications from the review questions defined above. To classify the papers, we have adopted the Conceptual Modeling Quality Framework (CMQF) of (Nelson, Poels, Genero, & Piattini, 2012). Their comprehensive quality framework is the synthesis of two other well-known quality frameworks: the framework of Lindland, Sindre, & Solvberg (LSS, 1994) and that of Wand

& Weber (BWW, 1990) based on Bunge's ontology. By unifying both frameworks, the CMQF is useful for evaluating not only the end result of the conceptual modeling process, i.e. the conceptual representation, but also the quality of the modeling process itself. The advantage of adopting this framework as our classification scheme is that it can be used to address both our review questions at once. The framework identifies both the generic issue that is being addressed and the type of quality measure that is being applied to solve this issue. We have briefly explained the CMQF framework in Appendix A and have added two tables, one that describes all the quality types as they occur in the CMQF, and another that describes and defines all the quality types that have been identified in this review study. For a complete explanation of the framework, see (Nelson et al., 2012). To give an example, the physical layer has seven Quality Types, of which the second type (P2) represents the Ontological Quality (see Appendix A). So, if a paper would analyze certain foundational constructs of an ontology for achieving a better ontological representation of certain phenomena, this paper would be categorized under the category P2 Ontological Quality. Or in other words, the problem that is being investigated (the Object of Interest) can be situated in the physical language, i.e. the constructs of a conceptual modeling grammar. The improvement of quality can be situated in the relationship between the Object of Interest (i.e. the physical language) and the Quality Reference (i.e. the physical model), in this example achieving a better ontological foundation of grammar constructs. The framework thus clearly relates the interest of improvement that is being investigated by a paper (i.e. Object of Interest) with the kind of improvement that is generated (i.e. the Quality Type).

4.4 Data Extraction

Figure 7 displays the number of included articles after each phase of the review selection process. We conducted our search of articles with the set of articles that we gathered in the mapping study. In total, we identified 72 articles, based upon their classification in the mapping study. Next, articles were assessed based on our inclusion and exclusion criteria, leaving 38 articles in total for review. All 38 articles can be found in the bibliography of this paper and in Appendix B of this paper.

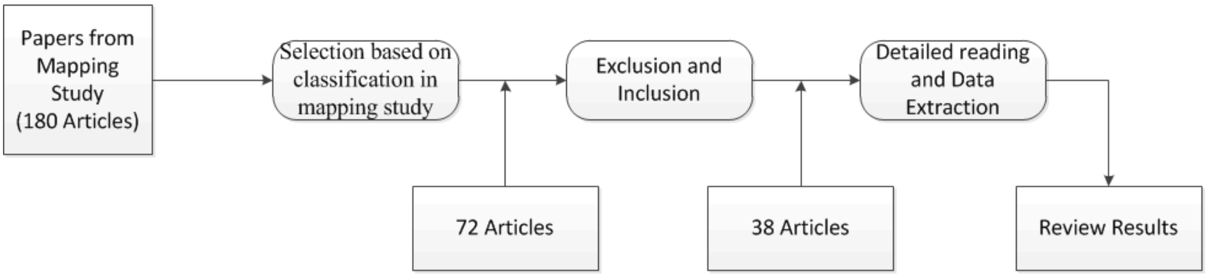

Figure 7: Review study selection procedure

The further development of the data extraction is similar to that of the mapping study as we again use nodes in order to group our papers according to the classification. To give an example of how the classification was performed, we discuss the classification of the paper of (Bera, 2012). First, the paper identifies and analyzes the way two different groups of modelers develop a conceptual model with and without the help of ontological rules. Since the paper assesses the development of a conceptual model, the Object of Interest is the physical representation. The ontological rules aim to improve the knowledge of the model that underlies the language and the domain for ultimately arriving at a better final representation. Therefore, the quality reference is model knowledge. Thus, we can recognize a first Quality Type: Applied Model Knowledge Quality (D5). Next, the paper identifies and analyzes the cognitive difficulties that two different groups of modelers had, when using a conceptual model that was either developed with or without the help of ontological rules, by letting them answer a domain understanding task. Since the paper aims to assess the perception and comprehension of the modelers who used the final representation, our Object of Interest is the cornerstone representation knowledge. Our quality reference is the physical representation since two kinds of models are compared, those developed with ontological rules and those without. Thus, we can categorize the paper to a second Quality Type, i.e. Pragmatic Quality (L4). Figure 8 displays the classification of the paper figuratively and displays the Quality Types (the arrows) between the Objects of Interests.

