SCHOOL OF COMPUTATION,
INFORMATION AND
TECHNOLOGY — INFORMATICS

TECHNICAL UNIVERSITY OF MUNICH

Master's Thesis in Robotics, Cognition, Intelligence

Ontology Enhancement of the Transport Sector in the Field of Energy System Modeling

Ludwig Mittermeier

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Ontologieerweiterung des Transportsektors im Bereich der Energiesystemmodellierung

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Abstract

With an increasing importance of energetic aspects of appliances, such as consumption and emission values, due to financial and political goals, energy system modeling is gaining more attention. This results in numerous frameworks and models for specific applications producing a huge amount of heterogeneous data. In order to leverage this data across models and frameworks, methods for data handling such as comparison, integration, or exchange need to be improved. As a first part of that, the meaning of vocabulary needs to be unified. Furthermore, a machine-readable approach is desirable, so that further processing can be automated more easily. The Open Energy Ontology (OEO) tries to solve these problems by providing definitions of concepts that can be used for the annotation of data sets, hence clarifying the meaning of used terms. A lack of concepts from the transport domain was identified, and therefore, this thesis provides an enhancement to the OEO by adding terms for the transport domain in a systematic, relevance-based manner. As a guidance for the approach, research questions were formulated and evaluated. Most of the added terms belong to one of the categories *vehicle types*, *transport types*, *infrastructure*, *operational environment*, *energy carrier for propulsion*, *operational mode*, or *measurement values*. In addition, the usage of the OEO for annotating three exemplary data sets is examined, and assumptions from two exemplary studies are formalized with OEO concepts. These applications showed some difficulties that are further discussed, alongside limitations and assumptions. Among the difficulties are the definition of axioms, the choice of concepts during annotation, and the expressiveness of the implementation language. For the limits, the scope and the level of detail are two important points. The most important assumption is about the handling of annotations, where no precise, single OEO concept exists. Lastly, some ideas for further research based on the contributions and insights of this thesis are suggested.

keywords - **ontology, energy system modeling, transport domain, knowledge exchange, data annotation, assumption formalization**

Statement of Academic Integrity

I,

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hereby confirm that the attached thesis,

Ontology Enhancement of the Transport Sector in the Field of Energy System Modeling

was written independently by me without the use of any sources or aids beyond those cited, and all passages and ideas taken from other sources are indicated in the text and given the corresponding citation.
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I have not previously submitted this thesis for academic credit.

Gilching, January, 12, 2023

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A project like this Master's Thesis is never a journey for a single person. If I compare it to a travel through an unknown terrain, I may be the one who needed to walk all the way to the goal far in the distance, but I have met wonderful people along the way, that helped me reach that goal. Starting with my advisors that showed me the best ways through the jungle, the people from the OEO, who thought me useful tips and tricks for survival, and my family, that provided me quite literally with accommodation and nourishment. And therefore, I would like to thank these people for their support and encouragement during this journey.

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List of Abbreviations

Abbreviation	Description
BEV	Battery electric vehicle
BFO	Basic Formal Ontology
CNG	Compressed natural gas
FCEV	Fuel cell electric vehicle
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
NUTS	Nomenclature of territorial units for statistics
OE	Open Energy
OEO	Open Energy Ontology
OEP	Open Energy Platform
OWL	Web Ontology Language
PHEV	Plug-in hybrid electric vehicle
pkm	Passenger-kilometer
RDF	Resource Description Framework
tkm	Ton-kilometer
UO	Unit Ontology
W3C	World Wide Web Consortium
XML	Extensible Markup Language

List of Color-Codes

Color	Description
Figures in section 3.3	
Blue	Used for concepts that were already part of the OEO.
Green	Used for concepts that were added or suggested as an addition to the OEO.
Orange	Used for axioms that relate two depicted concepts.
Black	Used for the subclass relation.
Figures in chapter 5 and appendix B	
Blue	Used for concepts that were already part of the OEO.
Green with green border	Used for concepts that were added to the OEO.
Green with red border	Used for concepts that were suggested as an addition to the OEO.
Red with green border	Used for concepts that are neither part of the OEO nor suggested as additions, but whose meaning can be expressed through other concepts in the OEO.
Red with red border	Used for concepts that are neither part of the OEO nor suggested as additions, and cannot be expressed through other concepts in the OEO.
Orange	Used for axioms that relate two depicted concepts.
Black	Used for the subclass relation.
Axioms in all chapters	
Blue	Used for logical operators in the same way as Protégé does.
Pink	Used for certain keywords in the same way as Protégé does.

Chapter 1

Introduction

1.1 Topic Introduction

The recent energy crisis as result of geopolitical developments shows the value and importance of energy and energy carriers for modern societies like Germany. In public media, there was a big discussion around dependency on energy carriers form other countries and how energy consumption could be reduced. Not only energy consumption itself, but also related factors such as emission of carbon dioxide, other greenhouse gases, and particulate matter are important, when it comes to the optimization of energy systems. Already ahead of the crisis, many studies looked upon energy consumption and greenhouse gas emission in various sectors, and which technological and political developments would be necessary to reach certain climate goals [1, 2, 3, 4, 5, 6].

In order to predict such developments, energy systems are modeled using various kinds of tools and frameworks. The next chapter provides a short overview over the variety of models and frameworks. There are even publications that focus on the comparison of different frameworks or tools [7, 8, 9, 10, 11].

As manifold as energy systems and purposes are, as numerous are approaches and terms used in modeling. This is a burden for research in the sense that the exchange of models and model data takes a lot of time. The used terms have to be inspected carefully whether they depict the same notion of information and thus can be compared or if they, although sounding similar, are used for different concepts. This starts already with the usage of terms like "framework", "model", and "scenario" [10]. Because of such issues, automation possibilities across frameworks and tools are reduced and comparing models and their data becomes a time consuming act.

The transport sector is one of the main sectors of energy consumption beneath heating and power generation, building and construction industry, and other industry [1, 2, 4, 5, 6]. In Germany, the transport sector is the sector that needs to achieve the biggest reduction in greenhouse gas emissions in order to achieve the climate goals of the country [3]. In 2019, the transport sector was the sector with the third most emissions in Germany [1].

Because of this importance, various institutes have modeled the development in the transport sector and how it relates to energy consumption and greenhouse gas emissions [1, 2, 3, 4, 5, 6]. A fast exchange of such model data would be highly appreciable, given the before mentioned impact of the transport sector on climate goals. But, because those models use their own vocabulary and views on the transport sector, the comparison of them needs again a lot of time. As a result, the exchange of information at the intersection of energy and transport domain remains difficult and lacks accelerating solutions.

In order to tackle this issue, this thesis proposes a solution for the facilitated exchange of modeling data related to the domains of energy and transport systems by leveraging an ontology. [12] defines an ontology as "an explicit specification of a conceptualization", where conceptualization refers to the formal representation of knowledge. The ontology should primarily serve as a collection of formalized knowledge that data sets can refer to. In the following, such references are referred to as annotations. Figure 1.1 illustrates the annotations as connections between the ontology and the data sets or results. If the data of two models A and B is annotated based on the same ontology, it becomes much easier to compare, combine or exchange them, because the definitions in the ontology are well defined and unambiguous.

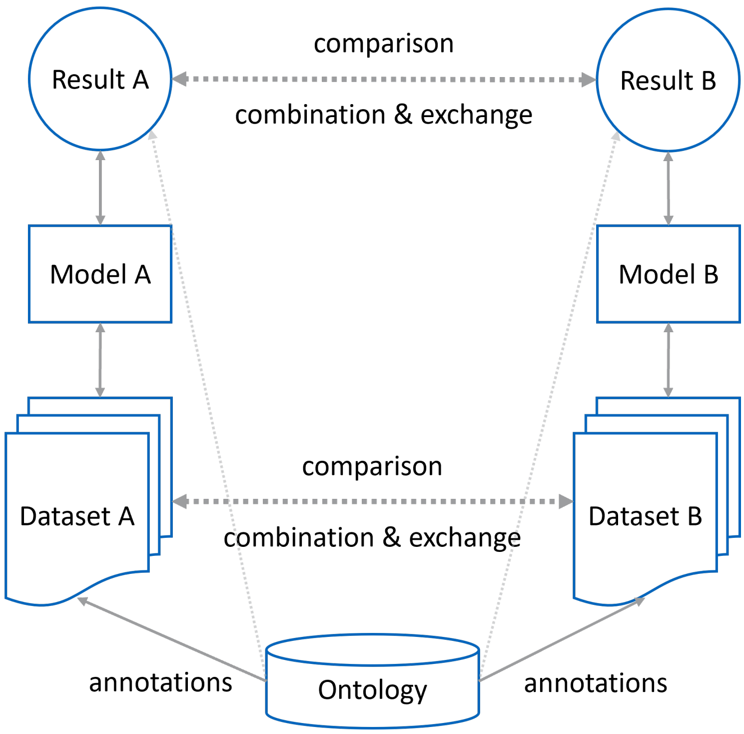


Figure 1.1: Graphical interpretation of the motivation behind this thesis. The ontology should provide a basis for facilitated comparison, combination and exchange of data as input for or result from different models.

1.2 Research Gap

Using the formalized knowledge defined in the ontology for improved data exchange is a central application of an ontology [12, 13]. Therefore, it is not surprising that many fields and use cases try to leverage ontologies. The literature research provides an overview for that. In the domain of energy systems, there are several ontologies that cover different aspects like buildings, smarts grids, or wind farms. Some of them even include concepts from the transport domain, but not in a sufficient manner. Those ontologies are presented in the next chapter. Transport covering ontologies exist as well, but these focus rather on logistics and spatial representation, and less on energy aspects. Those ontologies are presented in the next chapter, as well. An ontology that covers both energy and transport concepts in a sufficient manner is still missing. This leaves the research gap, which is an ontology as a common knowledge basis for both energy and transport systems.

Figure 1.2 provides an illustration of the research gap. Ontologies, energy system modeling, and transport system modeling are the three domains that are involved. Energy system modeling and transport system modeling have an overlap around topics like propulsion systems and infrastructure. Energy ontologies and transport ontologies are at the intersection of ontologies with energy system modeling and transport system modeling, respectively. In the middle, where all three domains intersect, the research gap is located, which is supposed to be filled by an ontology about transport systems with energy focus.

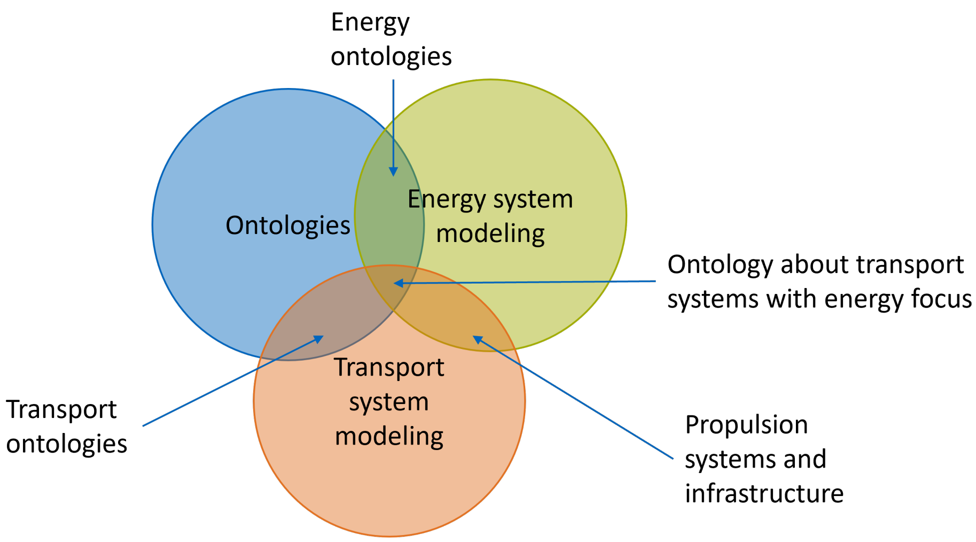


Figure 1.2: Research gap at the intersection of ontologies, energy domain and transport domain.

1.3 Novelty

This thesis tries to close the research gap by developing an ontology that focuses on the dependencies between transport and energy domain. To achieve this, an existing energy domain ontology is extended by concepts from the transport domain. The energy ontology of choice is the Open Energy Ontology (OEO). It is a general energy ontology, which means that it is not tailored to a specific application, and it is openly developed, allowing an easy contribution. The OEO is introduced in more detail in the next chapter. Extending an ontology, rather than building a new one, is preferred, because it avoids to "reinvent the wheel" and builds on knowledge that other experts already have agreed upon. This way coherence with existing terminology is ensured, thereby the chances for acceptance and further extension by users are hopefully increased. The choice to extend an energy ontology rather than a transport ontology is justified by the overarching topic, which is energy system modeling and not transport system modeling.

1.4 Research Questions

1.4.1 How is the transport sector represented in scientific literature?

The first research question is to understand how the transport sector can be described. For that, it is necessary to look at the used models and terms in these models. The following sub-questions support finding common descriptions:

- Which terms and classifications are used to describe the transport sector?
  Common ways of characterization should be identified.
- Which measurements are used to describe the transport sector?
  Common types of data collections should be identified.
- Which models are used to describe the transport sector?
  Similarities between models should be identified.

1.4.2 How can the transport sector be captured in an ontology from an energy perspective?

The second research question aims at finding a promising way to integrate the knowledge obtained from research question one into an ontology by taking an energy perspective. Several sub-questions help to achieve that by addressing crucial points:

- Which concepts are relevant for capturing the transport sector from an energy perspective?
  Only concepts that concern both energy and transport domain should be included.
- Which relations are relevant for capturing the transport sector from an energy perspective?
  Only relations that concern both energy and transport domain should be included.
- How can concepts and relations be defined such that they are consistent with existing terminology?
  New terms should not lead to contradictions with existing terminology and should avoid renaming common terms.

- Which level of detail is suitable for modeling the transport sector from an energy perspective?
  Only such details that are relevant for a large portion of both sectors should be included.
- How can different views on the same entity be modeled?
  The energy perspective should be the dominant view. If there is a necessity to include another perspective on the same entity, it should be subordinated.
- How can ontologies help with the representation of complex dependencies?
  Possibilities of ontologies such as equivalence axioms should be exploited to depict complex dependencies.

1.5 Structure of this Thesis

This thesis is partitioned into six chapters with different focus and purpose. All webpages that are linked in this thesis were last retrieved on January, 10, 2023.

Chapter 1, this introduction, shows the scientific context and the overarching goal that this thesis contributes to. In more detail, the purpose is clarified with the research gap that should be closed and with the novelty of this thesis. Furthermore, the research questions and their motivations are introduced. Lastly, the introduction presents this outline of the thesis.

Next, chapter 2 examines the current state of the art in modeling the energy and the transport domain in scientific literature. It also introduces ontologies in more detail and investigates existing ontologies for the energy and the transport domain respectively. Furthermore, it delimits this thesis from existing work and highlights useful input from the literature.

Chapter 3 presents the approach for developing the ontology concepts, the final definitions for them, and how the implementation process took place.

Following that, chapter 4 takes a look at possible applications. These are in particular the annotation of data sets and the generation of scenario assumption data from text.

Second to last, chapter 5 discusses difficulties during concept creation and application, limitations and restrictions of the ontology, and assumptions that were made for the applications. Furthermore, it provides a comparison of the implemented concepts to the first drafts of the approach and evaluates the research questions.

Lastly, chapter 6 summarizes the work of thesis including results and findings, and provides an outlook on possible further research.

In addition, the appendices provide supporting material. Appendix A explains some software related problems that occurred and how to solve them, and appendices B and C display an overview over the contributions of this thesis to the OEO.

Chapter 2

State of the Art

2.1 Literature Research Approach

The aim of the literature research is manifold. First, it collects literature that helps with gaining the knowledge necessary to answer the research questions. Second, it explains the distinction of the work in this thesis to previous work with similar aims. And third, it shows how the approaches and results of related work can be utilized for the approach in this thesis. Furthermore, this chapter introduces technological artifacts that will be used in the approach and explains their relation to scientific work.

In order to achieve these goals, the literature research is split in several parts addressing each of the main parts of this topic. There is one section for ontologies, one for the energy domain, and one for the transport domain. Furthermore, there is a section for the intersections of these areas, that is, energy ontologies and transport ontologies. The intersection for energy and transport domain is omitted for two reasons. First, it is easy to attribute a paper that would fit in the intersection to either one domain. Second, the focus of this thesis is on how knowledge of both domains can be integrated in an ontology.

As keywords for literature research, "energy system", "transport system", "energy domain", "transport domain" and more detailed "energy domain knowledge", "transport domain knowledge", "energy system modeling", and "transport system modeling" were used. Only results from recent years were included except for primary sources that were referenced by one of the search results.

2.2 Ontologies

Ontology definition

Ontology in a philosophical sense is a field of science that deals with questions about existence, structures and relations of entities [14]. In the field of information science the term is used more narrowly and may be compared to a database with additional information [15]. [16] investigates the differences between ontology in philosophy and information science. In their notes they mention that the definition by [12], presented in the introduction, seems to be the most influential one. There is an updated version, in which two key aspects of an ontology are highlighted. These are the representation of concepts and their relations, and the definition of these, which attributes a meaning to them[13].

When diving into the topic of ontologies, at some point the term *knowledge graph* will appear as well. The definitions vary and are not always clear to distinguish from ontologies [17]. In any case, an ontology as a knowledge base is an integral part of a knowledge graph [17], seen in their definition "A knowledge graph acquires and integrates information into an ontology and applies a reasoner to derive new knowledge." The authors of [18] view an ontology as something that formally represents terms and defines their meaning. According to them, knowledge graphs that use the same ontology have a higher interoperability. They also provide an extensive discussion of various aspects of knowledge graphs.

Web Ontology Language

There are several languages or frameworks that can be used to implement an ontology. Perhaps the most popular one is the Web Ontology Language, which is introduced in the next paragraph. Another interesting language is the distributed ontology, modeling and specification language (DOL) which tries to combine ontologies written in different ontology languages [19].There are also languages for specific domains like OntoDB/OntoQL for the domains of vehicle manufacturing and CO_2 storage [20].

The Web Ontology Language (OWL[1]) [21] is a description language for web documents developed by the World Wide Web Consortium (W3C) as a revision of older semantic markup languages. In terms of functionality and expressiveness, it is the fifth layer based on the layers RDF Schema, RDF, XML Schema, and XML, where the latter is the lowest layer. OWL formalizes ontologies such that the meaning of terms and their relationships can be further processed. Machine readability and automatic reasoning are mentioned as driving motivations behind the development of the language. There are the three dialects with decreasing expressiveness: OWL Full, OWL DL and OWL Lite. Furthermore, OWL is superseded by OWL 2, which adds slightly more expressiveness. In the following, when talking about OWL, full OWL 2 expressiveness is assumed.

For RDF based languages like OWL, there are several syntax in which the ontology can be written. These do not change the content of the ontology. Probably the most important ones are RDF/XML [22], Manchester Syntax [23], and Turtle [24]. As the name suggests, RDF/XML is an XML-based syntax. It is used on the OWL websites for explanations and examples, but lacks readability for larger projects. Therefore, the Manchester syntax became popular. It has better readability, because it gets rid of the typical XML structure. The Turtle syntax uses triples that follow a natural language-like structure, that is, subject-predicate-object, and avoids redundant usage of names.