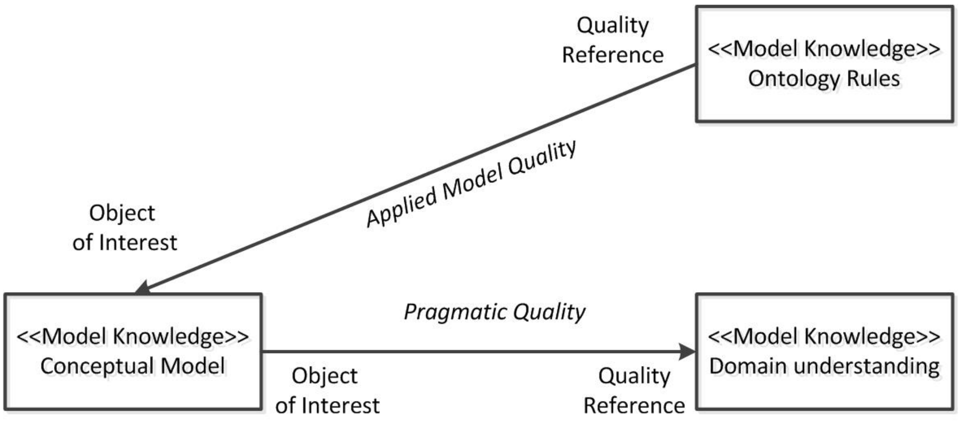

Figure 8: Example of data extraction in the Review Study

4.5 Review Results

RQ1: Which areas of interest does the research in ODCM improve?

To identify the areas of interest in ODCM that are being improved, we look at the Object of Interest from the CMQF. In figure 9, we have grouped the research according to their referred Objects of Interests. From the figure, we see that the *physical language* has been the most investigated Object of Interest. The physical language consists of the grammar and the vocabulary that are used to construct a conceptual representation. Most of the articles that performed research in this category employed an ontological analysis to examine the semantics or ontological deficiencies of modeling constructs and grammars (e.g. Evermann, 2005). Another stream of research (e.g. Milton et al., 2001) focused on how conceptual modeling languages were used in a certain context and applied ontologies to investigate and compare different modeling languages. The second and third most cited Objects of Interest are the *physical representation* and the *representational knowledge*. The physical representation is the users' description rendered into a formalized (ER diagram, UML diagram etc.) model-based representation. The representation knowledge can be described as the users' cognitive interpretation of the physical representation. Research related to the physical representation often addresses the lack of theoretical foundations of modeling constructs, or the failure of a conceptual schema to express the intended meaning and semantics (e.g. Parsons, 2011). Research related to representational knowledge compares different versions of a certain conceptual model based on the use of certain ontological constructs or modeling guidelines. Users' cognitive interpretations are then examined by measuring the impact of these differences on for example, the level of understanding obtained by model viewers (e.g. Gemino & Wand, 2005).

Finally, *Language knowledge* can be described as the language as understood by those modelers who are actively involved in the modeling process. Research in this category often addresses the issue of ontological deficiencies in conceptual modeling grammars (e.g. Recker et al., 2011), by assessing how some properties of these grammars inform usage beliefs, such as usefulness and ease of use. We would like to emphasize that due to the selection criteria of this literature study, some Objects of Interest are more represented than others. For instance, since this literature study does not focus on papers addressing only ontologies, the physical model and its cognitive counterpart the model knowledge are therefore less addressed as Objects of Interest.

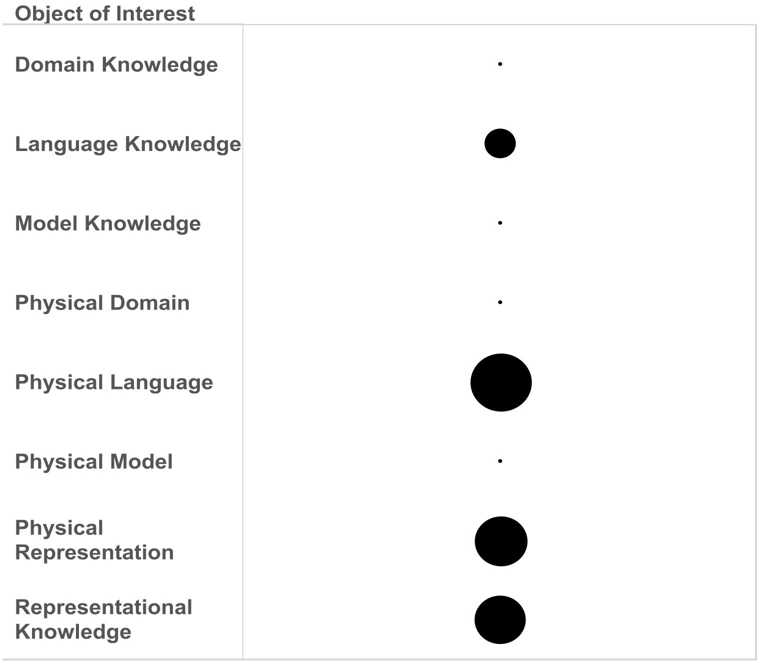

Figure 9: Number of references to Object of Interest

RQ2: What kinds of improvements have been made in ODCM?