[1] The acronym is indeed OWL, not WOL. For an explanation see `https://lists.w3.org/Archives/Public/www-webont-wg/2001Dec/0169.html`.

Basic Formal Ontology

The Basic Formal Ontology (BFO), first published in [25], is an upper ontology that tries to provide a structure in which all possible entities can be categorized. It divides the entities into *continuants*, roughly speaking temporally persistent entities, and *occurrents*, temporally occurring entities. *Continuants* are further divided into *independent continuants*, *specifically dependent continuants* (dependent on one specific independent continuant), and *generically dependent continuants* (dependent on the existence of at least one independant continuant of a certain type). The *occurents* are separated into *processes*, *process attributes*, and *temporal regions*, which are quite self-explaining.

There are many other upper or top-level ontologies such as DOLCE [26] or SUMO [27]. Such ontologies aim not necessarily at a universal depiction of entities. Some of them can already be targeted at a certain area. However, a more detailed structure for a domain belongs to so called domain ontologies that may use an upper ontology. The main idea is, not to "reinvent the wheel" that is, build upon the work others have done instead of redoing it. For the same reason, the integration of domain ontologies into each other can also be beneficial. A good example is a very specific ontology like the Unit Ontology (UO) [28] , which is also imported in the OEO.

Literature Research

The popularity of ontologies is growing and their application areas are getting more. Recent examples of application domains are cloud computing, where ontologies are used for automatic creation of container images [29], predictive maintenance for manufacturing systems [30], and the materials design domain [31]. Another example is the food and nutrition domain [32], which still struggles with knowledge exchange [33]. An application area that seems to be quite far away from technological research is mental health, where wearables are connected via the web to a knowledge base for emotions [34]. Further application areas are building information modeling [35], real estate business [36], didactic tools [37], virtual reality training [38], business cases [39], mechanical joining [40], and sustainability assessment [41].

Targeted even more towards data exchange and interoperability, the work by [42] uses a knowledge graph to integrate climate data from multiple data sources for analysis. Similarly, [43] uses an ontology that manages decentralized data for household appliances. In a more general fashion, [44] compares several mechanisms for ontology based data integration.

As pointed out by [45], creating ontologies is a time consuming act and, therefore, they present various approaches for faster ontology creation. With the same goal, [46] applies techniques from software product lines for ontology design.

There are also use cases where ontologies and their description languages are not the most suitable. [47] performed a systematic literature review to evaluate specification techniques for domain knowledge. They specifically excluded ontologies from that review with the justification that they are not more expressive than most of the domain modeling languages.

Ontologies as a way of knowledge representation and data annotation are related to the field of data science and artificial intelligence. In the "Report on the Department of Energy (DOE) Town Halls on Artificial Intelligence (AI) for Science" [48] the research opportunities in that domain for the next decade are outlined. The requirements for improved research are also mentioned. It says "participants highlighted the need to incorporate domain knowledge into AI methods to improve the quality and interpretability of the models" [48] which could at least partially be fulfilled by leveraging ontologies. Similarly, the work by [49] shows the possibilities of semantic web technologies for explainable AI.

Delimitation

The ontologies from the literature research so far do not cover energy or transport domain explicitly. A few of them include single concepts related to energy or transport, but are too shallow in that regard. Some of them can be extended to serve such purpose, which naturally applies to upper ontologies as they are designed to be extended.

Methodological Utilization

The manifold of application areas shows that ontologies are indeed a suitable way of collecting, organizing, and exchanging knowledge. With regards to content, there is little to utilize from these ontologies because they are too far away from the energy or transport domain. Also, the approaches for faster ontology creation from [45, 46] cannot be used as this thesis extends an existing ontology and does not build a new one. Lastly, the relation of formalized knowledge to artificial intelligence is something to bear in mind, but does not influence the design process per se. The only thing that could hinder the development of AI applications on top of an ontology, is a poor axiomatization of the incorporated knowledge. In other words, the knowledge in the ontology needs to be readable by both humans and machines. This is a core intent of ontologies [12, 13] and thus should be respected in the design process anyway.

2.3 Energy Domain

Literature Research

Many models are targeted towards a certain application or area such as [50] focuses on carbon capture and storage, or [51] focuses on battery energy storage. Energy system models can reach a high complexity as shown in [52], where they also propose an own model for smart grid architecture. Such complexity at times causes the creation of similar models for the same purpose. Therefore, [53] investigates modeling approaches for seasonal thermal energy storage. On a more general level, [54] compared different energy system models on a harmonized data set. They also highlight the advantages of machine-readable metadata.

While the typical perspective for energy system modeling looks at magnitudes of energy, different related views for modeling a possible. For example, the work by [55] looks at energy system models from an investment perspective. The relation between spatial development and energy consumption is put into focus by [56], where the spatial development also goes along with changes in the transport sector. Related to different view points, the work by [57] investigates how energy models are created and how modellers gain their knowledge about energy systems.

There are plenty of frameworks for energy system modeling, such as urbs [58], OEMOF [59] or OSeMOSYS [60], and new ones are continuously developed such as SpineOpt introduced in [61]. To figure out which one is the most suitable, [7] provides a comparison of energy system modeling frameworks and [8] evaluates the usability of such frameworks. For the urban domain, [9] reviews different energy modeling tools. Another review compares energy system models and techniques based on their final results [10]. A different point of view for comparison takes [11] in which energy system models are reviewed looking at flexibility and robustness of the models.

Another reason for the variety of models and frameworks are simply challenges that are not sufficiently solved by other models yet. A topic-wise challenge is the relation of energy systems and climate. Although closely related, [62] points out that there is still a disconnect in modeling, which they try to overcome. A rather technological challenge is the temporal or spatial resolution that too high might not be feasible. Using aggregation as a solution could lead to deviations, which [63] tries to reduce.

There is also research regarding the exploitation of knowledge and improvement of such for the energy domain. As an example, [64] investigate how knowledge exchange and analysis can help reduce energy consumption in construction processes. In another work, the same authors examine the use of semantic networks for the same use case [65]. More broadly, [66] shows the possibilities of knowledge management systems for an incumbent energy company and an energy startup. Similarly, [67] investigates how knowledge infrastructure can help energy related research in general and the transition from fossil to renewable energy sources in particular. Related to the exploitation of knowledge, the field of data science including machine learning has also outreaches to energy data. Work such as from [68] is an example for approaches that try to gain knowledge from analyzing energy data with methods from machine learning.

For the usage of energy within an application, energy efficiency is probably the most interesting aspect. [69] reviews the current developments in that area. A recent example for research about energy efficiency is electrified aviation [70].

Delimitation

On one side, these publications do not include the transport domain in a sufficient manner if at all. On the other side, the literature that addresses knowledge exchange uses different approaches than ontology based solutions. Therefore, this thesis is clearly distinct from these works.

Methodological Utilization

These papers yield valuable insights regarding various aspects of energy system modeling. The first one is that energy system models can have very different application areas and can be based on a variety of different frameworks. This highlights once again the need for a facilitated exchange of data across models and frameworks. The literature also shows how many areas are related to the energy domain. For the ontology enhancement, most core energy concepts (e.g. energy carrier) as well as related concepts of a more general nature (e.g. efficiency) are expected to be already included in the ontology that will be extended.

2.4 Transport Domain

Literature Research

Oftentimes the transport sector is one of several sectors investigated in a bigger study that looks at overarching goals such as climate goals or desired energy transitions. The studies [1, 2, 3, 4, 6] are examples for that. They present several paths for Germany to reach its climate goals in general and in the transport sector in particular. As a basis for many models, [71] presents a detailed review of mobility in Germany.

A broad picture of transport in geographical terms is presented in [72] including relations to other domains. A quite different view takes [73] that examines expertise and strategies for the actual transport processes. They point out how difficult it is to make valid generalizations in the transport domain because of the great number of actors and variety of transport circumstances. Related to that is the choice of suitable measurement methods. For the field of intermodal freight transport systems, [74] compares performance measurement methodologies. Other types of models in the transport sector compare different propulsion techniques and fuels used by them. A popular question is, whether traction batteries or fuel cells are better. [75] compares them for cars and trucks and sees the future in traction batteries.

Not only transport demand, efficiency and resource consumption are interesting for transport modeling. Some models also cover ecological, economical, social and/or political aspects. For example, [76] investigates air traffic and its noise and the costs it causes. [5] and from the before mentioned studies [1, 2, 3, 4, 6] take a political perspective by providing a detailed overview over the transport situation in Germany and/or by providing political recommendations. One step further, the paper by [77] looks at the social, ecological and economic impacts of changes in the transport sector. Sustainable transport in general, specifically logistics, is the goal of a whole research area [78]. For the social dimension of sustainability, [79] investigates how responsible transport can support decision making for sustainable transport. Another way to improve socially sustainable transport is proposed in [80] as a result of a literature research.

Data science and the analysis of large data amounts is also considered in the transport domain. In [81], big data for the field of transport and mobility is investigated in a general fashion. More specific, the review in [82] addresses big data in road freight transport modeling.

Beneath desired outcomes and developments in the transport sectors, there are also developments that are not entirely controllable or will occur independent of targeted actions. The work by [83] predicts changes in the transport sector in Europe until 2030 and categorizes the changes as "highly probable" or "plausible". An example for a development in the transport domain, is the field of carsharing services. [84] performs a literature research to investigate the state of the art in carsharing and research gaps. Similar work is done by [85] for demand-responsive transport services. For such services, [86] proposes a framework for key performance indicator (KPI) prediction. They also highlight the issue of having to integrate data from different domains into this framework.

Delimitation

Energy consumption and efficiency is addressed in a lot of the literature, but except for some bigger studies limited to a narrow scope or a certain application. Efforts to improve data and knowledge exchange are very limited in those works. With the aim to facilitate data exchange, this thesis has a clear distinction to them.

Methodological Utilization

The most helpful literature are the bigger studies, which already take an energy perspective when describing the transport sector. However, the studies use unique divisions for further assessment and accordingly different vocabulary. Contrarily, for the numeric parameters and model outcomes the same units are used. It is also interesting to see how some technologies (or their combination) or further distinctions are neglected in some models in these studies. Presumably, because they are not deemed important enough.

As some of the papers mention, there is more to consider about transport systems than just physical aspects. While some social aspects such as transport demand are of interest, a lot of them, especially political aspects, are not considered in this thesis. The economic perspective is only relevant on a high level as in some things have costs. Which type of cost is actually accurate is more a question of modeling itself than a question of ontology building.

2.5 Intersections

2.5.1 Energy Ontologies

Open Energy Ontology

The Open Energy Ontology (OEO), introduced in [87], will be the basis for the extension in this thesis. It is part of the Open Energy Family that collects various services and research efforts on the Open Energy Platform (OEP). Its main goals are to improve accessibility and collaboration efforts in energy system research. The OEO is openly developed from various experts with a given workflow. It uses the BFO [25] as an upper ontology and includes several domain ontologies. These are the Information Artifact Ontology (IAO) [88], the OBO Relations Ontology (RO) [89], the Unit Ontology (UO) [28], and the OBO Metadata Ontology (OMO) [90]. These provide a lot of basic concepts that are not directly related to the energy domain and thus allow the OEO to focus on new energy concepts. The OEO is written in OWL with Manchester syntax and distributed over several files. The main file, `oeo.omn` integrates all others, including the imported ontologies.

The OEO is used as a basis for the extension for several reasons. First, the OEO is actively and openly developed and thus the results from this thesis can be directly included and used. Second, the OEO is not bound to a specific application but aims at a general representation of knowledge of the energy domain. Thirdly, it includes already many central terms from the energy domain and thus this thesis can focus on the enhancement by concepts from the transport sector. Fourth, as a part of the Open Energy Family, other tools and schemes on the OEP can be used for the annotation of data sets, such as the OEMetadata and the OEMetabuilder. Following that metadata scheme contributes to the central aspect of facilitated data exchange.

Lastly, as a remark for the reader, the OEO uses British English whereas this thesis uses American English following the TUM guidelines for the usage of English[2]. In some cases this leads to different spelling in continuous text, tables, and/or images. For the presentation of new concepts in the next chapter, the spelling in tables and figures is kept consistent with the OEO spelling. In any case, the semantics should always be clear from the context and do not depend on the spelling.

Literature Research

There are several other ontologies that focus on energy terms and concepts. The domain of buildings and homes is more frequently addressed in ontologies than other energy sectors. A recent example is the ontology presented by [91], which focuses on energy system models of buildings and is used for fault detection. In [92], the authors leverage an ontology as part of a virtual city model to enhance interoperability of energy simulations with urban focus. Within the NewOSEIM solution, [93] use an ontology with the aim to decrease the energy consumption in a residential building. Another energy ontology is SARGON, introduced in [94]. It aims at facilitating communication between devices for the Internet-of-Things including

[2] https://www.in.tum.de/fileadmin/w00bws/in/2.Fur_Studierende/Pruefungen_und_Formalitaeten/5.Abschlussarbeit/TUM_The_Use_of_English_in_Thesis_Titles_at_TUM.pdf

buildings and electrical grid automation. Instead of creating an own ontology, [95] extracts common concepts from sixteen ontologies about smart home and smart building based on similarity measures.

There are other energy sectors that use ontologies as well. OntoPowSys is an ontology for power systems used as part of a knowledge management system for an eco-industrial park [96]. In [97] an ontology is developed, which integrates knowledge about co-simulation of software and hardware for smart grids. Also for a specific subfield in the energy domain, [98] developed an ontology for wind farms. An ontology for battery-related knowledge is developed in [99]. Another specialized energy domain is nano-energy, which recently was captured in an own ontology [100]. For nuclear energy, in [101] an analysis of the nuclear energy ontology DIAMOND was performed.

Delimitation

Those ontologies do not cover the transport sector sufficiently, which also holds for the OEO before this thesis. Many of these ontologies are targeted at specific subdomains or applications areas, which is another contrast. Also, the aim of data exchange is not mentioned explicitly for all of those ontologies.

Methodological Utilization

The specific focus of some of the ontologies makes them interesting for a possible integration into the OEO. The lack of transport concepts, on the other side, yields little utilizable insights. Core concepts of the energy domain are already included in the OEO. Therefore, those ontologies are primarily interesting in comparison to the OEO, in which the OEO has several benefits for the enhancement as described in the corresponding section above.

2.5.2 Transport Ontologies

Literature Research

There are not that many ontologies for the transport sector. Most of these focus on spatial or temporal aspects of transport, related to logistics. An example is the ontology from [102], already developed in 2005, which focuses on the representation of geospatial data. The approach from [103] addresses spatial representation as well. They use knowledge graphs for data interoperability while focusing on geospatial modeling including 3d modeling of cities. The ontology for transport networks developed in [104] also focuses on spatial aspects of transport. In paper [105], the "Global City Index Transportation Ontology" is developed. This ontology aims at representing the transportation indicators defined in ISO 37120:18 and allows easy answering of linked competency questions via SPARQL queries. A bit different from the previous ontologies, [106] uses an ontology for a travel bot application with the purpose of identifying and warning of disruptions in transport.

Delimitation

Energy aspects are not included in those ontologies. Some terms imply an energy consumption such as traveled distance or costs, but a consumption concept is not included explicitly. Furthermore, many of them are targeted at certain applications or services.

Methodological Utilization

The ontologies include a variety of useful concepts from the transport domain, although the definitions, if provided, take a logistical view rather than an energy perspective. For certain areas, the level of detail is too deep for energy system modeling, such as fain grained concepts for road segments. Other concepts like timetables and other logistical concepts are not relevant for the energy perspective.

Chapter 3

Approach

3.1 Outline of the Approach

The general approach of finding suitable additions for the OEO that respect the research questions can be outlined with the following keywords: brainstorming, studies, research, adaption, issue, discussion, pull request, and application example. Figure 3.1 illustrates the steps of the approach and their interplay.

At first, a brainstorming was conducted to collect terms without prior influence of any literature. The idea behind that was to prevent getting stuck in a bubble that could have lead to missing out on aspects that are only considered in few works. Furthermore, ideas that lack relevance can easily be dropped.

The second step was to look at a couple of scientific studies, specifically [1, 2, 3, 4, 5, 6, 71, 107], with the aim of gathering commonly used terms in modeling. These studies cover the intersection between energy and transport system modeling very well, which is why they were examined more thoroughly.

In the third step, other literature sources were taken into account, both scientific literature as well as non-scientific but informative sources. An example for non-scientific sources are webpages like wikipedia.org or websites of companies that sell related technology. The scientific literature, including the studies from the previous step, is presented in chapter 2.

These first three steps are not strictly performed one after the other, but rather how it seemed suitable. This lead to a cyclic process as shown in figure 3.1 that only ended once a clear and useful concept was identified. Sometimes during the following steps, it was necessary to further clarify or reevaluate the usefulness of a concept and thus to come back to this assessment cycle of the first three steps.

In the adaption step, the so far found concepts, or rather ideas for concepts, were compared to what was already included in the OEO. It is trivial to say that redundancies should be avoided. This step should also help to figure out, where the new concepts could be added. Together, this may lead to the necessity to go back to the previous steps to work out distinctions and refine the concepts.

Based on the results of the previous steps, a formal definition was suggested in the issue step, that is, creating an issue on GitHub and proposing the new concepts with their definitions and related axioms.

Usually after a certain duration of waiting, the discussion with other OEO developers started. The discussion made sure the terms are indeed useful for the OEO and their definitions and axioms are sound. If necessary, the discussion was brought to one of the regular OEO developer live meetings. Any new input during the discussion was brought back to the assessment cycle (steps 1 to 3) and passed through the adaption step as well, before suggesting and further discussing a change in the same issue (see figure 3.1). This way a proper rework of the concepts was ensured.

In the following step, the approved concepts and their axioms were implemented using the Protégé editor. Then, the implementation was added to the OEO code via a pull request on GitHub that generally needs to be approved by at least one other OEO developer.

After this part of the approach, the application examples were constructed and conducted. As expected, they yielded more ideas for concepts, which were brought back to the initial cycle and followed the usual approach from there (see figure 3.1).

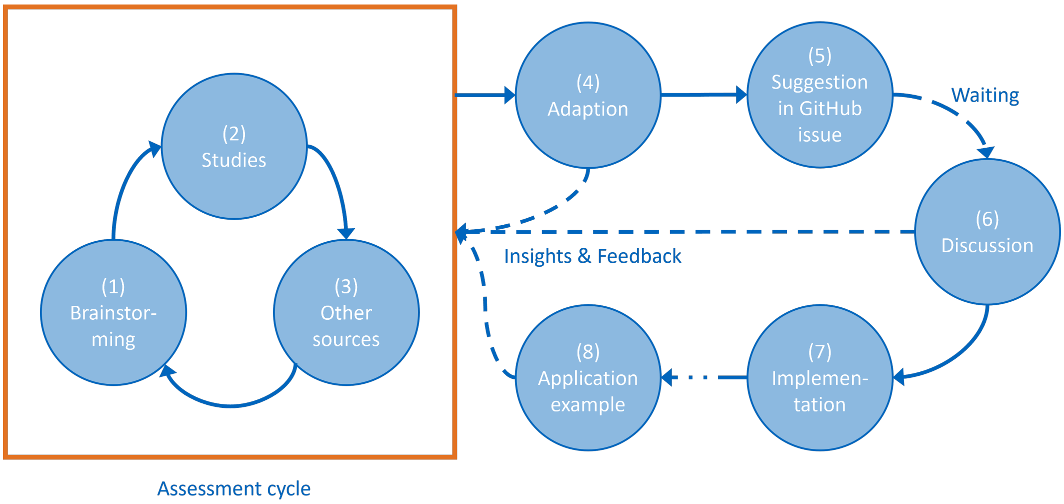


Figure 3.1: Outline of the approach. Steps 1 to 3 form a repetitive assessment cycle leading to a collection of knowledge about about terms used in the transport and energy domain. From steps 4, 6, and 8 feedback is brought back to the assessment cycle.