To give an overview of the classification of the papers in the review study, we summarized the different Quality Types from every paper in figure 10. Each of these quality types is being defined in Appendix A, table 3. We discuss the results according to the different layers an article belongs to in order to assess the kind of Quality Types that have been investigated. In total, 31 Quality Types were related to the physical layer, 18 in the knowledge layer, 9 in the development layer and 4 in the learning layer. It is clear that the majority of the research focused on improvements situated in the *physical layer*, i.e. the physical, observable elements that are learned, analyzed and manipulated by the modelers as they try to understand the domain. When reconsidering the results of the review question above, the Object of Interest with the highest number of references was the physical language. As we can see from figure 10, the quality of the physical language has been investigated through several different Quality Types. Most of the articles from our literature review aimed at improving the Ontological Quality (P2). Much research (e.g. Opdahl & Henderson-Sellers, 2002) in this category suggested ontological improvements of modeling constructs (e.g. UML) based upon an analysis with an ontological model (e.g. BWW) and a mapping of the phenomena the constructs represent in terms of the phenomena in the problem domain it represents. Or in other words, many articles aimed to increase the quality (the completeness and validness) between the physical language and the physical model. The second largest layer, the *knowledge layer*, is the cognitive counterpart of the physical layer. The knowledge layer is composed of “the more tacit and individual elements of the quality framework, which exist only in the minds of the stakeholders involved in the conceptual modeling process and in the process of using the final representation". Most of the research in this layer (e.g. Bera & Evermann, 2012), investigates how the users of a model perceive the usefulness of ontologically founded conceptual representations. Next, articles belonging to the *development layer,* examine how well this knowledge was used to create the physical elements. Most of the research in the development layer involves designing and testing ontological rules for assisting information system designers to use them in their conceptual modeling activities. These ontological rules help a modeler or designer to construct a physical representation based upon the knowledge of the model that underlies the language and the domain. Finally the *learning layer*, which received the least amount of attention in the articles, measures how well that learning, interpretation and understanding takes place. Articles in the learning layer address the comprehension and understanding of the final physical representation by the stakeholders who use the model. We consider this lack of research performed in the development layer and learning layer as the fifth research gap in ODCM.

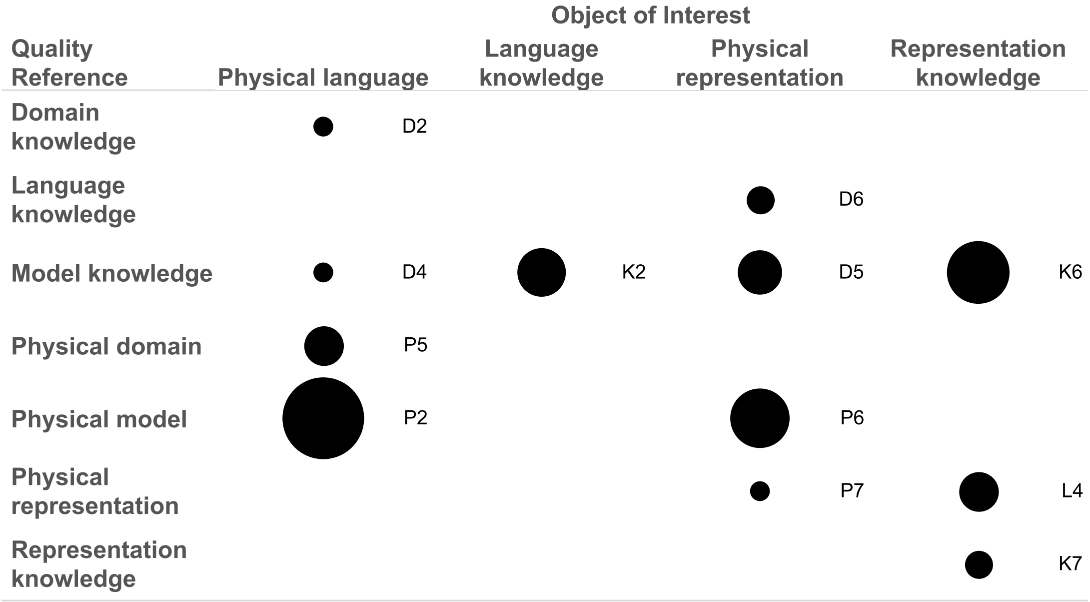

Figure 10: Comparison of the Quality Types per Object of Interest and Quality Reference

Additionally, to gain more insight in the evolution of the kind of improvements that have been made in the field of ontology-driven conceptual modeling, we composed a graph that displays the number of references according to the type of layer the Quality Type belongs to. This evolution is presented in figure 11. The graph clearly shows that from the years '93-'04', most of the articles tended to discuss elements of the conceptual model that belonged to the physical layer.

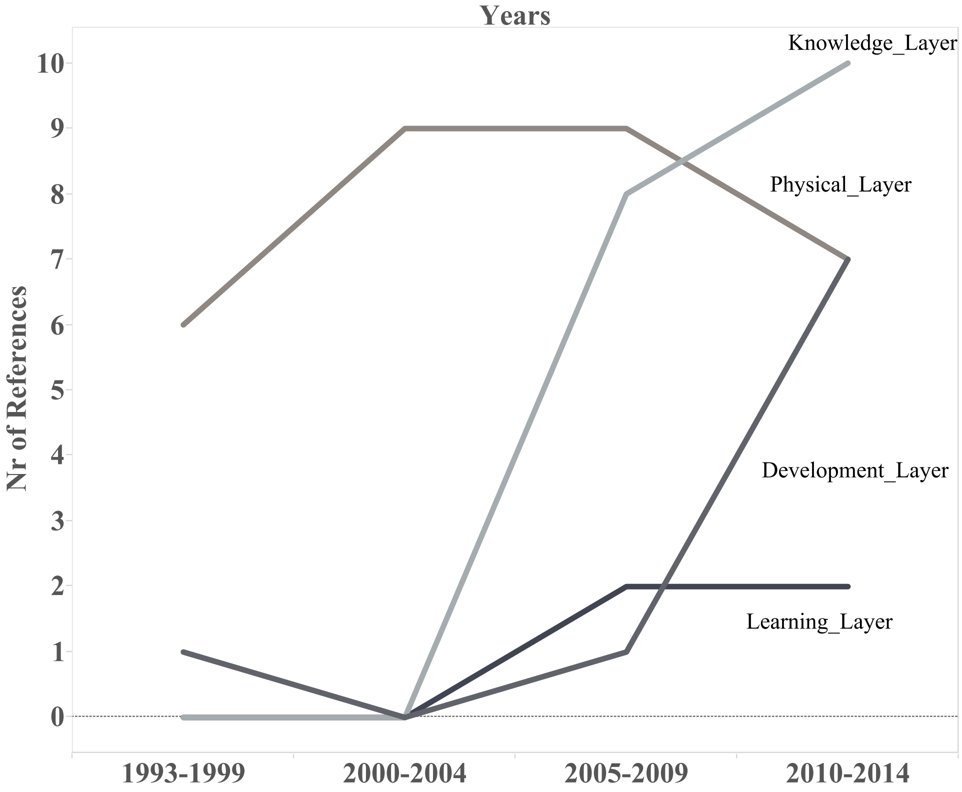

Figure 11: Number of references according to layer per year

In the early years ('93-'00) of ODCM, the emphasis of most papers was on improving the ontological expressiveness of grammars for describing real-world phenomena completely and clearly. Different approaches were followed however. Several researchers aimed at improving ontological clarity by adapting and extending Bunge's ontology to provide theoretical guidelines in order to capture the relevant knowledge about a domain and facilitate the mapping from the conceptual model to the design model of a system (Wand & Weber, 1993; Wand, Monarchi, Parsons, & Woo, 1995; Wand, 1996). Guarino on the other hand systematically introduced formal ontological principles for the practice of knowledge engineering and explored the various relationships between ontology and knowledge representation (Guarino, 1995). Additionally, the branch of ontology still had to find its place in conceptual modeling. In order to prove and position the potential of ontologies, its value as foundation for conceptual modeling was demonstrated and discussed next to other foundations such as concept theory, speech act theory and epistemology (Guarino, 1995; Wand et al., 1995). Around the years '00, ontologies were more and more used to perform ontological analyses and evaluations of conceptual modeling languages to (1) define the semantics of modeling constructs in terms of the kind of real-world phenomena they are intended to represent, (2) identify improvements of conceptual modeling languages by identifying ontological deficiencies in modeling constructs and grammars such as ontological overload or redundancy and (3) investigate the ontological assumptions underlying conceptual modeling languages. Most of these ontological analyses were performed with the BWW ontology as proposed by Wand and Weber (Milton et al., 2001; Opdahl & Henderson-Sellers, 2001, 2002). Accordingly, also articles to support and improve ontological analysis were introduced. The paper of (Rosemann & Green, 2002) for example tackle two issues concerning the use of the BWW model, i.e. understandability of the constructs in the model and the difficulty in applying the model to a modeling technique. Also Welty & Guarino (2001) introduced a methodology for ontological analysis based upon several notions of formal ontology that are used for ontological analysis.