In order to become better acquainted with the topic, the assessment cycle was conducted at least two times before moving to step 4. The goal of the first iteration was to identify relevant terms for transport modeling without paying special attention to the energy domain. The second iteration had the goal to determine which of the identified terms are actually relevant for energy system modeling. Only after that, the adaption step was entered the first time. For any following concept ideas, arising during discussions or as a result from the application example, this split into without and with energy perspective was obviously not necessary. The main purpose of those separate steps was to get a better understanding of the transport and energy domains in a structured manner.

The concepts were suggested in roughly three batches: various concepts at the beginning, mainly measurement related terms in between, and concepts from the application examples at last. There is no further reference to this, as it is not important for the results. The only reason to mention it, is that some of the rather obvious and/or simple concepts are still in discussion, because they were suggested at a later time.

For the elements and concepts that are introduced in this chapter it might be desirable to have them linked to occurrences in papers, frameworks or other sources. However, the simple occurrence of a term does not imply, that it is a useful term, and the non-occurrence of certain terms does not imply uselessness. This is also addressed in the beginning of the chapter about the application examples. In addition, the OEO should not only capture terms that are relevant for annotating data sets or describing studies and scenarios in the energy domain but also provide an overview over the entities that exist within the domain and how these are related to each other. This includes terms that might not be necessary for applications like in chapter 4, but are still helpful to depict dependencies and mechanisms in the energy domain. Therefore, usually no references to literature are made in the sections below. The terms can be seen as the condensed results from the knowledge gathered by cycling through the approach as described above.

From the following sections and subsections, section 3.2 covers steps 1 to 4 of the approach. Subsection 3.2.1 looks specifically at the first iteration of steps 1 to 3 for transport sector modeling without explicit energy perspective. Subsection 3.2.2 does the same for the consideration of relevant energy aspects. Then, subsection 3.2.3 explains the adaption process for new concepts during step 4.

Following that, section 3.3 presents the results of steps 5 to 7, that is, the actual definitions of the new concepts, how they were integrated in the OEO, and, if applicable, which axioms were added. Because not all concepts were implemented or even discussed yet, the section is split into subsections 3.3.2, where the concepts are actually implemented (step 7), and 3.3.3, where the concepts are either just suggested (step 5) or in discussion (step 6).

In the last section of this chapter, 3.4, the implementation process of step 7 and underlying technology are explained in more detail. Lastly, whole chapter 4 introduces and explains the application examples and highlights the new concept ideas arising from them (step 8). The concepts are, however, already presented in section 3.3 together with all other concepts.

3.2 Methodological Utilization

3.2.1 Transport Sector Modeling without an Explicit Energy Perspective

As first part of the approach, the three steps of the assessment cycle were performed to identify common elements in models of the transport sector without considering relevance for energy modeling. The identified elements are in particular *vehicle types*, *transport types*, *infrastructure*, *operational environment*, *energy carrier for propulsion*, *operational mode*, and *measurement values*. For each of these elements, except *measurement values*, taxonomies, which provide a further refinement, were built, as shown in figures 3.2 to 3.7. In addition, the relations of the elements to each other and to selected measurement values were assessed. The result of that is shown in figure 3.8.

The first element is *vehicle types*, which describes the vehicles that are used for transport. An example structure is given in figure 3.2. The first layer differentiates between water, ground, rail and air vehicles. The water vehicles are further distinguished by their purpose, that is, to transport passengers, to transport freight, to provide a certain utility, or to be used privately, e.g. for recreation. The ground vehicles are separated by traction mechanism into wheeled and tracked vehicles. For the wheeled vehicles, the number of wheels is another criteria. The rail vehicles have a flat further hierarchy. Only ordinary trains are distinguished by their purpose, which goes along with the travel distance. Lastly, air vehicles are distinguished by propulsion type: Airplanes with jet or propeller engines, helicopters, ballons, zeppelins, and rockets.

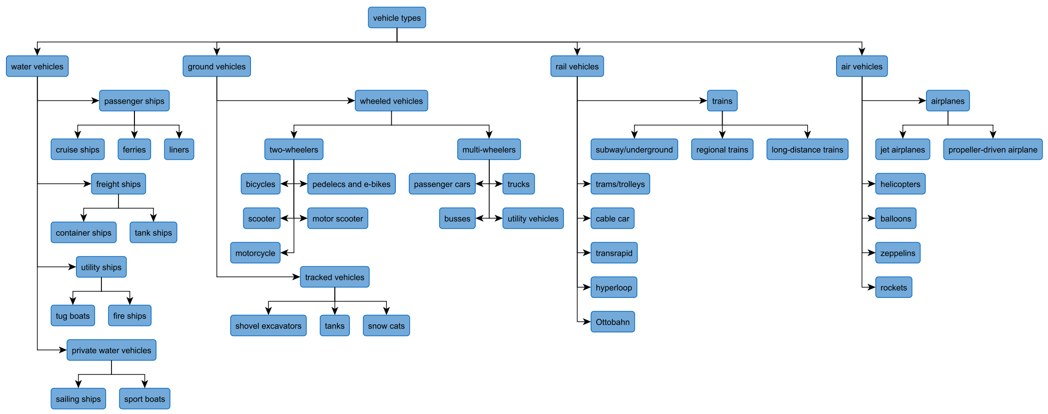


Figure 3.2: Hierarchy for vehicle types without energy perspective.

The next element is *transport types*, which describes purpose and circumstance of transport processes. It distinguishes between passenger transport, freight transport, and utility transport. For passenger transport private cars, rail, air, and public road transport are the most prominent forms, together with cycling and walking. Freight transport separates further by environment: road, rail, water, and air. For freight transport on roads, the allowed load of the vehicle is a further criteria, and for shipping the transport on inland waterways and across oceans is distinguished. The utility transport is separated by vehicle into emergency vehicles and vehicles for other specialized purposes. The structure for the transport types is shown in figure 3.3. For the utility transport more than for the others holds that these are only examples and not a complete list of possibilities. This also means that passenger and freight transport only show the at this point relevant concepts.

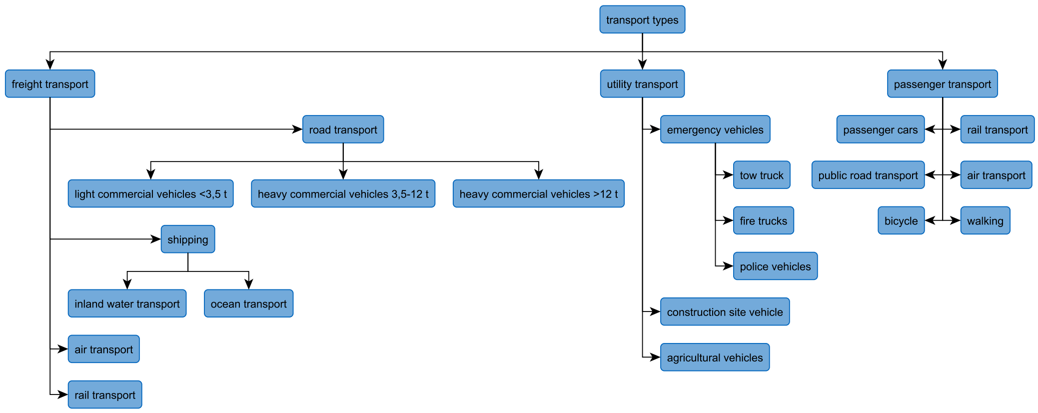


Figure 3.3: Hierarchy for transport types without energy perspective.

The structure for the next element, *infrastructure*, is depicted in figure 3.4. The main distinction is between connections and places. Connections are elements like roads, rails and canals. Places are further divided by purpose into range extension and transfer / further transport. Infrastructural elements besides charging stations and specialized filling stations are not mentioned a lot in literature. That is probably, because the existing infrastructure supports traditional transport already very well and literature focuses on new infrastructure. Furthermore, some infrastructural elements like waterways cannot simply be built in the middle of nowhere but require a supportive natural environment like a river. In a country like Germany, it is to assume that there is little environment left for such types of infrastructure.

Next, *operational environment* is structured as shown in figure 3.5. Similar to infrastructure, only few of the shown terms are used in literature, usually in combination with a transport type. The most common concepts are land, water, and air on the highest level, and road and rail networks on the lowest level. For water environments, it is sometimes distinguished between open sea, coastal regions, rivers, and inland lakes.

Another element is *energy carrier for propulsion*. Although undoubtedly central for an energy perspective, energy carriers are of such a general nature and importance for the transport sector, that they should be addressed already here. The structure, shown in figure 3.6, distinguishes fossil energy carriers, natural energy carriers, electricity, hydrogen, e-fuels and related terms, and mixed energy carriers. Fossil energy carriers are further divided into oil-based, natural gas-based, and coal-based. The natural energy carriers are separated into wind, thermodynamic

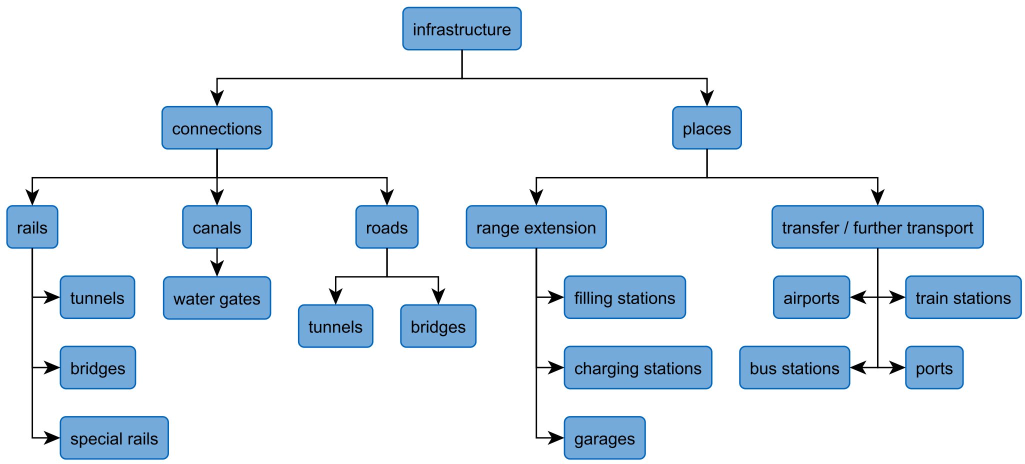


Figure 3.4: Hierarchy for infrastructure without energy perspective.

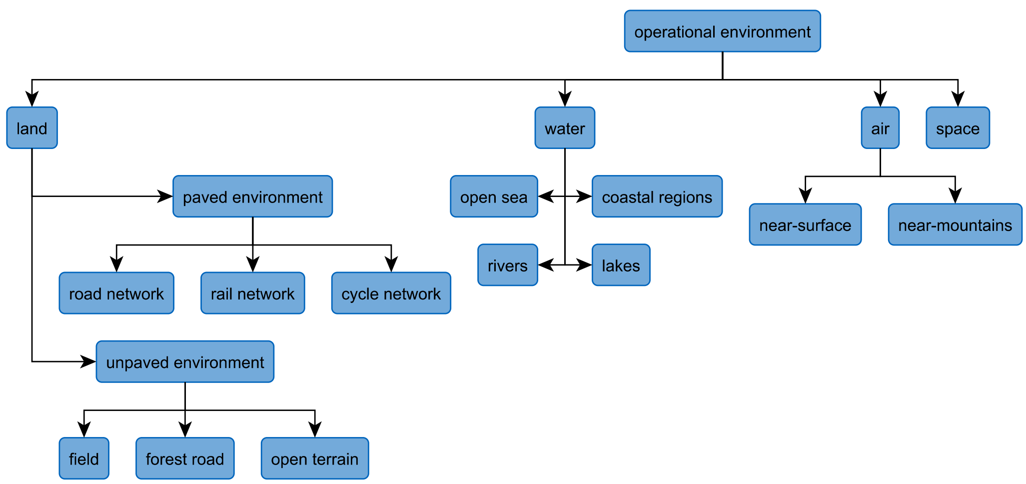


Figure 3.5: Hierarchy for operational environment without energy perspective.

currents, sunlight, and muscle power. For electricity, it is distinguished between stored electricity and directly supplied electricity via induction or power line.

The last taxonomy is about *operational modes*. The structure is comparably small as figure 3.7 shows. The main distinction is between human control and autonomous control. Human control can be further divided into individual control, central control, or multi-person control. In literature, the operational mode is usually neglected. Perhaps, because further consequences of autonomous control cannot accurately be predicted yet [1].

For the last element, *measurement values*, it is hardly suitable to build a taxonomy, because of the great variety of interesting values. In this context, measurement values refer to any quantity values that may be measured or calculated and depict an aspect of the transport domain. The probably most prominent values are transport

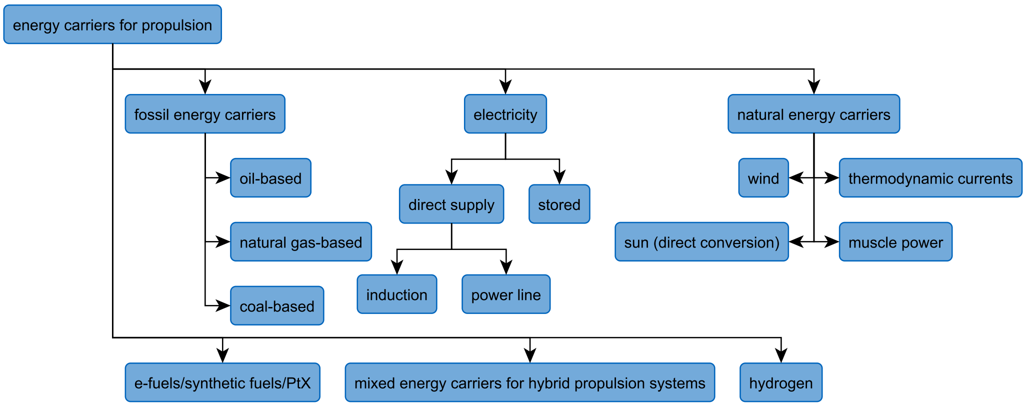


Figure 3.6: Hierarchy for energy carriers.

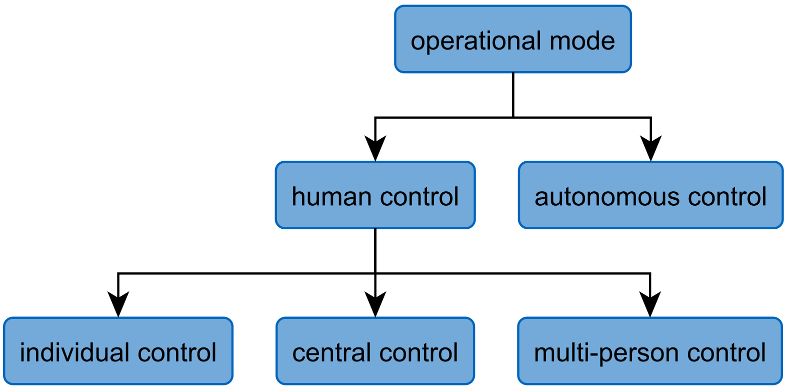


Figure 3.7: Hierarchy for operational mode without energy perspective.

demand or performance values measured in passenger-kilometer or ton-kilometer. Another important measure is the number of certain vehicles or their share in comparison to the whole fleet in a scenario. For infrastructure, values such as the size of a road network or the number of charging / filling stations are interesting. Already relating to the energy domain, consumption and emission values are to be considered as well. There are many more possible measurement values. Especially, specific values that relate two values like energy consumption per traveled distance or a share of vehicles can be needed and created in any arbitrary form. Therefore, it will not be possible to address all of them.

Figure 3.8 shows the relations of the introduced elements. There is a close relation between vehicle type and transport type as the vehicle participates in some transport and the transport depends on a vehicle. Transport has also a performance value. A vehicle type has a certain operational mode, moves in a certain operational environment, uses some infrastructure, and uses energy from a certain energy carrier. Furthermore, a vehicle contributes to a share of vehicles. The consumption of the energy carrier can be measured and leads to emissions. The operational environment influences the possible operational modes and the necessary infrastructure. The infrastructure in turn influences the operational mode as well and is needed to get energy carriers to the vehicles. Infrastructure is furthermore measured by values such as to the size of traffic networks and the number of charging and filling stations. The last measurement value included here is cost, which depends on vehicle type, infrastructure, emissions, and consumption values.

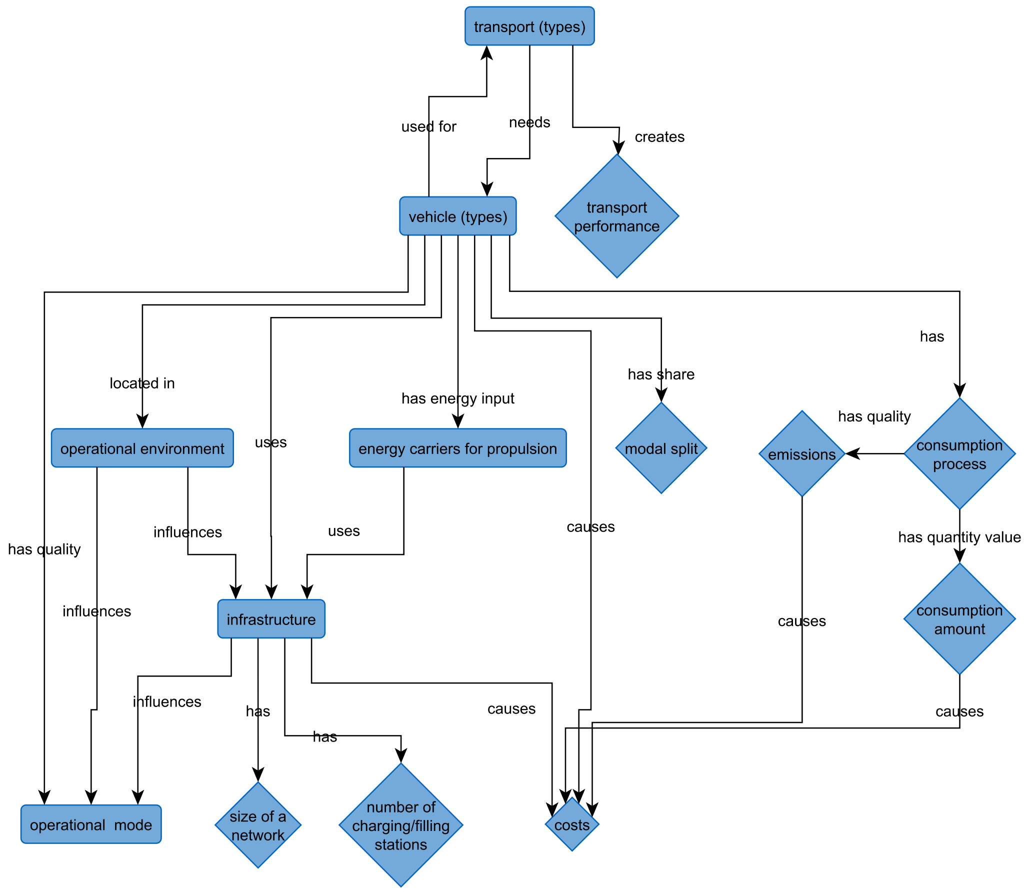


Figure 3.8: Visualization of the relations between the elements. Diamonds are examples for measurement values. Consumption process, although diamond-shaped is not per se a measurement value but a prerequisite for emission and the consumption amount to measure.

3.2.2 Model Adaption under Consideration of Relevant Energy Aspects

In this step, the knowledge from the previous step is assessed regarding its relevance for energy system modeling. This is done by going through the cycle of the three first steps of the approach and omitting, restructuring or refining elements. In addition, the relation of the elements to the energy domain are investigated.

The basic relations to the energy domain are already shown in figure 3.8. These are in particular the connections between vehicle and energy carrier, and energy carrier and infrastructure. The vehicle needs some sort of energy supply, which is provided via infrastructure. This can be directly via a power line or indirectly via an energy carrier like gasoline or an energy storage like an electric traction battery. Therefore, the supply related infrastructure like charging or filling stations is particularly interesting for the energy perspective. A vehicle is also involved in an energy consumption process which consumes a certain amount of energy and leads to a certain amount of emissions. These two measurement values are probably the two most important ones in the energy domain. As described in the introduction, the reduction of energy consumption and greenhouse gas emissions are important to reach desired climate goals.

When shifting the focus to energy aspects, the interplay of energy consumption and vehicles becomes a central aspect. Therefore, the suitable terms from the taxonomies about vehicles types, transport types, operational environment, and energy carrier were integrated into a single graph. This graph should provide a combined hierarchical structure for transport instead of having different views in a silo-like structure. Infrastructure, operational modes and measurement values are not integrated into the graph, because literature showed that they are less important for structuring transport. The graph follows this structure from highest to lowest level: transport type, operational environment, vehicle type, energy carrier. For better visibility, the graph was split into two graphs on the highest level. The first one addresses passenger transport (see figure 3.9), the second one concerns freight transport (see figure 3.10). The complete graph can be found in the appendix (see figure B.2).

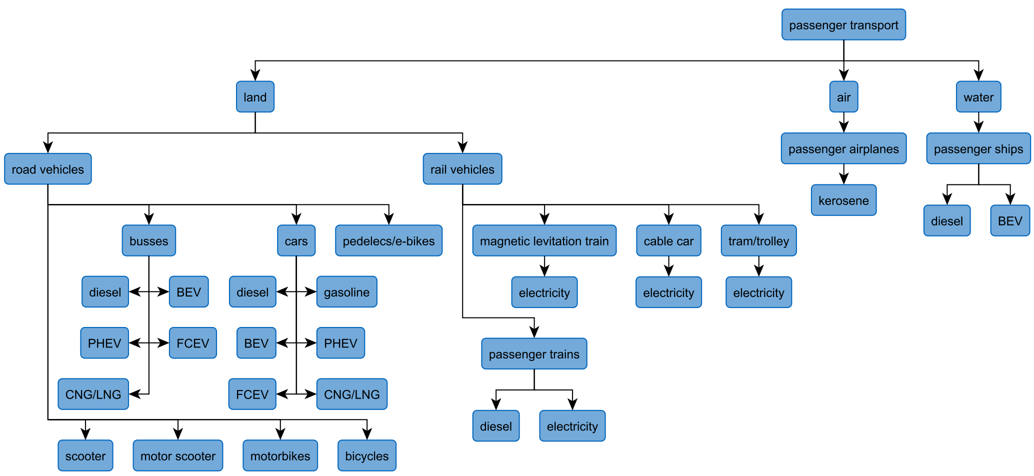


Figure 3.9: Hierarchy for passenger transport from an energy perspective.

Other than this concentrated structure of transport, this step was kept short. Any more extensive structuring might be in contradiction to the structure of the OEO and thus could require rework. Beneath the structure, the level of detail that is desired by the OEO could differ from the usual literature, as well. Therefore, to avoid

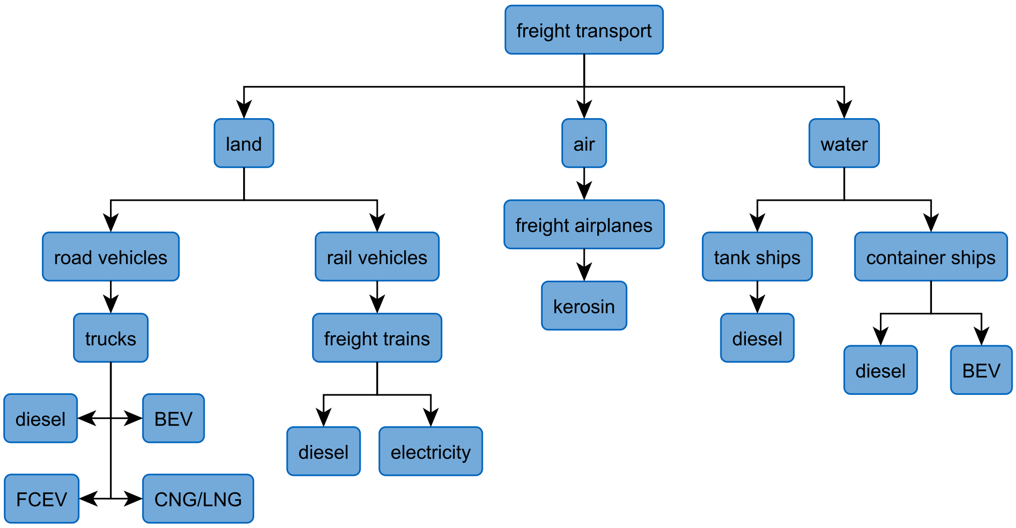


Figure 3.10: Hierarchy for freight transport from an energy perspective.

redundant work, it was directly proceeded with the adaption to the OEO.

3.2.3 Comparison and Adaption to the Open Energy Ontology

The previous steps lead to a collection of knowledge about elements that are important for both transport and energy system modeling and the relation of these elements. Based on that, possible connection points to the OEO are reviewed. Additionally, implications and demands on the structure of the knowledge are investigated, that is, which classifications are already included in the OEO, and how new terms should be structured.

There were already some concepts that touch the transport domain included in the OEO, before the contributions of this thesis. The probably most important ones of these are *transport*, *vehicles* and *motors*, *energy carriers* and *energy (service) demand*, *consumption process* and *consumption value*, and *emission*. The original structure of these are shown in figures 3.11 to 3.17, respectively.

Transport is a process in the OEO with the three subclasses *freight transport*, *passenger transport* and *international transport*. Passenger transport is further divided into private and public transport (see figure 3.11). There are plenty of options to enhance this with concepts that respect the type of vehicle or the environment. The difficulty here will be to select and agree on the most suitable ones.

For the vehicles, there are already *diesel vehicles* and *gasoline vehicles* as subclasses of *internal combustion vehicle*. Furthermore, there are *battery electric vehicle*, *fuel cell electric vehicle* and *grid supplied electric vehicle* as subclasses of *electric vehicle*. Lastly, there is *plug-in hybrid electric vehicle* (see figure 3.12). This structure from type of engine to used energy carrier suggests to ignore non-

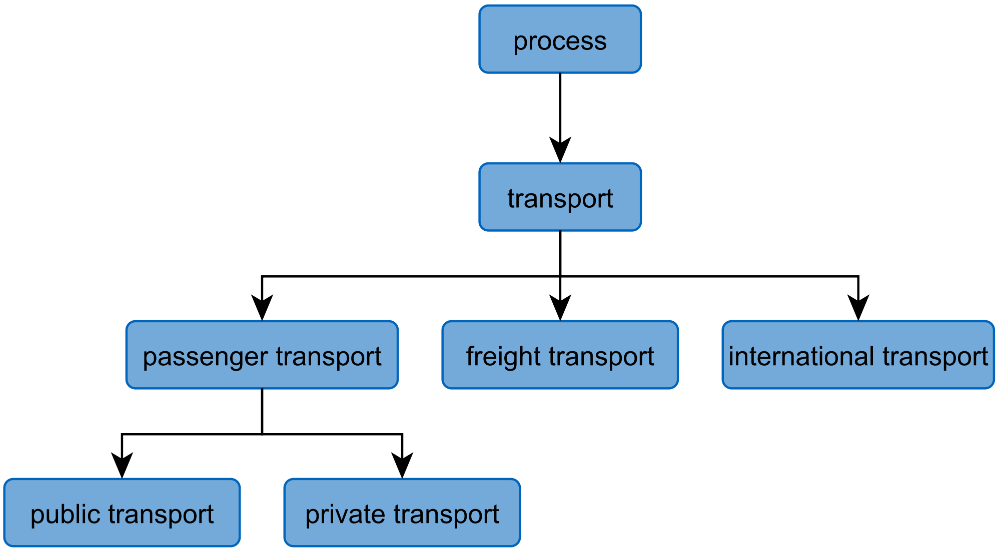


Figure 3.11: Transport in the OEO before new concepts were added.

energy descriptions of vehicles. New concepts like CNG or LNG vehicles could be added under internal combustion vehicle. For vehicles that use turbines, a new subclass should be created.

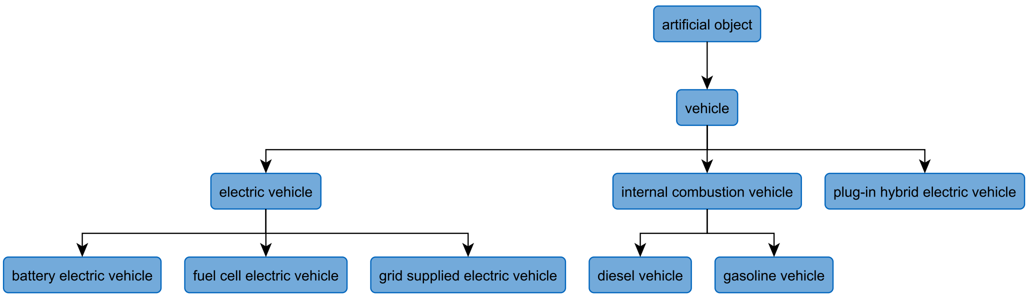


Figure 3.12: Vehicles in the OEO before new concepts were added.

There is a notable analogy from vehicle to *motor* as shown in figure 3.13. Noteworthy is the traction motor concept, which is necessary, because a motor may be used for another purpose than propulsion as well. As a possible extension, a gas engine may be added under internal combustion engine.

The list of energy carriers in the OEO includes already the most relevant ones. Possible additions are liquefied petroleum gas (LPG) and compressed natural gas (CNG). There is no specialty to the structure of these as they simply belong to *portion of matter* in the OEO, specifically to *gas mixture*. However, it is worth to note that the OEO distinguishes between different types of energy carriers (primary, secondary, final, and renewable; see figure 3.14), even more energy carrier

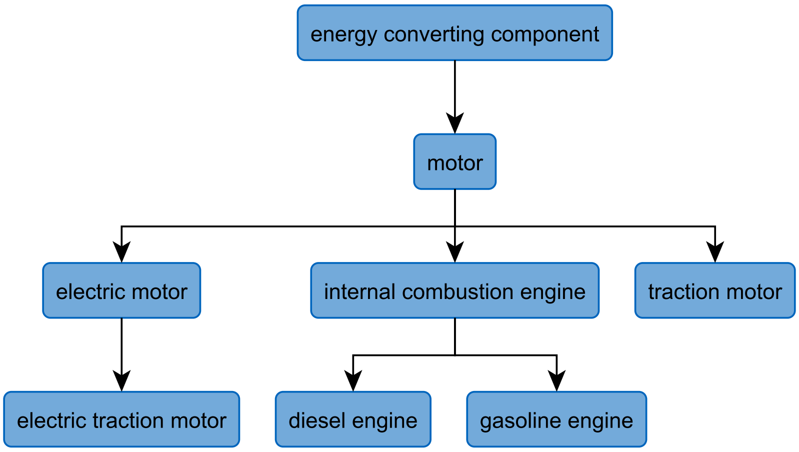


Figure 3.13: Engines in the OEO before new concepts were added.

dispositions, fuel, and fuel roles. The main idea behind that is to attribute a portion of matter with an energy carrier disposition and/or a fuel role and then infer it as energy carrier and/or fuel. This prevents an overly complex hierarchy under portion of matter and allows a simple addition of new concepts. A good example is the addition of LPG and CNG. They should be placed somewhere under portion of matter and be attributed with both a fuel role and a combustible energy carrier disposition. This way they would be inferred as both an energy carrier and a combustion fuel.

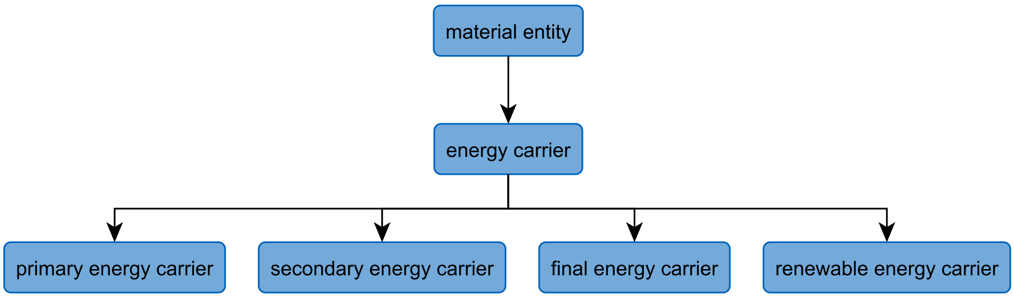


Figure 3.14: Energy carriers in the OEO before new concepts were added.

For the demand of energy, the OEO distinguishes between *energy demand* and *energy service demand* as displayed in figure 3.15. The first one refers to a direct demand of energy, while the latter refers to the demand of a service that in turn needs energy to be provided. Energy service demand has two subclasses for passenger- and ton-kilometer and needs no further concepts. Energy demand could be further refined by specifying energy carriers that are demanded like fuel or electricity.

The consumption process in the OEO distinguishes between energy and non-energy use of energy carriers, that is, whether the carried energy is leveraged

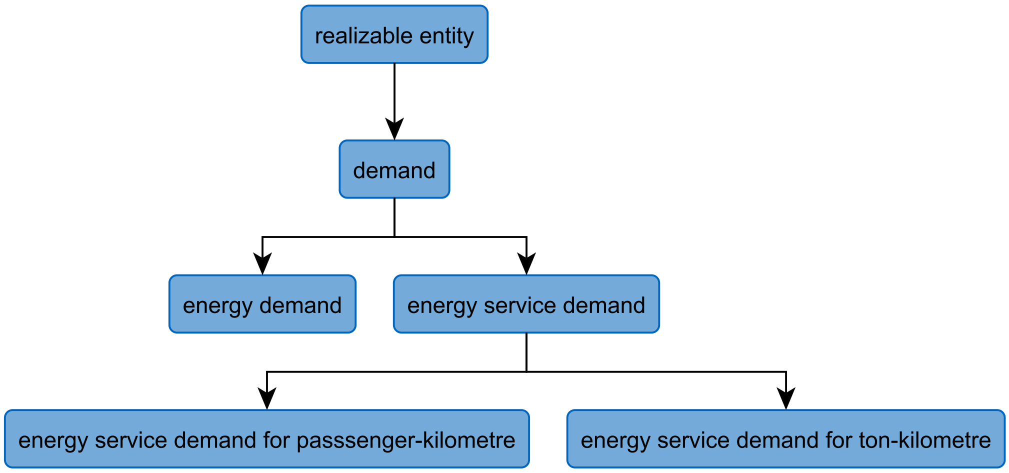


Figure 3.15: Energy demand in the OEO before new concepts were added.

during consumption (see figure 3.16). It should not be mistaken with energy transformation that addresses changes of the energy type or of the location of an energy carrier without reducing the total amount. For the quantification, there is the energy consumption value as a specialized energy amount value. For any specific energy consumption values this might be a suitable connection point.

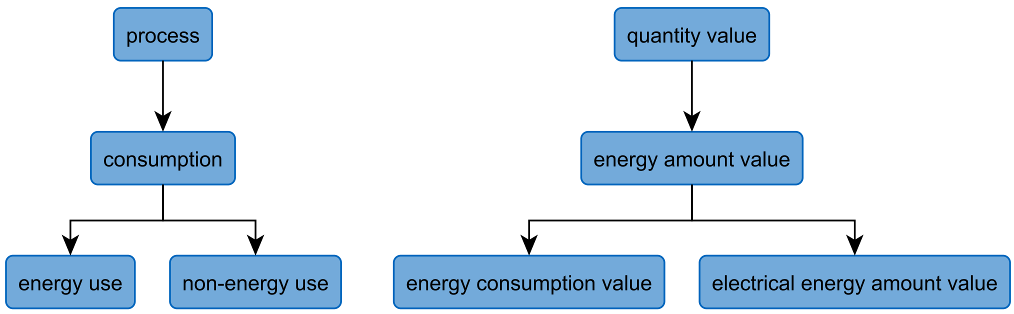


Figure 3.16: Energy consumption in the OEO before new concepts were added.

Emission is not just a value but another process in the OEO (see figure 3.17). It has the subclasses CO_2 emission, greenhouse gas emission, and pollution. These are linked to emission factor and emission value, which are process attributes. Emission value has again subclasses CO_2 emission value and greenhouse gas emission value. These are linked to emission quantity value. For relative emission values, this could be a suitable extension point, but otherwise the topic of emission is already very well covered by the OEO.