Starting from ’04, we see a clear upward trend of research performed in the knowledge layer. It seems that after years of research focusing on the physical elements of the conceptual model, the focal point shifted to how these physical elements of the conceptual model were perceived by individual users and modelers. Parallel to research of the physical layer that focused on the semantics and ontological deficiencies of modeling constructs and grammars, there was a similar stream of research in the knowledge layer that aimed at assessing the perceptions of users and modelers of these modeling constructs and grammars. To assess these perceptions, experimental studies were performed to observe “how users and modelers perceive ontological constructs and more specifically to determine their perception of the clarity and comprehensibility of these grammars and constructs” (Evermann & Halimi, 2008; Gemino & Wand, 2005; Parsons, 2011; Shanks, Tansley, Nuredini, & Tobin, 2008). Another line of research in the knowledge layer focused more on the shortcomings of conceptual modeling languages for representing certain domains. While similar research in the physical layer conducted only ontological and hence more theoretical analyses, research in the knowledge layer validated their theoretical contribution with additional empirical evidence (Recker, Indulska, Rosemann, & Green, 2005, 2006; Recker, Rosemann, Boland, Limayem, & Pentland, 2008). As a consequence of conducting more empirical studies concerning the perceptions of users, also more attention was given to the modelers and designers on how they perceived the conceptual modeling process and the overall construction of a conceptual model. Around the year ’05, we can see a new evolution in the research of ODCM, where more emphasis is put on the developmental aspect of conceptual modeling. Especially the creation and adoption of ontological guidelines or ontological guidelines in the conceptual modeling process has received much attention (Bera, Burton-Jones, & Wand, 2009; Bera & Evermann, 2012; Bera, 2012; Evermann & Wand, 2011; Recker, Indulska, Rosemann, & Green, 2010). The purposes of these rules and guidelines are (1) to help analysts create conceptual models that convey semantics more accurately and more clearly and/or (2) to improve the effectiveness of the created models as ways to communicate and reason about the domain. Some empirical evidence (Bera, 2012) has already confirmed that ontological rules can alleviate cognitive difficulties when developing conceptual models and that modelers commit fewer modeling errors when applying these ontological rules. However, (Hadar & Soffer, 2006) obtained less promising results. Their results agreed with those of (Bera, 2012) that the use of ontology-based modeling rules can indeed provide guidance in developing a conceptual model and can reduce modeling variations, although the overall effect of these rules was not convincingly significant and did not always seem sufficient enough. Similarly, also (Guizzardi, Das Graças, & Guizzardi, 2011) noticed that complexity posed a significant issue for novice modelers who were using the ontologically founded conceptual modeling language OntoUML. However, as noted by (Gemino & Wand, 2005), we cannot solely focus on the complexity and comprehension of models without considering the domain understanding obtained through these models. For example, their study indicated that the use of mandatory properties with subtypes added to the overall complexity of the model but did provide a better understanding and comprehension of semantics of the model.

5 Discussion

In order to improve and contribute to the field of ODCM, we discuss certain shortcomings and possible research opportunities that have been identified within this literature study.

Research opportunity 1: As mentioned before in this paper, we considered ODCM as design science research. Evaluation is a "central and essential activity in conducting rigorous design science research" (Venable, Pries-heje, & Baskerville, 2012). The validity of any resulting artifacts must be justified, which is often performed through empirical methods (Baskerville, Kaul, & Storey, 2015). Although we can deduce an increase of empirical research over the last couple of years of articles belonging to the knowledge layer and development layer, we still agree with (Moody, 2005) that there is an overall *lack of empirical research* in the field of ODCM. In MQ1, more specifically in the upper and lower panel of figure 3, we encounter a much larger number of theoretical contributions compared to the number of empirical research studies that are being performed. Empirical studies however, are essential to perform design science research, since they allow the validation of research ideas, testing of theoretical arguments and theories and the evaluation of the efficacy of new practices.

Research opportunity 2: We have noticed in the articles of this literature study, especially those papers situated in the knowledge layer and learning layer of the SLR, that many of these empirical results often encounter the issue of *complexity* in the process of ontology-driven conceptual modeling (Gemino & Wand, 2005; Guizzardi et al., 2011). In order to tackle this ill-favored effect of complexity, we agree with (Guizzardi & Halpin, 2008) that research in ontology-driven conceptual modeling on the one hand needs to provide theoretically sound conceptual tools with precisely defined semantics but on the other hand must hide as much as possible the complexity that arise of these ontological theories. It is on this aspect that ontological rules or modeling guidelines seem promising, since it is their aim to support the conceptual modeling process to arrive at clearer, more effective and more understandable models.

Research opportunity 3: Perhaps the cause for this perceived complexity in ODCM could be traced to our findings on the scarcity of research concerning the *pragmatic quality* of conceptual models. As the graph in figure 11 demonstrates, much research has been performed in the physical and knowledge layer, however, we notice an overall shortage of research performed in the development layer and especially the learning layer of conceptual modeling. Articles in this last layer measure how learning, interpretation and/or understanding takes place. It is rather odd that one of the most frequent given definitions of conceptual modeling (Mylopoulos, 1992) states that the purposes of conceptual models are communication, learning and problem solving, but that there is relatively few research conducted in how the learning, interpretation and understanding in conceptual modeling takes place. As our mapping results also confirmed, 60,5% of our articles mentioned the purpose of conceptual modeling as either communication or understanding. Therefore, more research in the learning aspect of conceptual modeling would be beneficial for the field of ODCM, since the principal purpose of a conceptual model is to be understood and comprehended by anyone who uses it. Additionally, the process of learning, interpreting and understanding a conceptual representation is a complicated matter and much influenced by individual and contextual factors. Therefore, capturing how and to which extent the stakeholder completely and accurately understands the conceptual model, and to identify which contextual and individual factors encourage or discourage this comprehension, is a research opportunity in the field of ODCM that still needs further investigation.