Infrastructural elements from the transport domain were not present in the OEO at that point. They could be added under artificial object or under object aggregate depending on whether a single object like a building or a single road is meant, or

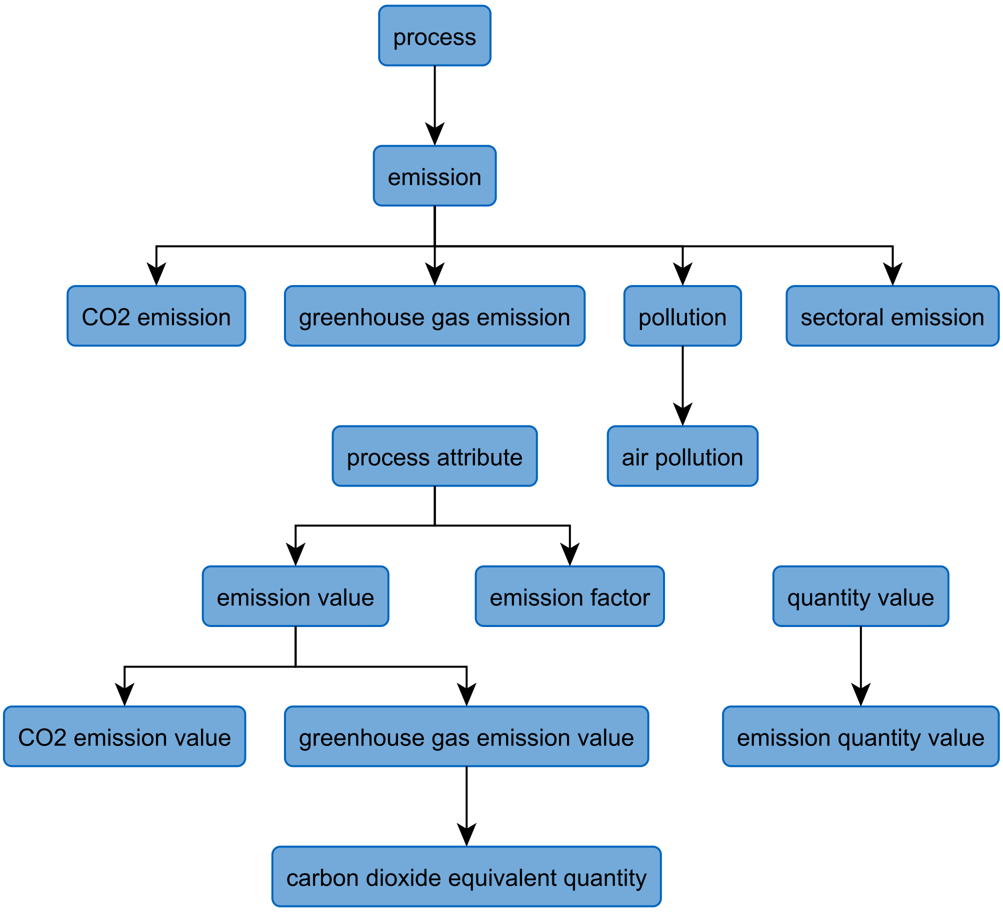


Figure 3.17: Emission in the OEO before new concepts were added.

a network of roads, for example. Since there are already infrastructural elements from other domains like electricity generation in the OEO, no problems are expected with the addition of infrastructure from the transport domain.

Operational modes were not present in the OEO either. Since they are bound to a vehicle and may be changed during operation, the specifically dependent continuant class from the BFO seems to be a suitable superclass. A possible point for discussion with other OEO developers could be the level of detail.

For measurement values, there are two common places to introduce them in the OEO. The first one is as a quantity value in the hierarchy below the BFO concept generically dependent continuant. The second one is as a process attribute hierarchically under the BFO concept occurrent. The main difference is whether the measurement value is bound to a process. At times it can be difficult to determine whether that is the case, and oftentimes the process attribute is related to a quantity value anyway (like the emission value above).

Which concepts are actually included in the OEO, and where, is also a result of the discussion. With the ideas from the approach so far in mind, new concepts were suggested. The results of the following discussion or the suggested concepts, if not implemented yet, are presented in the next section.

3.3 Definition of Concepts and Relations

3.3.1 General Remarks

In the previous steps, relevant concepts were identified and where they could be added to the OEO. In order to integrate them into the OEO, a formal definition is necessary. Finding a good definition can be very difficult and always depends on the point of view and the context. It would be possible, for example, to define objects by their appearance, their functionality or purpose, their origin etc. The OEO guidelines recommend to use Aristotelian definitions wherever possible[1]. These definitions follow the scheme *an X is a Y that Zs*. In other words, X is a subclass of Y that has the characteristic Z. This characteristic Z is used to distinguish X from other subclasses of Y. Since the OEO is an energy ontology, the preferred way to distinguish concepts is by energy aspects. If there is no such suitable distinction, functionality is the next best decider. In any case, it is also recommended to keep the definition simple and easily understandable.

As mentioned in the outline of the approach, not all suggested concepts have been implemented yet. For this reason, the concept presentation is split in two subsections: one for the implemented concepts, which passed step 7 of the approach, and one for the suggested concepts, which passed step 5 and either are in discussion or are waiting for it. Furthermore, only concepts that have been implemented by myself are included. Contributions to other discussions around the OEO, like vehicles categorized by type and not propulsion, and gas turbine vehicles, can easily be found on GitHub[2].

The presentation of the new concepts will follow the grouping of concepts used for the GitHub issues, with two small and indicated exceptions. The corresponding issue and pull request, if existent, are provided in footnotes. This makes it easier for the interested reader to follow the discussions in which the definitions and axioms were created. More about the implementation process and the role of GitHub can be found in the corresponding section below. While the connection to the OEO is shown in a figure for each concept, figure B.1 in the appendix shows all of them together for a better overview. In these figures only new axioms that relate new concepts are shown. A visualization of relations to previous OEO concepts would require to include this concepts as well and would make the figures too crowded, thus neglecting the main point of a visualization: getting a quick and easy grasp. As a last remark, the simple subclass relations as in *X is a subclass of Y* (or OWL syntax `X SubClassOf Y`) are not included with the axioms. From the figures and the

[1] See the entry in the OEO wiki: `https://github.com/OpenEnergyPlatform/ontology/wiki/Principles-for-Definitions`.

[2] See `https://github.com/OpenEnergyPlatform/ontology/issues?q=is%3Aissue+involves%3Alumi321`.

definitions these relations are obvious, and listing them as well adds no benefit, but would make it rather messy with more than 70 implemented and more than 60 suggested concepts. A collection of all definitions and axioms is shown in the appendix part C.

As for the color-coding of the figures in the next sections, green denotes an addition to the OEO, while blue depicts previous OEO concepts. The axioms follow the color-coding used by Protégé, where special keywords are highlighted in blue and pink. Similar, the syntax is the one that would be entered into Protégé for adding such a axiom.

3.3.2 Implemented Concepts

Ton-kilometer and Passenger-kilometer

The first issue addresses ton-kilometer and passenger-kilometer[3], two central measurement values for the transport domain. Passenger-kilometer and ton-kilometer get a common parent class called *transport performance unit*, which itself is a subclass of *unit of measurement*. Following the distinction between unit and value that is used in the OEO, a *transport performance value* is created as well. They are connected via a *has unit* relation with the axiom shown in listing 3.1. As a result of the annotation process in the *quetzal_germany* example in chapter 4, vehicle kilometer was added as an additional unit[4]. Figure 3.18 shows the structure of the new classes and their relations. The definitions of the concepts are shown in table 3.1. The abbreviations pkm, tkm and vkm were added as synonyms during implementation.

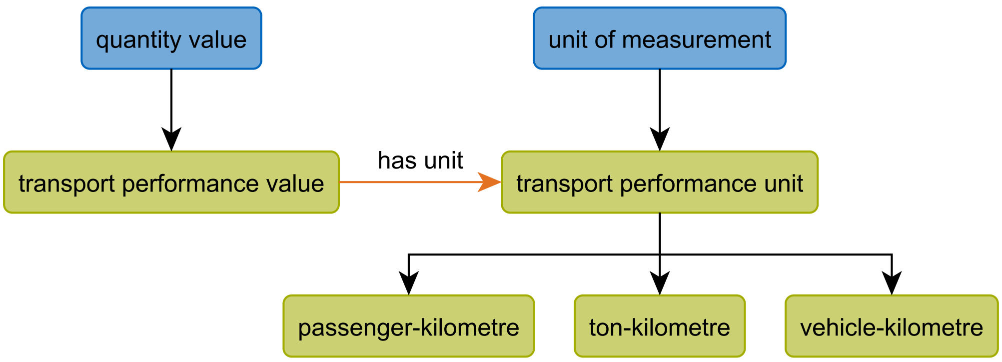


Figure 3.18: Structure of passenger-kilometer and ton-kilometer.

[3] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1272`.
View pull-request on GitHub: `https://github.com/OpenEnergyPlatform/ontology/pull/1289`.
[4] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1375`.
View pull-request on GitHub: `https://github.com/OpenEnergyPlatform/ontology/pull/1388`.

Concept	Definition
transport performance value	A transport performance value is a quantity value that indicates the performance of a transport process in terms of its mileage and amount of transported people and/or goods.
transport performance unit	A transport performance unit is a unit of measurement for the accumulated transport distance of a number of people and/or amount of goods.
passenger-kilometre	Passenger-kilometre is a transport performance unit for the accumulated transport distance of people where one passenger-kilometre equals the transport distance of 1 km for one person.
ton-kilometre	Ton-kilometre is a transport performance unit for the accumulated transport distance of goods where one ton-kilometre equals the transport distance of 1 km for one ton of goods.
vehicle-kilometre	Vehicle-kilometre is a transport performance unit for the accumulated transport distance of the used vehicles themselves where one vehicle-kilometre equals the transport distance of 1 km for one vehicle.

Table 3.1: Definitions for transport performance and related concepts.

```
'transport performance value' 'has unit' some 'transport performance unit'
```

Listing 3.1: Axiom for transport performance value.

Gas Vehicle and Related Terms

The second issue is about gas vehicles and terms related to them[5]. Figure 3.19 shows the general structure of these terms. A *gas vehicle* is distinguished into subclasses by the gas fuel it uses (see table 3.2) and it has a gas engine (see table 3.3). Since a lot of different gases, but not all, can be used as a fuel in a compressed state (see table 3.4), the *compressed gas fuel role* was introduced to help distinguish them (see table 3.5). The axioms arising from these concepts are shown in listings 3.2, 3.3 and 3.4. Most axioms should be self-explaining. Axiom 2 in listing 3.2 is needed to assure that the concept is not used to refer to a hybrid vehicle. Furthermore, it should be noted that the compressed gases inherit their combustible energy carrier disposition from their parent classes and thus need no axiom for that. For the compressed natural gas and the liquefied petroleum gas were the respective synonyms CNG and LPG added during implementation.

[5] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1279`.
View pull-request on GitHub: `https://github.com/OpenEnergyPlatform/ontology/pull/1290`.

Concept	Definition
gas vehicle	A gas vehicle is an internal combustion vehicle that has only a gas engine as a motor for propulsion.
liquefied petroleum gas vehicle	A liquefied petroleum gas vehicle is a gas vehicle that uses liquefied petroleum gas as fuel.
liquefied natural gas vehicle	A liquefied natural gas vehicle is a gas vehicle that uses liquefied natural gas as fuel.
compressed gas vehicle	A compressed gas vehicle is a gas vehicle that uses a compressed gas fuel.

Table 3.2: Definitions for gas vehicles.

Concept	Definition
gas engine	A gas engine is an internal combustion engine that uses a gaseous combustion fuel.
compressed gas engine	A compressed gas engine is a gas engine that uses a compressed gas fuel.

Table 3.3: Definitions for gas engines.

Concept	Definition
liquefied petroleum gas	Liquefied petroleum gas (LPG) is gas mixture of hydrocarbon gases, mainly propane and butane.
compressed natural gas	Compressed natural gas (CNG) is natural gas that has been compressed.
compressed biomethane	Compressed biomethane is biomethane that has been compressed.
compressed synthetic methane	Compressed synthetic methane is synthetic methane that has been compressed.
compressed gas fuel	A compressed gas fuel is a combustion fuel that has a compressed gas fuel role.

Table 3.4: Definitions for gas-based fuels.

Concept	Definition
compressed gas fuel role	A compressed gas fuel role is a fuel role that expresses that a portion of matter can be used in a compressed gas engine.

Table 3.5: Definition for compressed gas fuel role.

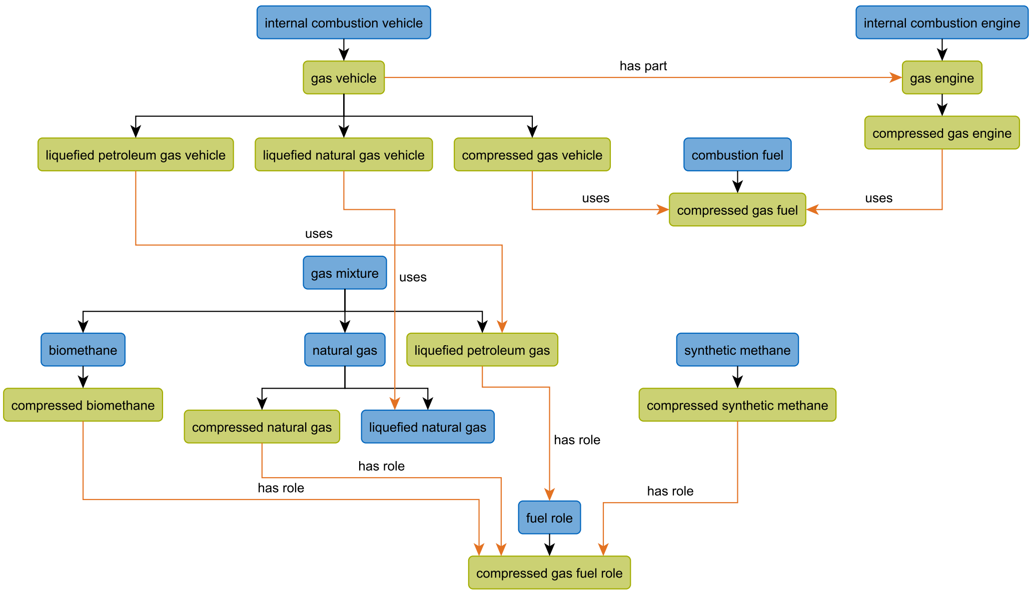


Figure 3.19: Structure of gas vehicle and related terms.

```
'gas vehicle' 'has part' some 'gas engine'
'gas vehicle' 'has part' only ('gas engine' or (not (motor)))
'gas vehicle' uses some 'gaseous combustion fuel'
'liquefied petroleum gas vehicle' uses some 'liquefied petroleum gas'
'liquefied natural gas vehicle' uses some 'liquefied natural gas'
'compressed gas vehicle' uses some 'compressed gas fuel'
```

Listing 3.2: Axioms for gas vehicles.

```
'gas engine' uses some 'gaseous combustion fuel'
'compressed gas engine' uses some 'compressed gas fuel'
```

Listing 3.3: Axioms for gas engines.

```
'liquefied petroleum gas' 'has state of matter' value liquid
'liquefied petroleum gas' 'has normal state of matter' value gaseous
'liquefied petroleum gas' 'has disposition' some 'combustible energy
    carrier disposition'
'liquefied petroleum gas' 'has role' some 'fuel role'
'compressed natural gas' 'has role' some 'compressed gas fuel role'
'compressed biomethane' 'has role' some 'compressed gas fuel role'
'compressed synthetic methane' 'has role' some 'compressed gas fuel role'
'compressed gas fuel' EquivalentTo: 'combustion fuel' and ('has role' some
    'compressed gas fuel role')
```

Listing 3.4: Axioms for gas fuels.

Transport Network

The next issue is about transport networks[6]. The new concepts should capture the necessary infrastructure to enable a certain type of transport. It was implemented together with the next two issues, *subclasses of transport hub* and *transport network component*, as they are quite closely related and small. Figure 3.20 shows the structure of *transport network* and its subclasses, which are defined in table 3.6. The new axioms are defined in listing 3.5, most of which refer to transport network components defined in the next issue.

[6] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1266`.
View pull-request on GitHub: `https://github.com/OpenEnergyPlatform/ontology/pull/1297`.

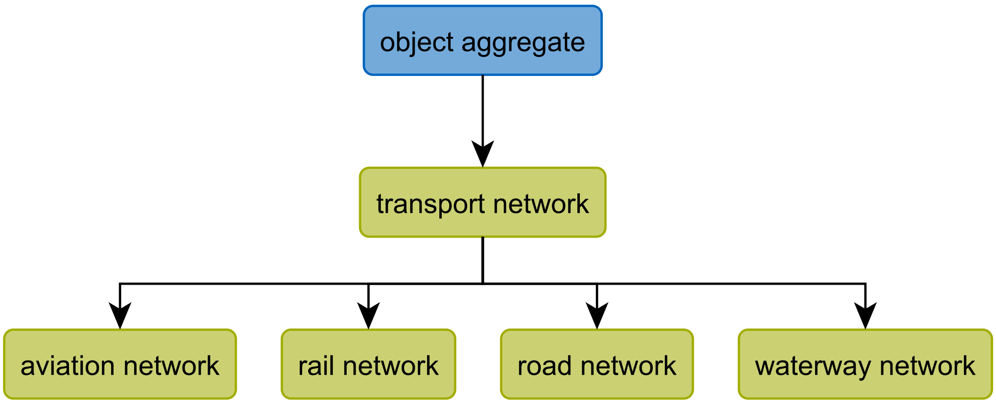


Figure 3.20: Structure of transport network.

Concept	Definition
transport network	A transport network is an object aggregate of transport network components that enables the transport of people and/or goods.
road network	A road network is a transport network that enables transport on roads.
rail network	A rail network is a transport network that enables transport on rails.
waterway network	A waterway network is a transport network that enables transport on water.
aviation network	An aviation network is a transport network that enables air transport.

Table 3.6: Definitions for transport network and subclasses.

```
'transport network' 'has part' some 'transport network component'
'transport network' 'has quantity value' some 'length value'
'road network' 'has part' some 'road'
'rail network' 'has part' some 'railway'
'rail network' 'has part' some 'train station'
'waterway network' 'has part' some 'port'
'aviation network' 'has part' some 'airport'
```

Listing 3.5: Axioms for transport networks.

Transport Network Component

This issue is about transport network components, that is, elements that are part of a transport network[7]. Most elements defined in table 3.7 are connections between places with the exception of *transport hub*, whose subclasses are defined in the next issue. The structure is shown in figure 3.21. To ensure that not only subclasses of this transport network component, but also other parts of a transport network

[7] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1267`.
View pull-request on GitHub: `https://github.com/OpenEnergyPlatform/ontology/pull/1297`.

are correctly inferred as transport network components, an equivalence axiom is added. Together with the other axioms, this is shown in listing 3.6.

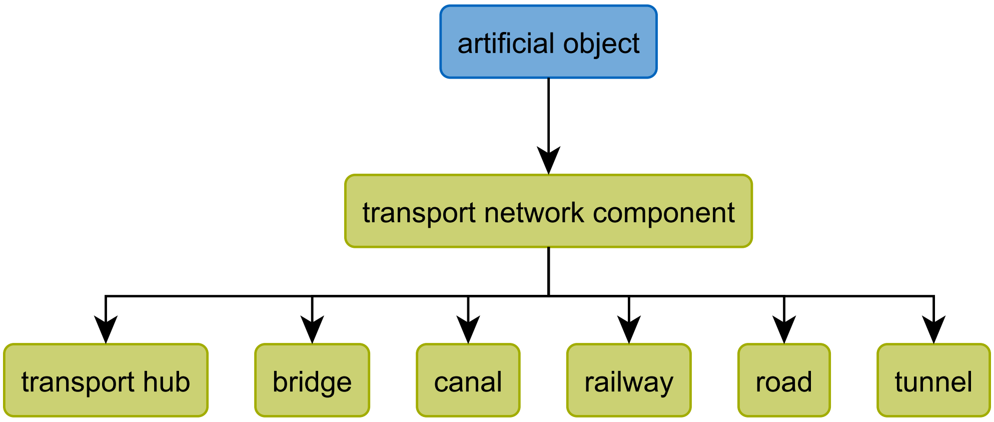


Figure 3.21: Structure of transport network component.