Research opportunity 4: A particularly interesting observation was made by the research of (Hadar & Soffer, 2006), where they analyzed two ontology-based modeling frameworks in order to evaluate their potential contribution to a reduction in variations and thus facilitate model understanding. Their findings highlight contradictions in the guidance provided by the different frameworks, where differences in the underlying ontology exist. These results indicate that the *choice of an ontology* may affect the resulting model and that not all ontologies are equivalent in terms of modeling guidance. We believe that a careful consideration of an ontology applies even more for foundational ontologies than for domain ontologies, since foundational ontologies are often used to provide guidance in the conceptual modeling process. This observation is equivalent to Quality Types such as Applied Domain-Model Appropriateness (D1), Pedagogical Quality (L2) and the (perceived) Model-Domain Appropriateness (P1 and K1), which address the appropriateness of an ontology to the understanding and mindset of a certain modeler. In our review study however, we did not identify any articles performing research into these aspects of ODCM. Similarly, in figure 6 of our second mapping question, we noticed that many researchers are also vague in defining the specific application of the ontology and in motivating their choice of ontological theories for the intended purpose.

Research opportunity 5: One element of the contextual factors, i.e. the *purpose of a conceptual model*, also deserves some additional attention. As the results of our second mapping question indicated, many articles do not clearly mention a specific or intended purpose of their model or performed research. The same observation applies for the purpose of an ontology. Often, when for example an ontological analysis is performed or patterns are developed, the given purpose for this analysis or patterns is usually very broad and opaque. We agree with (Evermann & Halimi, 2008), that in order to have well-defined meaning of constructs and statements of a representation, these elements must be defined in terms of the phenomena of the application domain they are intended to describe. Thus, if one does not clearly state the intended purpose, one cannot clearly define meaning, which as a result leads to ambiguous or confusing models.

To conclude this section, we would like to discuss the significance and relevance of our research opportunities and how they reflect upon the field of ODCM. Perhaps, from all the research gaps and opportunities we have identified, the complexity concerning ODCM (research opportunity 2) is the greatest challenge research in this field has to face. As mentioned above, we are aware that an increase of complexity can also be paired with an increase in the understanding of the semantics of the model, which is by no coincidence one of the main purposes of ODCM. However, evidence provided by (Davies, Green, Rosemann, Indulska, & Gallo, 2006; Recker, 2010) report that perceived usefulness and perceived ease of use (measured as complexity) are the two most frequently reported factors influencing the decision to continue using conceptual modeling in practice. Therefore, in order for ODCM to be used and stay used by practitioners in the field of conceptual modeling, our priority should be on managing the complexity in ODCM by finding a balance between the increase of the understanding of the semantics of a model through ontological theories, and the additional increase of complexity that arises from these ontological theories. It is at this point that the importance of the other research opportunities becomes apparent, since they can facilitate this balance. For example, if we can clearly identify the purpose of the preferred model by the end-user, we can adopt our ontology-founded models according to this purpose (research opportunity 5). For example, if an end-user has to perform a thorough analysis of a certain system and desires a higher emphasis on the semantics of the model, we can allow an increase in complexity in order to accomplish the needs of this end-user. Also, some modelers or end-users may prefer or posses a better understanding towards a specific ontology and how this ontology represents real-world phenomena. By applying the preferred ontology in ODCM, we could produce conceptual models that are better perceived by these users (research opportunity 4). However, probably the first step towards finding the adequate balance between an increased understanding of the semantics of a model and its increased complexity is first identifying how learning, interpretation and understanding of these models takes place (research opportunity 3). Finally, we agree with Gemino & Wand (2005), that the issue of understanding versus complexity "can be studied by combining theoretical considerations and empirical methods". Theoretical contributions and artifacts should be validated and evaluated by empirical studies that assess the perceived usefulness and perceived ease of these theoretical contributions (research opportunity 1). This approach enables researchers to address the quality of a model, the perceived understanding from its users and the given complexity of the contribution.

6 Threats to validity

The main threats to the validity of a SLR are (1) publication selection bias, (2) inaccuracy in data extraction and (3) misclassification (Sjøberg et al., 2005). We acknowledge that is it impossible to achieve complete coverage of everything written on a topic. However, we aimed to maximize this coverage by selecting our papers from six digital sources, including journals, conferences and workshops that are relevant to ODCM. The scope of journals and conferences covered are sufficiently wide to attain reasonable completeness in the field studied. To reduce the publication selection bias, we defined research questions in advance, organized the selection of articles as a multistage process based upon well-established research and involved four researchers in this process. Both the inclusion and exclusion criteria and the classification schemes of the SLM and SLR were carefully evaluated by all researchers and were several times discussed for their impact. When performing the data extraction for both the SLM and SLR, we first classified our papers into three categories, according to the inclusion and exclusion criteria: (1) Included: the researcher is sure that the paper is in scope and meets all inclusion criteria; (2) Excluded: the researcher is sure that the paper is out of scope and applies to at least one of the exclusion criteria or (3) Uncertain: the researcher is not sure whether the paper fulfills either the inclusion or exclusion criteria. When a paper was classified as 'uncertain', the paper was given to a fellow author for a second evaluation and was then discussed whether the paper should be included or excluded. Concerning the classification, during the SLM, all authors classified several papers independently from one another and the classification results were afterwards compared for their consistency. Overall, there was a general agreement on the classification of papers. When necessary, disagreements were resolved through discussion. Additionally, two authors performed the classification of the SLR, frequently comparing the classification results with each other for consistency. Also, one of the authors of this SLR was also a co-author of the CMQF framework, increasing the correct application of the framework in the review study. Although data extraction and classification from prose is difficult at the outset, we believe that the extraction and selection process was rigorous and that we followed the guidelines as provided in (Kitchenham & Charters, 2007), (Petersen, 2011) and (Dybå et al., 2007).

Acknowledgements

This research has been funded by the National Bank of Belgium.

7 Conclusion

This paper conducted a literature study, composed of a systematic mapping review and a systematic literature review, in the field of ODCM. The mapping study aims at structuring the area that is being investigated and displays how the work is distributed within this structure. The aim of the review study on the other hand is to provide recommendations based on the strength of evidence. We searched six digital libraries, producing 180 articles dealing with ODCM. We have provided two classification schemes founded on previously developed research, of which both attempt to clearly and thoroughly categorize papers dealing with ODCM. The first classification scheme was used in the SMR, to provide a general categorization of articles. Our second classification scheme was applied in the SLR, for a more in-depth categorization of articles. The results of the SMR identified certain gaps and trends in the domain of ODCM. Based upon these results, we conducted the SLR to gather more evidence on these results. This led to the identification of five research gaps that need more attention and five research opportunities that could be future areas for improvement in the field of ODCM. The research gaps were: (1) a shortage of empirical developments compared to the theoretical developments, (2) a lack of experimental, observational and testing evaluation methods, (3) many articles do not clearly mention a specific or intended purpose of their model or performed research, (4) similar to the purpose of conceptual models, many researchers are also vague in defining the specific application of the ontology and in motivating their choice of ontological theories for the intended purpose, and (5) certain areas in ODCM still need more research, such as studies that measure how well that learning, interpretation and understanding of a conceptual representation takes place. Based upon these research gaps, we formulated five research opportunities to address these gaps.

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9 Appendix

Appendix A

The Conceptual Modeling Quality Framework (CMQF) is composed out of eight cornerstones. Each of these *cornerstones* can be thought of as an aspect that is involved in the conceptual modeling process and is needed to arrive at a conceptual model and representation. The cornerstones are: physical domain, domain knowledge, physical model, model knowledge, physical language, language knowledge, physical representation and representation knowledge. These cornerstones can be thought of as either sets of statements that constitute physical artifacts or statements that represent cognitive artifacts. *Quality dimensions* represent relations between two out of a set of eight cornerstones in total. Quality dimensions can be grouped in four layers, which roughly follow the conceptual modeling process and include all the aspects that can be linked to a conceptual model. These layers are the physical layer, knowledge layer, learning layer, and development layer. The physical layer contains the physical, observable elements of the quality framework. The knowledge layer parallels the physical layer, since it represents the cognitive counterpart of this layer. The learning layer measures how well that learning, interpretation and/or understanding takes place. Finally, the development layer measures how well that a modeler's knowledge is being used to create the physical elements. Further, a *Quality Type* is defined as a relationship between a Quality Reference and an Object of Interest. The *Object of Interest* represents the cornerstone that is being examined (i.e. the cornerstone where the arrow arrives). The *Quality Reference* represents the cornerstone to which the Object of Interest is being compared for completeness and validity (i.e. the cornerstone where the arrow departures). Figure 12 displays the different cornerstones, quality dimensions and quality types that are included in each layer. Table 2 describes all the quality types that are being defined in the CMQF framework. Finally, in order to reduce the overhead for the reader, we have summarized and defined the quality types that only occur in this literature study in table 3.

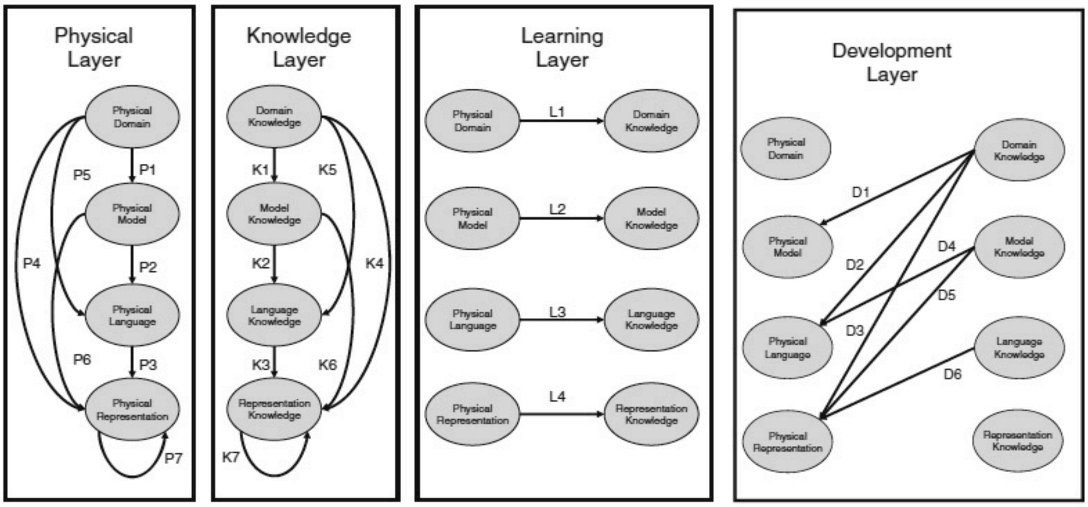

Figure 12: The CMQF quality layers and their Quality Types, figure obtained from (Nelson et al., 2012)

Table 2: Total number of Quality Types, described in (Nelson et al., 2012).