Concept	**Definition**
transport network component	A transport network component is an artificial object that is part of a transport network.
road	A road is a transport network component with an artificial surface that allows transport for road vehicles.
bridge	A bridge is a transport network component that spans a physical obstacle without blocking the way underneath.
tunnel	A tunnel is a transport network component that is built through a certain environment (e.g. a mountain or water) and allows to pass through that environment.
railway	A railway is a transport network component that can only be used by trains.
canal	A canal is a transport network component that is an artificially created waterway.
transport hub	A transport hub is a transport network component that allows the exchange of people and/or goods.

Table 3.7: Definitions for transport network and subclasses.

```
'transport network component' equivalentTo 'artificial object' and ('part of' some 'transport network')
'transport network component' 'has economic value' some 'cost'
'road' 'is used by' some 'road vehicle'
'railway' 'is used by' some train
```

Listing 3.6: Axioms for transport network components.

Subclasses of Transport Hub

The next issue is about subclasses of transport hub from the previous issue and implemented together with that one[8]. For that, the structure is quite simple as shown in figure 3.22. It distinguishes common infrastructural elements for exchange purposes as shown in table 3.8. With the axioms shown in listing 3.7, relations to vehicles that use these types of infrastructure are established.

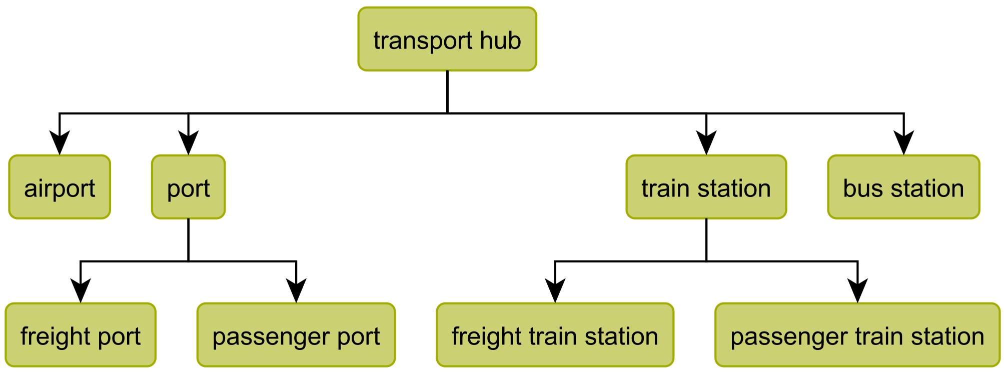


Figure 3.22: Structure of transport hub.

Concept	Definition
train station	A train station is a transport hub for trains.
freight train station	A freight train station is a train station for the exchange of goods.
passenger train station	A passenger train station is a train station for the exchange of passengers.
bus station	A bus station is a transport hub for busses.
port	A port is a transport hub for ships.
freight port	A freight port is a port for the exchange of goods.
passenger port	A passenger port is a port for the exchange of passengers.
airport	An airport is a transport hub for airplanes.

Table 3.8: Definitions for the subclasses of transport hub.

[8] View issue on GitHub: https://github.com/OpenEnergyPlatform/ontology/issues/1278.
View pull-request on GitHub: https://github.com/OpenEnergyPlatform/ontology/pull/1297.

```
'train station' 'is used by' some train
'freight train station' 'is used by' some 'freight train'
'passenger train station' 'is used by' some 'passenger train'
'bus station' 'is used by' some bus
port 'is used by' some ship
'freight port' 'is used by' some 'cargo ship'
'passenger port' 'is used by' some 'passenger ship'
airport 'is used by' some aircraft
```

Listing 3.7: Axioms for transport hubs.

Subclasses for Energy Transfer

This issue adds more classes for energy transfer[9] for a more fine grained distinction. The charging concept was added in a later issue[10]. The concept *heat transfer* was already included in the OEO, but the definition was adapted. These terms try to capture the processes of getting energy to the vehicles, that is, electrical energy or chemical energy within a fuel. For a precise distinction, there are separate concepts for *fuel transport*, *combustion fuel transport*, and *chemical energy transfer*. The resulting structure is shown in figure 3.23, the concept definitions in table 3.9 and the axioms in listing 3.8. These terms are related to other newly introduced concepts such as *vehicle charging station*, *filling station*, and *tank*.

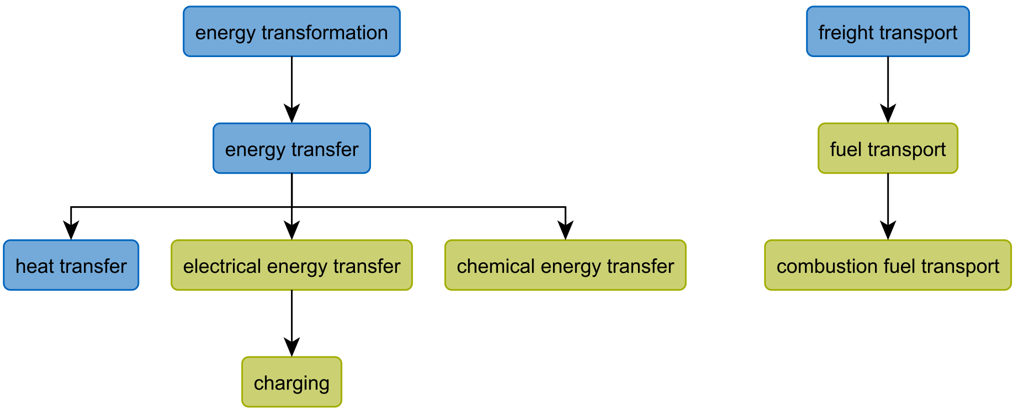


Figure 3.23: Structure of energy transfer and fuel transport.

[9] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1269`.
View pull-request on GitHub: `https://github.com/OpenEnergyPlatform/ontology/pull/1299`.

[10] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1368`.
View pull-request on GitHub: `https://github.com/OpenEnergyPlatform/ontology/pull/1394`.

Concept	Definition
electrical energy transfer	Electrical energy transfer is an energy transfer of electrical energy.
charging	Charging is an electrical energy transfer where the transferred energy is stored in a battery.
chemical energy transfer	Chemical energy transfer is an energy transfer of chemical energy.
fuel transport	Fuel transport is a transport of fuel.
combustion fuel transport	Combustion fuel transport is a fuel transport for combustion fuel.
heat transfer	Heat transfer is an energy transfer of thermal energy.

Table 3.9: Definitions for the subclasses of energy transfer.

```
'electrical energy transfer' 'has energy input' some 'electrical energy'
'electrical energy transfer' 'has energy output' some 'electrical energy'
'chemical energy transfer' 'has energy input' some 'chemical energy'
'chemical energy transfer' 'has energy output' some 'chemical energy'
'fuel transport' 'has participant' some 'fuel'
'combustion fuel transport' 'has participant' some 'combustion fuel'
'combustion fuel transport' 'has energy input' some 'chemical energy'
'combustion fuel transport' 'has energy output' some 'chemical energy'
'fuel' 'has role' some 'good role'
'freight transport' 'has participant' some good
```

Listing 3.8: Axioms for the subclasses of energy transfer.

Vehicle Charging Station

The issue about vehicle charging station[11] is related to previous issues by the axioms in listing 3.9. In a later issue, the bidirectional vehicle charging station was added[12]. The idea of transferring energy back into the electricity grid is also the reason why axiom 1 in listing 3.9 only refers to *electrical energy transfer* and not *charging*, which would contradict the reverse directional transfer. The structure, shown in figure 3.24, is straight forward.

Concept	Definition
vehicle charging station	A vehicle charging station is an electricity grid component that transfers electrical energy into the traction battery of a battery electric vehicle.
bidirectional vehicle charging station	A bidirectional vehicle charging station is a vehicle charging station that can also feed electrical energy from the traction battery back into the electricity grid.

Table 3.10: Definitions for charging stations.

[11] View issue on GitHub: https://github.com/OpenEnergyPlatform/ontology/issues/1307.
View pull-request on GitHub: https://github.com/OpenEnergyPlatform/ontology/pull/1312.

[12] View issue on GitHub: https://github.com/OpenEnergyPlatform/ontology/issues/1369.
View pull-request on GitHub: https://github.com/OpenEnergyPlatform/ontology/pull/1393.

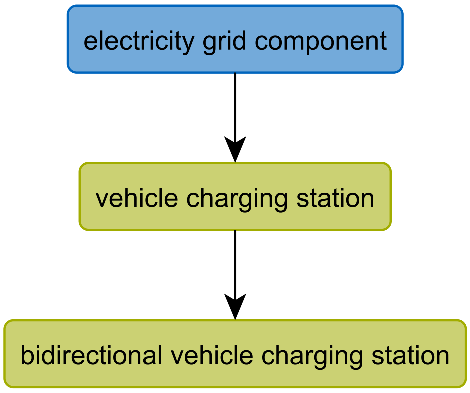


Figure 3.24: Structure of charging station and bidirectional charging station.

```
'vehicle charging station' 'participates in' some 'electrical energy transfer'
'vehicle charging station' 'part of' some 'transport network'
```

Listing 3.9: Axioms for charging stations.

Operational Mode

The issue about the operational mode is a simple one[13]. The concept name was refined to *vehicle operational mode* to indicate that it refers only to vehicles. That is included in the definition, see table 3.11, and the mutual axioms, see listing 3.10, as well. Figure 3.25 shows the simple structure. Realizable entity is a suitable parent class, because the vehicle operational mode existentially depends on a vehicle, but can be activated or deactivated, or in other words, it can be realized.

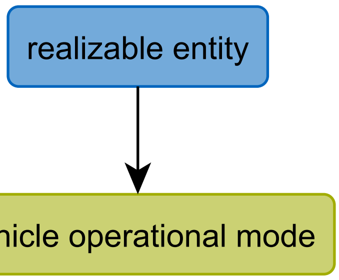


Figure 3.25: Structure of operational mode.

[13] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1304`.
View pull-request on GitHub: `https://github.com/OpenEnergyPlatform/ontology/pull/1314`.

Concept	Definition
vehicle operational mode	A vehicle operational mode is a realizable entity that determines how a vehicle is operating.

Table 3.11: Definition for vehicle operational mode.

```
vehicle 'bearer of' some 'vehicle operational mode'
'vehicle operational mode' 'has bearer' some vehicle
```

Listing 3.10: Axioms for vehicle operational mode.

Fuel Supply System

Fuel supply system is also a simple issue[14]. The idea is to have a concept that captures the entirety of elements that are involved in supplying vehicles with fuel. Since the scope of "entirety" can widely vary, there are no axioms that restrict it. Fuel supply system is straight forward a subclass of energy system as shown in figure 3.26 and defined in table 3.12. It is not a subclass of supply system, because fuel as an energy carrier belongs to the energy system, as opposed to water, for example.

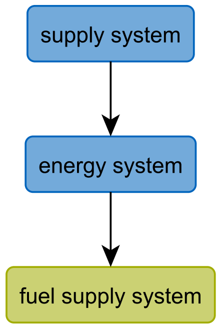


Figure 3.26: Structure of fuel supply system.

Concept	Definition
fuel supply system	A fuel supply system is an energy system covering the distribution of fuels.

Table 3.12: Definition for fuel supply system.

[14] View issue on GitHub: https://github.com/OpenEnergyPlatform/ontology/issues/1300.
View pull-request on GitHub: https://github.com/OpenEnergyPlatform/ontology/pull/1316.

Equivalence Subclasses for Vehicles

For car and truck, several subclasses with equivalence axioms are defined that combine the propulsion concept with the type of vehicle[15]. As shown in the sections about the energy focus and the adapation to the OEO, a lot of vehicle types were deemed unimportant for an energy perspective at least in a pure sense. Only the combination of energy carrier/propulsion technique and vehicle type seemed to be interesting for a more fine grained distinction. However, there was an effort to include such pure vehicle type concepts in the OEO by other developers. In consequence, a combined concept only seemed suitable for the most common vehicle types, that is, car and truck, because a rarer combination could still simply be achieved by a combination of two concepts. Figure 3.27 shows the structure, table 3.13 shows the definitions and listing 3.11 the equivalence axioms, which are simply interpretations of the definitions.

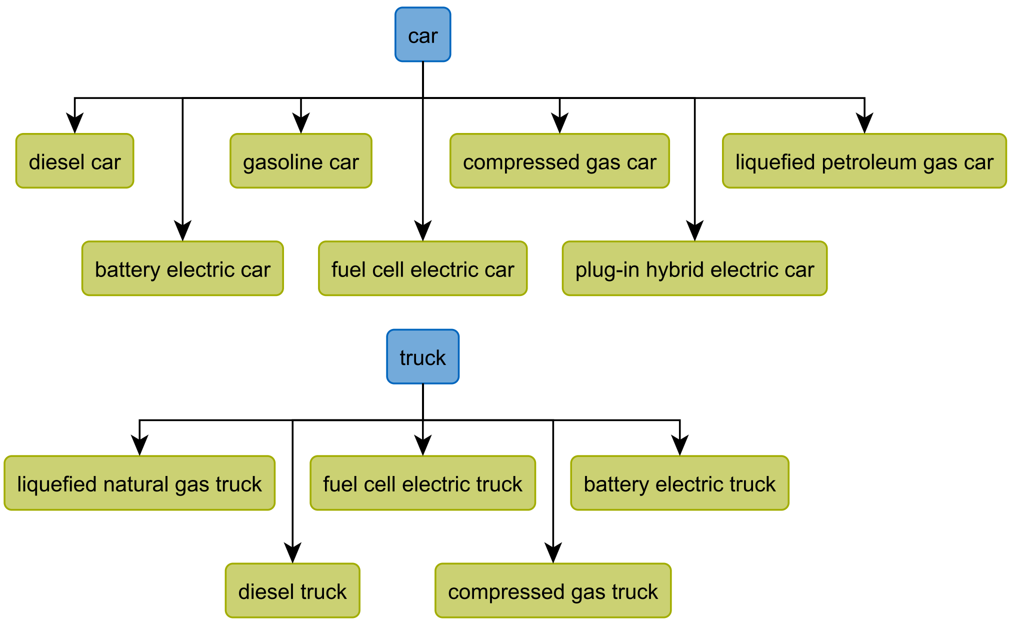


Figure 3.27: Structure of equivalence subclasses for vehicles.

[15] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1298`.
View pull-request on GitHub: `https://github.com/OpenEnergyPlatform/ontology/pull/1345`.

Concept	Definition
diesel truck	A diesel truck is a truck that has only a diesel engine as motor for propulsion and thus is also a diesel vehicle.
diesel car	A diesel car is a car that has only a diesel engine as motor for propulsion and thus is also a diesel vehicle.
gasoline car	A gasoline car is a car that has only a gasoline engine as motor for propulsion and thus is also a gasoline vehicle.
battery electric car	A battery electric car is a car that as an electric traction motor and a traction buttery and thus is also a battery electric vehicle.
fuel cell electric car	A fuel cell electric car is a car that has an electric traction motor and uses electrical energy from a fuel cell and thus is also a fuel cell electric vehicle.
compressed gas car	A compressed gas car is a car that uses compressed gas in a gas engine and thus is also a compressed gas vehicle.
liquefied petroleum gas car	A liquefied petroleum gas car is a car that uses liquefied petroleum gas in a gas engine and thus is also a liquefied petroleum gas vehicle.
plug-in hybrid electric car	A plug-in hybrid electric car is a car that can switch between an electric traction motor and an internal combustion engine for propulsion and thus is also a plug-in hybrid electric vehicle.
battery electric truck	A battery electric truck is a truck that has an electric traction motor and a traction battery and thus is also a battery electric vehicle.
fuel cell electric truck	A fuel cell electric truck is a truck that has an electric traction motor and uses electrical energy from a fuel cell and thus is also a fuel cell electric vehicle.
compressed gas truck	A compressed gas truck is a truck that uses compressed gas in a gas engine and thus is also a compressed gas vehicle.
liquefied natural gas truck	A liquefied natural gas truck is a truck that uses liquefied natural gas in a gas engine and thus is also a liquefied natural gas vehicle.

Table 3.13: Definitions for new vehicle subclasses.

```
'battery electric car' EquivalentTo car and ('has part' some 'traction battery') and ('has part' some 'electric traction motor')
'compressed gas car' EquivalentTo car and (uses some 'compressed gas fuel') and ('has part' some 'gas engine') and ('has part' only ('gas engine' or (not (motor))))
'diesel car' EquivalentTo car and ('has part' some 'diesel engine') and ('has part' only ('diesel engine' or (not (motor))))
'fuel cell electric car' EquivalentTo car and ('has part' some 'fuel cell') and ('has part' some 'electric traction motor')
'gasoline car' EquivalentTo car and ('has part' some 'gasoline engine') and ('has part' only ('gasoline engine' or (not (motor))))
'liquefied petroleum gas car' EquivalentTo car and (uses some 'liquefied petroleum gas') and ('has part' some 'gas engine') and ('has part' only ('gas engine' or (not (motor))))
'plug-in hybrid electric car' EquivalentTo car and ('has part' some 'electric traction motor') and ('has part' some ('internal combustion engine' and ('participates in' some propulsion)))
'battery electric truck' EquivalentTo truck and ('has part' some 'traction battery') and ('has part' some 'electric traction motor')
'compressed gas truck' EquivalentTo truck and (uses some 'compressed gas fuel') and ('has part' some 'gas engine') and ('has part' only ('gas engine' or (not (motor))))
'diesel truck' EquivalentTo truck and ('has part' some 'diesel engine') and ('has part' only ('diesel engine' or (not (motor))))
'fuel cell electric truck' EquivalentTo truck and ('has part' some 'fuel cell') and ('has part' some 'electric traction motor')
'liquefied natural gas truck' EquivalentTo truck and (uses some 'liquefied natural gas') and ('has part' some 'gas engine') and ('has part' only ('gas engine' or (not (motor))))
```

Listing 3.11: Axioms for new vehicle subclasses.

Tank

For a more precise depiction of the energy storage in a vehicle, the concepts *tank* and *fuel tank* were added in this issue[16]. Along with it, a volume concept to indicate the size of a tank was integrated. For batteries in a vehicle, the concepts *battery* and *traction battery* were already included. Figure 3.28 shows the general structure, table 3.14 the definitions, and 3.12 the axioms. Due to its purpose to store a combustion fuel, the fuel tank is attributed with a chemical energy storage function. The axioms 7 to 10 relate various vehicles to a fuel tank with a *has part* relation, while axiom 11 simply ensures that a tank ship has indeed a tank.