Quality Type	
P1 Model-domain appropriateness	K6 Perceived intensional quality
P2 Ontological Quality	K7 Perceived empirical quality
P3 Syntactic quality	L1 View quality
P4 Semantic quality	L2 Pedagogical quality
P5 Language-domain appropriateness	L3 Linguistic quality
P6 Intensional quality	L4 Pragmatic quality
P7 Empirical quality	D1 Applied domain—model appropriateness
K1 Perceived model-domain appropriateness	D2 Applied domain—language appropriateness
K2 Perceived Ontological Quality	D3 Applied domain knowledge quality
K3 Perceived syntactic quality	D4 Applied model—language appropriateness
K4 Perceived semantic quality	D5 Applied model knowledge quality
K5 Perceived language-domain appropriateness	D6 Applied language knowledge quality

Table 3: Quality Types discussed in this literature review, described in (Nelson et al., 2012).

Quality Types	**Definition**
P2 Ontological Quality	The appropriateness of a physical language to express the concepts of the physical model and physical representation.
P5 Language-domain appropriateness	The ability of a language to express anything in the physical domain in order for the user to create a faithful representation.
P6 Intensional quality	The intentional quality aims at keeping the physical representation true to the mindset and the meanings defined by the physical model.
P7 Empirical quality	The empirical quality measures the readability of a conceptual representation.
K2 Perceived Ontological Quality	The perceived ontological quality can be described as how a stakeholder perceives the validity and completeness of a physical, external language (the grammar and the vocabulary of the language) for expressing the concepts of a physical model
K6 Perceived intensional quality	Measures how the user of a model perceives the mindset and the meanings defined by the physical model.
K7 Perceived empirical quality	Measures how the user perceives the readability of a conceptual representation.
L4 Pragmatic quality	Addresses the comprehension and understanding of the final physical representation by the stakeholders who use the model.
D2 Applied domain—language appropriateness	The appropriateness of a modeling language that is being developed to the modeler’s knowledge of the real-world domain.
D4 Applied model—language appropriateness	The appropriateness of the modeling language being developed to the developer’s knowledge of the particular mindset or ontology it will be based upon.
D5 Applied model knowledge quality	Measures the knowledge of the model that underlies the language and the domain.
D6 Applied language knowledge quality	Addresses the knowledge of the modeler using the modeling language, the vocabulary and the grammar to create the physical representation.

Appendix B

Paper	Quality Type	D2	D4	D5	D6	K2	K6	K7	L4	P2	P5	P6	P7
(Bera et al., 2009)	2			X					X				
(Bera, 2012)	2			X					X				
(Bera & Evermann, 2012)	2						X		X				
(Burton-Jones, Clarke, Lazarenko, & Weber, 2012)	1						X						
(Clarke, Burton-jones, & Weber, 2013)	1									X			
(Evermann & Halimi, 2008)	1						X						
(Evermann & Wand, 2011)	1			X									
(Evermann, 2005)	1									X			
(Evermann & Fang, 2010)	2						X					X	
(Evermann & Wand, 2006)	1						X						
(Gehlert & Esswein, 2007)	1									X			
(Gemino & Wand, 2005)	2						X		X				
(Green, Rosemann, Indulska, & Recker, 2011)	2				X	X							
(Guarino, 1995)	1											X	
(Guarino & Welty, 2000a)	1									X			
(Guarino & Welty, 2000b)	1									X			
(Guizzardi et al., 2011)	1				X								
(Guizzardi & Zamborlini, 2014)	2		X	X									
(Hadar & Soffer, 2006)	2						X					X	
(Milton, Rajapakse, & Weber, 2012)	2						X	X					
(Milton et al., 2001)	2									X	X		
(Opdahl & Henderson-Sellers, 2001)	1									X			
(Opdahl & Henderson-Sellers, 2002)	2									X		X	
(Parsons, 2011)	2						X					X	
(Recker et al., 2005)	3					X				X	X		
(Recker et al., 2006)	3					X					X	X	

(Recker et al., 2010)	3	X				X				X			
(Recker & Rosemann, 2010)	1					X							
(Recker et al., 2008)	2							X					X
(Recker et al., 2011)	2					X				X			
(Rosemann & Green, 2002)	1									X			
(Shanks et al., 2008)	2						X					X	
(Wand & Weber, 1993)	1									X			
(Wand, 1996)	1											X	
(Wand et al., 1995)	2									X		X	
(Wand, Storey, & Weber, 1999)	2			X								X	
(Welty & Guarino, 2001)	1									X			
(zur Muehlen & Indulska, 2010)	2									X	X		