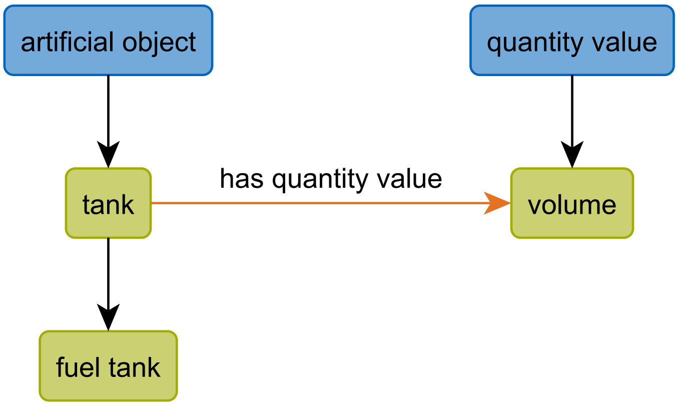


Figure 3.28: Structure of tank and volume.

Concept	Definition
tank	A tank is an artificial object that stores a liquid or gaseous portion of matter.
fuel tank	A fuel tank is a tank that stores a combustion fuel.
volume	A volume is a quantity value indicating the size of a three-dimensional spatial region.

Table 3.14: Definitions for tank and volume.

[16] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1301`.
View pull-request on GitHub: `https://github.com/OpenEnergyPlatform/ontology/pull/1356`.

```
1  'tank' 'has quantity value' some volume
2  'fuel tank' 'has quantity value' some 'storage capacity'
3  'fuel tank' 'has function' some 'chemical energy storage function'
4  volume 'has unit' some 'volume unit'
5  volume 'quantity value of' some 'three-dimensional spatial region'
6
7  'internal combustion vehicle' 'has part' some 'fuel tank'
8  'plug-in hybrid electric vehicle' 'has part' some 'fuel tank'
9  'fuel cell electric vehicle' 'has part' some 'fuel tank'
10 'gas turbine vehicle' 'has part' some ''fuel tank'
11 'tank ship' 'has part' some 'tank'
```

Listing 3.12: Axioms for tank and volume. Line 6 is intentionally left blank.

Filling Station

Analogously to the charging station concept, a concept for filling stations is added[17]. As a subclass the *hydrogen filling station* was added. It is specifically distinguished, because it has an important role in the buildup of a supply infrastructure for hydrogen vehicles [2, 6], and its count is taken as a measurement for that like in [1]. Along with it, hydrogen transport is defined for a complete depiction of hydrogen supply. As before, the structure is shown in figure 3.29. the definitions are displayed in table 3.15 and the axioms are written in listing 3.13. Notice that the axiom in line 2, as complicated as it may look, is the logical description of the purpose of a filling station, which is to transport fuel into the fuel tank of a vehicle.

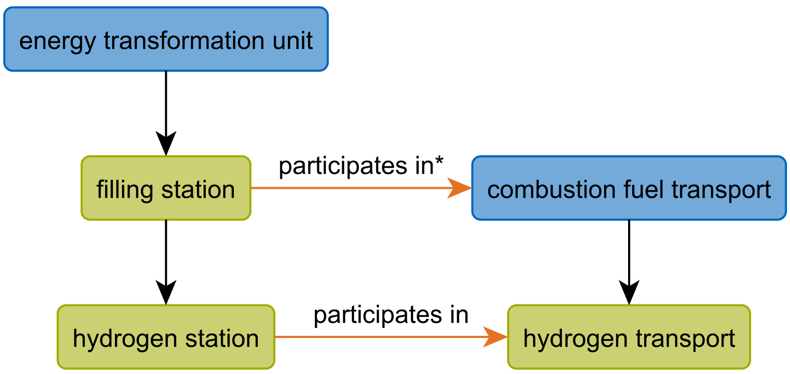


Figure 3.29: Structure of filling station. The "participates in*" denotes that this relation is not a complete axiom, but only part of one.

[17] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1308`.
View pull-request on GitHub: `https://github.com/OpenEnergyPlatform/ontology/pull/1357`.

Concept	Definition
filling station	A filling station is an energy transformation unit that transfers fuel into the fuel tank of a vehicle.
hydrogen station	A hydrogen station is a filling station that transfers hydrogen.
hydrogen transport	Hydrogen transport is the combustion fuel transport of hydrogen.

Table 3.15: Definitions for filling station and hydrogen transport.

```
'filling station' 'part of' some 'transport network'
'filling station' 'participates in' some ('combustion fuel transport' and
    ('has participant' some ('fuel tank' and ('part of' some vehicle))))
'hydrogen station' 'participates in' some 'hydrogen transport'
'hydrogen transport' 'has participant' some hydrogen
```

Listing 3.13: Axioms for filling station and hydrogen transport.

Electricity and Fuel Demand

Although the demand in the transport domain is oftentimes simply stated as an energy value or as a pkm/tkm value, it is worth to introduce more specific terms for such demand. As earlier mentioned, concepts for pkm or tkm demand are already included, but no concepts for electricity or fuel demand, which were added in this issue[18]. As usual, the structure is shown in figure 3.30, while table 3.16 shows the definitions. Because there are no universally valid restrictions, there are no axioms attached to these concepts. The need for these were identified during the annotation of the `Laos TED` data set.

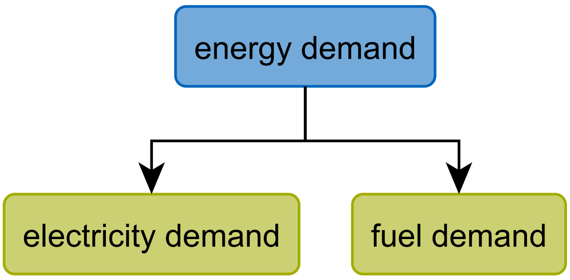


Figure 3.30: Structure of energy demand.

[18] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1366`.
View pull-request on GitHub: `https://github.com/OpenEnergyPlatform/ontology/pull/1389`.

Concept	Definition
electricity demand	Electricity demand is the energy demand for electricity.
fuel demand	Fuel demand is the energy demand for fuel.

Table 3.16: Definitions for electricity and fuel demand.

Ton of Oil Equivalent

As another inspiration from the data set `Laos TED`, ton of oil equivalent was suggested as another energy unit[19]. They were implemented together with analog classes referring to coal, but only the suggested oil equivalents are shown in the structure (figure 3.31) and the definitions (table 3.17). There are no axioms attached to these concepts. Notice, that all three of them are subclasses of energy unit, even though two of them are just magnitudes of the plain ton of oil equivalent. This follows the structure of the other energy units in the OEO. During the implementation, the abbreviations toe, ktoe and Mtoe were added as synonyms.

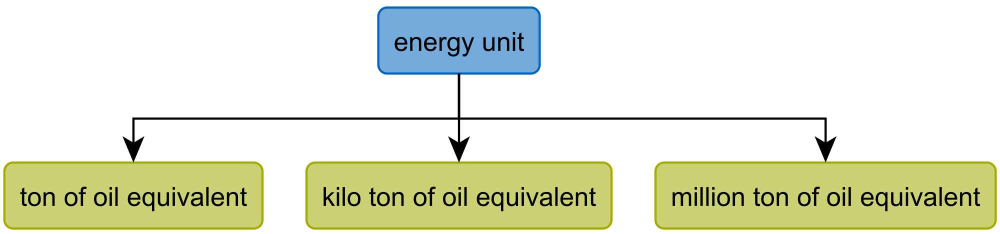


Figure 3.31: Structure of ton of oil equivalents.

Concept	Definition
ton of oil equivalent	A ton of oil equivalent is an energy unit which is equal to the amount of energy released by burning one metric ton of crude oil with a certain net calorific value. That is defined as 41.868 gigajoules or 11.63 megawatt-hours.
kilo ton of oil equivalent	A kilo ton of oil equivalent is an energy unit which is equal to 1,000 tons of oil equivalent.
million ton of oil equivalent	A million ton of oil equivalent is an energy unit which is equal to 1,000,000 tons of oil equivalent.

Table 3.17: Definitions for ton of oil equivalent and common magnitudes of it.

[19] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1367`.
View pull-request on GitHub: `https://github.com/OpenEnergyPlatform/ontology/pull/1398`.

Amortization Time

Amortization time is an economical concept that seemed to be a suitable addition[20], because financial aspects are often important for users. An example is the choice of fuel, for which the cost is the most important criterion for consumers [107]. The expertise of OEO developers with economical background was requested to ensure a proper definition and also to elaborate on the distinction to economical life time. The resulting definitions are shown in table 3.18 and their integration under time span is depicted in figure 3.32.

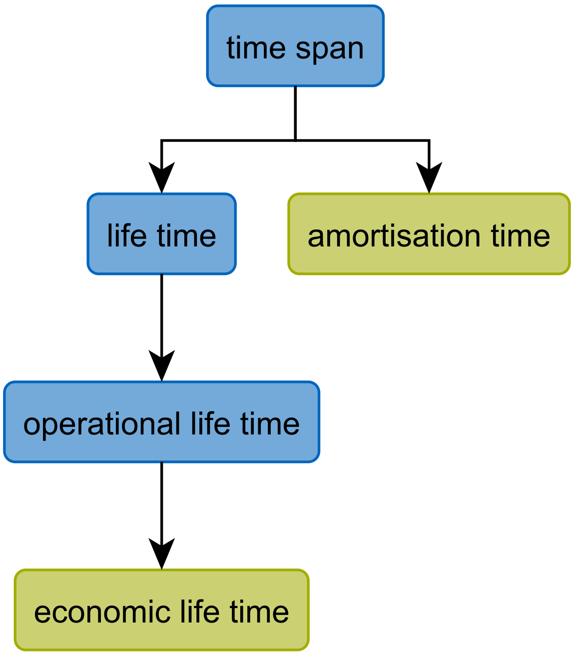


Figure 3.32: Structure of amortization time and economic life time.

Concept	Definition
amortisation time	An amortisation time is the time span in which the investment costs are refinanced from the annual profits and depreciation of the investment.
economic life time	An economic life time is the operational life time during which an artificial object is profitable to the owner.

Table 3.18: Definition for amortization time and economic life time.

[20] View issue on GitHub: https://github.com/OpenEnergyPlatform/ontology/issues/1380.
View pull-request on GitHub: https://github.com/OpenEnergyPlatform/ontology/pull/1436.

Utilization Value

Utilization value[21] is another measurement value, which was initially thought to be already included in the OEO, because of its general nature. Since that was not the case, it was added after a short discussion with the definition in table 3.19 resulting in the simple structure in figure 3.33.

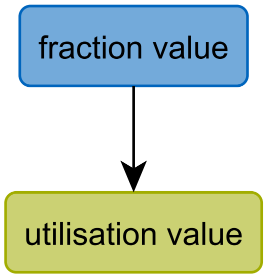


Figure 3.33: Structure of utilization value.

Concept	Definition
utilisation value	A utilisation value is a fraction value that describes the instantaneous share of a maximum value that is utilised.

Table 3.19: Definition for utilization value.

3.3.3 Suggested Concepts

Modal Split and Transport Mode

The issue about modal split and transport modes evolved around the idea to integrate values that capture the share of a certain transport mode in a given context[22]. For *modal split* and *modal share* the definitions and relating axioms are already agreed upon, but for transport modes the discussion about relevant modes and their definitions is not yet concluded. In order to be able to distinguish between a model or result and the actual value, the modal split is the entirety of all modal shares, each about another transport mode, within a certain context. For the structure see figure 3.34 and for the definitions table 3.20. Listing 3.14 shows the axioms for the connection of modal split, modal share, and transport mode.

After a discussion and an OEO developer meeting, it was decided to add transport modes as subclasses of transport. The way transport is divided into transport modes is different across literature. The application examples in the next chapter use again different transport modes. Therefore, not all possible transport modes can be respected, but only the most common ones.

[21] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1377`.
View pull-request on GitHub: `https://github.com/OpenEnergyPlatform/ontology/pull/1435`.
[22] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1276`.

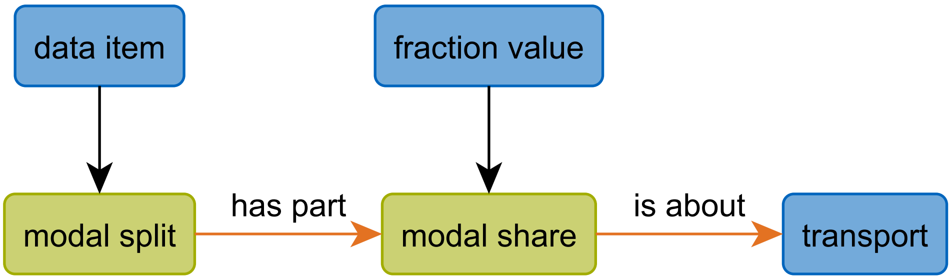


Figure 3.34: Structure of modal split.

Concept	Definition
modal split	A modal split is a data item that contains modal shares.
modal share	A modal share is a fraction value that describes the share of a transport mode.

Table 3.20: Definitions for modal split and modal share.

```
'modal split' 'has part' some 'modal share'
'modal share' 'is about' some 'transport'
'modal share' 'has unit' some 'percent'
```

Listing 3.14: Axioms for modal split and modal share.

Table 3.21 defines micromobility and subclasses walking and cycling. Micromobility is not suitable to be classified as passenger or freight transport, because it could be either one of them. Walking and cycling in turn are better suited as specialized micromobility than as passenger or freight transport. For the structure, see figure 3.35.

Concept	Definition
micromobility	Micromobility is transport on short distances.
walking	Walking is micromobility without any vehicle.
cycling	Cycling is micromobility with a bicycle.

Table 3.21: Definitions for transport modes about micromobility.

For the transport modes that belong to passenger transport, table 3.22 holds the definitions and figure 3.36 shows the structure. Car sharing is considered to be private transport, because it fits the definition of private transport, which refers to people using their own vehicles. Beneath public road, rail, water, and air transport, a concept *local public transport* is suggested to capture all public transport possibilities in a certain area. This could include other transport modes like city bus transport or city train transport. For public road and train transport, a distinction by distance is suggested. The main idea here is to have terms for transport within a city, between cities on a regional level, and for long distances, because there are

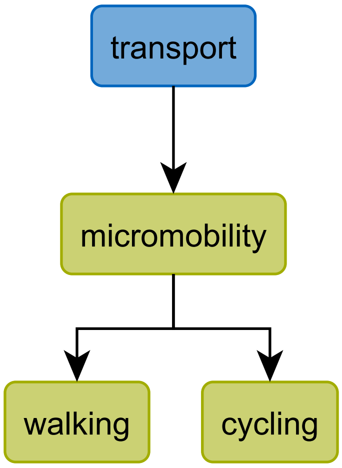


Figure 3.35: Structure of micromobility.

oftentimes great distinctions in used vehicle types, availability, and departure frequency. The `quetzal_germany` data set from the next chapter is an example, where such transport modes are used.

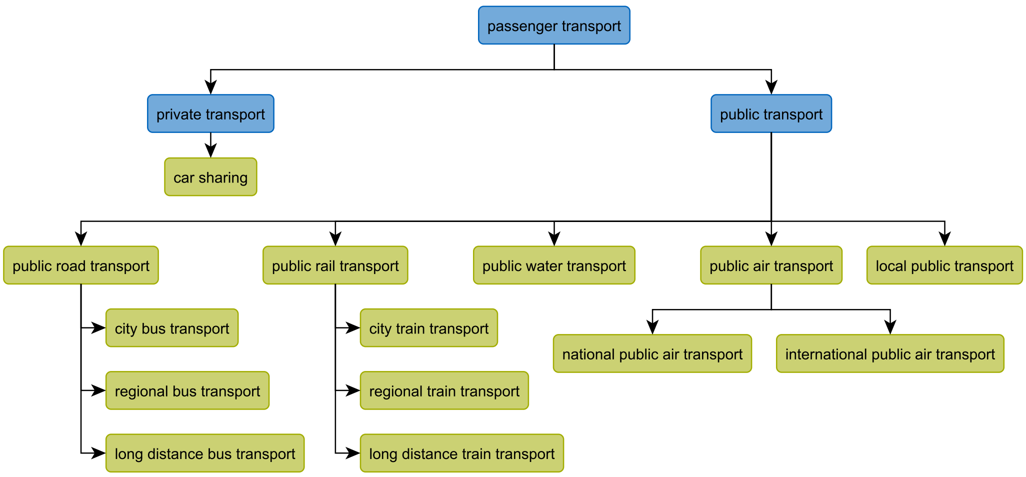


Figure 3.36: Structure of private and public transport modes.

For the freight transport, definitions of modes are suggested in table 3.23, resulting in the structure in figure 3.37. Like for passenger transport before, there are modes for road, rail, air, and water freight transport. Additionally, there is pipeline transport as well, inspired by the annotation of the `iTEM harmonized_dataset`. It is certainly somewhat special, because no vehicle is involved, but that is no requirement of the transport concept. Road freight transport is further divided into small, intermediate, and heavy truck transport. The reason for this is that some studies distinguish between trucks of different weights. However, the weight limits they use are dif-

Concept	Definition
car sharing	Car sharing is the private transport where people share a car.
local public transport	Local public transport is public transport where the used transport networks cover a certain local area.
public road transport	Public road transport is public transport that takes place on roads.
city bus transport	City bus transport is public road transport for short distances.
regional bus transport	Regional bus transport is public road transport for medium distances.
long distance bus transport	Long distance bus transport is public road transport for long distances.
public rail transport	Public rail transport is public transport that takes place on rails.
city train transport	City train transport is public rail transport for short distances.
regional train transport	Regional train transport is public rail transport for medium distances.
long distance train transport	Long distance train transport is public rail transport for long distances.
public air transport	Public air transport is public transport that primarily takes place in the air.
national public air transport	National public air transport is public air transport that does not cross country borders.
international public air transport	International public air transport is public air transport that crosses the borders of one or more countries.
public water transport	Public water transport is public transport that takes place on water.

Table 3.22: Definitions for private and public transport modes.

ferent, and therefore, these vague sounding transport modes seem to be suitable container concepts. For air and freight transport, it is furthermore distinguished between national and international transport.

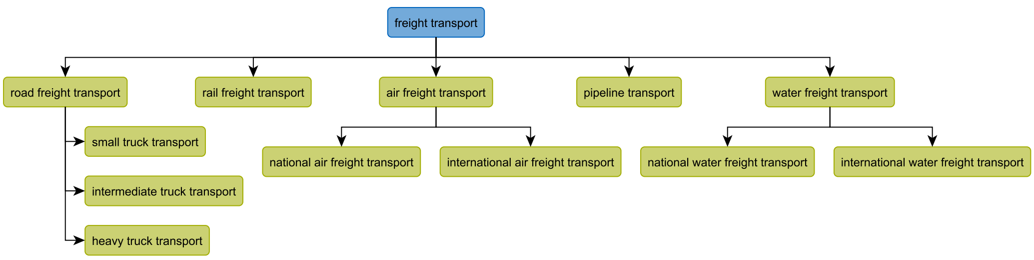


Figure 3.37: Structure of freight transport modes.

Concept	Definition
road freight transport	Road freight transport is freight transport that takes place on roads.
small truck transport	Small truck transport is the road freight transport with small trucks.
intermediate truck transport	Intermediate truck transport is the road freight transport with intermediate trucks.
heavy truck transport	Hevy truck transport is the road transport with heavy trucks.
rail freight transport	Rail freight transport is freight transport that takes place on rails.
air freight transport	Air freight transport is freight transport that primarily takes place in the air.
national air freight transport	National air freight transport is air freight transport that does not cross country borders.
international air freight transport	International air freight transport is air freight transport that crosses the borders of one or more countries.
water freight transport	Water freight transport is freight transport that takes place on water.
national water freight transport	National water freight transport is water freight transport that does not cross country borders.
international water freight transport	International water freight transport is water freight transport that crosses the borders of one or more countries.
pipeline transport	Pipeline transport is freight transport that uses pipelines.

Table 3.23: Definitions for freight transport modes.

Electricity Cost

This issue is about a simple addition of electricity cost analogously to the fuel cost that is already part of the OEO[23]. The idea came from the annotation of the *Laos TED* data set in chapter 4. Figure 3.38 shows the structure and table 3.24 the definition.

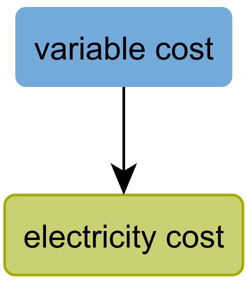


Figure 3.38: Structure of electricity cost.

[23] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1365`.

Concept	Definition
electricity cost	An electricity cost is a variable cost that depends on electricity price and amount.

Table 3.24: Definition for electricity cost.

Specific Values for Cost and Energy Consumption

The annotation of the *Laos TED* data set also showed the necessity for some specific values, that is, values that are set in relation to another value. The two cases that occurred are specific costs and specific energy consumption[24]. The concepts were suggested as shown in figure 3.39 and table 3.25, but their implementation depends on the outcome of the discussion about compound concepts in the OEO that currently takes place. Units that measure energy or cost per pkm, tkm, 100 km, or passenger are in particular desirable for the transport domain.

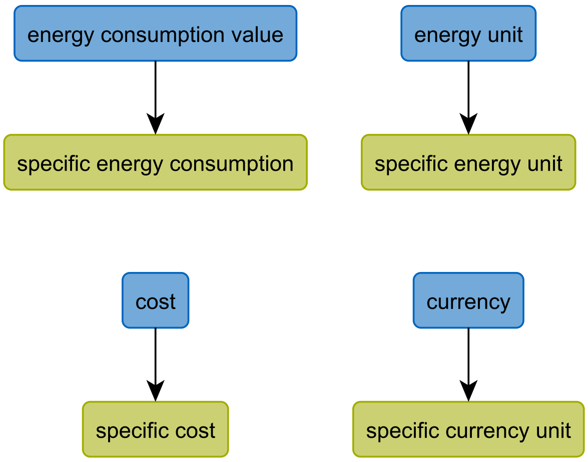


Figure 3.39: Structure of specific values.

Concept	Definition
specific cost	A specific cost is a cost that is calculated by dividing the total considered costs through the quantity value of interest.
specific currency unit	A specific currency unit relates currency to another unit.
specific energy consumption	A specific energy consumption is an energy consumption value that is calculated by dividing the total considered energy consumption through the quantity value of interest.
specific energy unit	A specific energy unit relates an energy unit to another unit.

Table 3.25: Definitions for specific costs and specific energy consumption.

[24] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1370`.

Recycling and Recyclability

Among the initial ideas for measurement values was a term for the ability to recycle something, that is, to regain materials or energy from it[25]. In the transport domain, vehicles and theirs parts like engine or traction battery are possible objects. Because of the long life time of vehicles and the improvement of recycling techniques in the mean time, a concept for expected recyclability was suggested as well. Because these are not widely used terms in energy system modeling, they were suggested in a later phase and are still in discussion. Figure 3.40 shows the structure and table 3.26 the definitions of the suggested concepts.

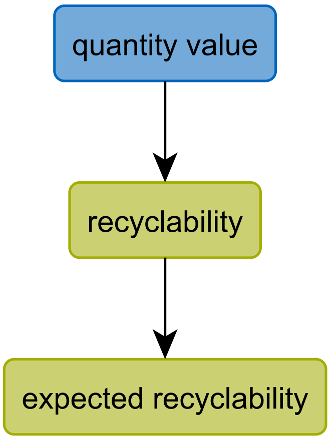


Figure 3.40: Structure of recycling and recyclability.

Concept	Definition
recycling	Recycling is a transformation that regains materials and/or energy from an artificial product or waste.
recyclability	Recyclability is a quantity value that indicates the percentage of materials that can be regained during a recycling process.
expected recyclability	Expected recyclability is the recyclability an artifical object is expected to have at the end of its operational life time.

Table 3.26: Definitions for recycling and recyclability.

Spatial Context Information

From annotating the *quetzal_germany* data set came the idea to add concepts about spatial context[26]. Specifically, about whether or not the boundary of a spatial region is crossed during a transport process (or any other process). It was discussed in an OEO developer meeting, but not finally decided upon, because there might be a limit of OWL to properly axiomatize the difference between a starting

[25] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1376`.
[26] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1379`.

and ending location. More about this is discussed in chapter 5. The suggestions are shown in figure 3.41 and table 3.27. It is to note that there are multiple names suggested for the concepts, separated by "/".

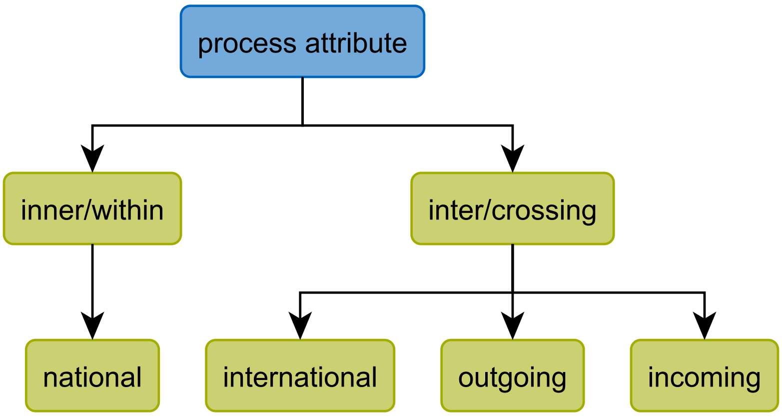


Figure 3.41: Structure of concepts about spatial context.

Concept	**Definition**
inner/within	Inner/within is a process attribute that describes that a process takes entirely place within the same spatial region.
national	National is inner/within whereby the spatial region is a country.
inter/crossing	Inter/crossing is a process attribute that describes that a process crosses the boundaries of one or more spatial regions.
international	International is inter/crossing whereby the boundaries of the spatial regions are boundaries of countries.
outgoing	Outgoing is inter/crossing for processes that leave the spatial region of interest.
incoming	Incoming is inter/crossing for processes that arrive at the spatial region of interest.

Table 3.27: Definitions for concepts about spatial context.

Load of Vehicles

Coming from the utilization value, a capacity value for vehicles that the utilization value could refer to was deemed useful[27]. The concepts were also inspired by the application example in section 4.3.1, which refers to "activity per vehicle" values. As further extension, absolute values for the vehicle load and relative values in comparison to the number of vehicles in a fleet were suggested. The structure is shown in figure 3.42, the definitions in table 3.28 and the axioms to connect the values to units in listing 3.15.

[27] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1381`.

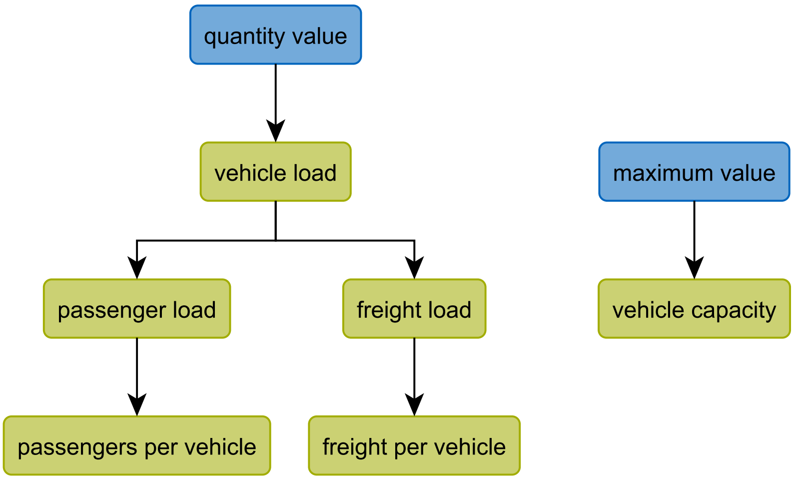


Figure 3.42: Structure of vehicle load.

Concept	Definition
vehicle load	A vehicle load is a quantity value indicating the magnitude of the load (passengers or goods) of a vehicle.
passenger load	A passenger load is a vehicle load that results from passengers.
passengers per vehicle	Passengers per vehicle is a passenger load averaged over a number of vehicles.
freight load	A freight load is a vehicle load that results from freight.
freight per vehicle	Freight per vehicle is a freight load averaged over a number of vehicles.
vehicle capacity	A vehicle capacity is a maximum value that indicates the maximum load of a vehicle.

Table 3.28: Definitions for the load of vehicles.

```
'passenger load' 'has unit' some ('mass unit' or 'count unit')
'freight load' 'has unit' some ('mass unit')
'vehicle capacity' 'has unit' some ('mass unit' or 'count unit')
```

Listing 3.15: Axioms for the load of vehicles.

Fuel Blending Quota

Since fuels like diesel or gasoline are oftentimes not pure, but mixed with combustible fuel from a renewable origin, a concept for the share of renewable fuel could be useful[28]. This is also shown be the application example in section 4.3.2. The suggested definition is presented in table 3.29 with the simple structure shown in figure 3.43, and the axiom to link the value to fuel depicted in listing 3.16.

[28] View issue on GitHub: https://github.com/OpenEnergyPlatform/ontology/issues/1413.

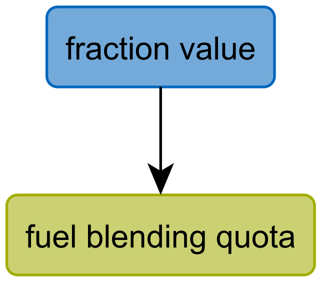


Figure 3.43: Structure of fuel blending quota.

Concept	Definition
fuel blending quota	A fuel blending quota is a fraction value that indicates the share of renewable fuel mixed into fossil fuel.

Table 3.29: Definition for fuel blending quota.

```
'fuel blending quota' 'quantity value of' some 'combustion fuel'
```

Listing 3.16: Axiom for fuel blending quota.

Battery Efficiency

In the first example for the assumption extraction in the next chapter (see section 4.3.1), a variety of efficiency values were assumed. Based on that an efficiency value for batteries was suggested[29]. The discussion showed, that it might be better to specify a bit more detailed and include an efficiency value for a new class storage process. This provides a clear distinction to the efficiency of energy transfer into and out from the battery for which sufficient concepts are already included in the OEO. The resulting structure, definitions, and axioms are shown in figure 3.44, table 3.30, and listing 3.17, respectively.

Concept	Definition
energy storage process	An energy storage process is an energy transformation that whereby input energy and output energy are of the same type, apart from energy losses.
energy storage efficiency	An energy storage efficiency is an energy conversion efficiency that describes the ratio between the input and the useful output of an energy storage process.
battery efficiency	A battery efficiency is the energy storage efficiency of a energy storage process in which a battery is used.

Table 3.30: Definitions for battery efficiency and related concepts.

[29] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1414`.

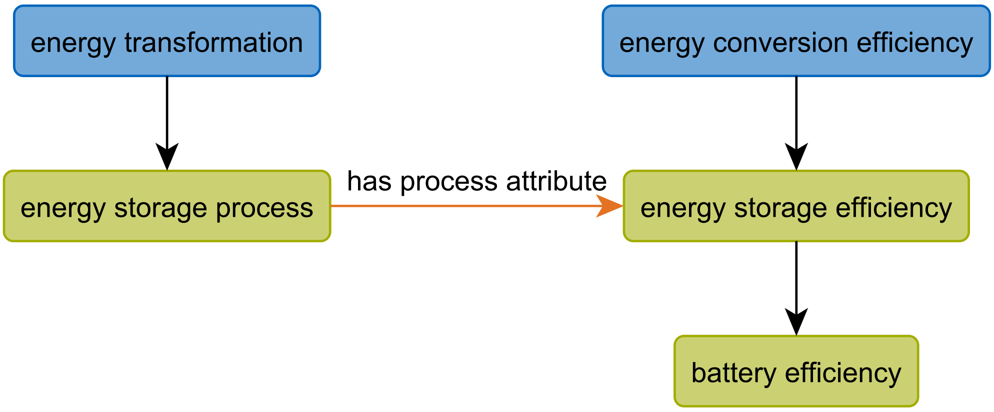


Figure 3.44: Structure of battery efficiency and related concepts.

```
'energy storage process' 'has process attribute' some 'energy storage
    efficiency'
'energy storage process' 'has participant' some 'energy storage object'
```

Listing 3.17: Axioms for the energy storage.

Well-to-Wheel, Well-to-Tank and Tank-to-Wheel Measurements

Like battery efficiency, these terms were suggested as a response to the application example in section 4.3.1[30]. The idea is to have concepts that cover efficiency, energy consumption, and emission for each of the three observation areas well-to-wheel, well-to-tank, and tank-to-wheel. The proposed structure is shown in figure 3.45 and the definitions in table 3.31.

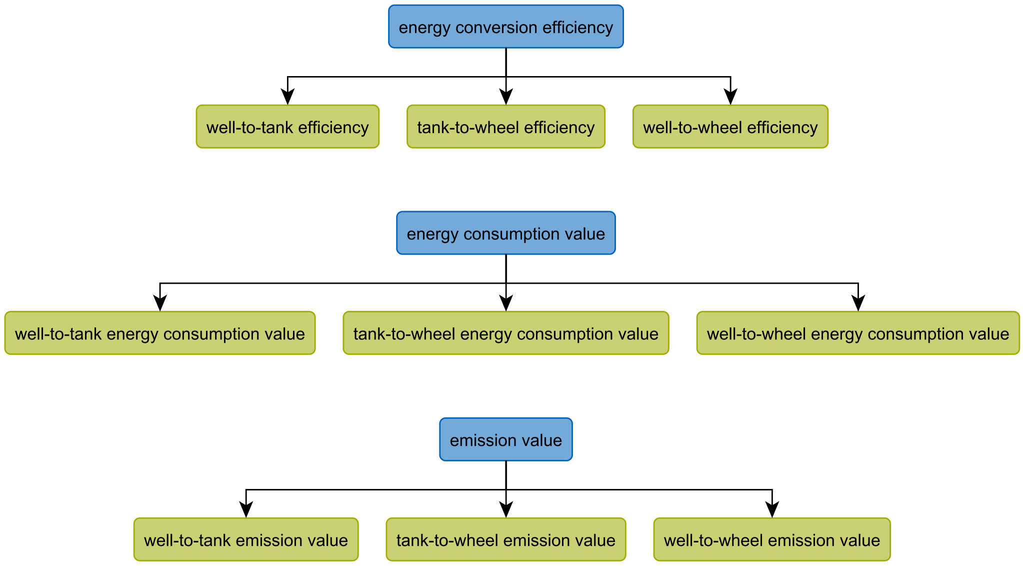


Figure 3.45: Structure of the suggested well-to-tank, tank-to-wheel, and well-to-wheel concepts.

[30] View issue on GitHub: `https://github.com/OpenEnergyPlatform/ontology/issues/1415`.

Concept	Definition
well-to-tank efficiency	A well-to-tank efficiency is the energy conversion efficiency of a series of energy transformation processes from the primary energy production to the storage in a tank or traction battery of a vehicle.
tank-to-wheel efficiency	A tank-to-wheel efficiency is the energy conversion efficiency of a series of energy transformation processes of the energy stored in a tank or traction battery of a vehicle until the conversion into kinetical energy for propulsion.
well-to-wheel efficiency	A well-to-wheel efficiency is the energy conversion efficiency of a series of energy transformation processes from the primary energy production to the conversion into kinetical energy for propulsion.
well-to-tank energy consumption value	A well-to-tank energy consumption value is the energy consumption value of a series of energy transformation processes from the primary energy production to the storage in a tank or traction battery of a vehicle.
tank-to-wheel energy consumption value	A tank-to-wheel energy consumption value is the energy consumption value of a series of energy transformation processes of the energy stored in a tank or traction battery of a vehicle until the conversion into kinetical energy for propulsion.
well-to-wheel energy consumption value	A well-to-wheel energy consumption value is the energy consumption value of a series of energy transformation processes from the primary energy production to the conversion into kinetical energy for propulsion.
well-to-tank emission value	A well-to-tank emission value is the emission value of a series of energy transformation processes from the primary energy production to the storage in a tank or traction battery of a vehicle.
tank-to-wheel emission value	A tank-to-wheel emission value is the emission value of a series of energy transformation processes of the energy stored in a tank or traction battery of a vehicle until the conversion into kinetical energy for propulsion.
well-to-wheel emission value	A well-to-wheel emission value is the emission value of a series of energy transformation processes from the primary energy production to the conversion into kinetical energy for propulsion.

Table 3.31: Definitions for the well-to-wheel, well-to-tank, and tank-to-wheel measurements.

3.4 Implementation

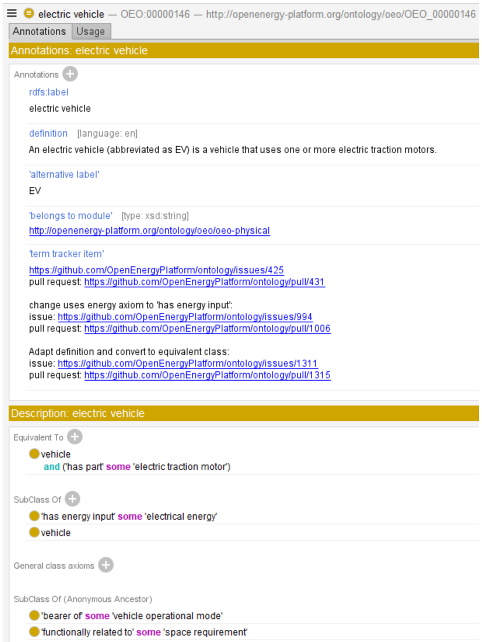
As this project develops an extension to the OEO, the guidelines and workflow for contributing to the OEO have to be respected[31]. As part of these, code sharing and discussion of changes and additions takes place on GitHub.

For the implementation, the Protégé editor from the Stanford Center for Biomedical Informatics Research at the Stanford University School of Medicine [108] was used. It provides a handy interface for the inspection and definition of concepts. Another advantage is the dual usage of numerical identifiers and human-readable

[31] See `https://github.com/OpenEnergyPlatform/ontology/wiki/Workflow` for more information on the OEO specific workflows.

labels. While in the ontology files itself the relations are encoded using the numerical identifiers like in 3.46a, the Protégé editor shows these relations using the human-readable labels like in 3.46b. In Protégé, new relations can also be defined using the labels, making editing the ontology much easier. The ontology can be saved in multiple data formats, like RDF/XML, Manchester Syntax or Turtle, where Protégé takes care of the respective encoding. Nevertheless, a couple of minor problems occurred, which are described together with their solution in appendix A.

(a) Plain text editor.



(b) Protégé editor.

Figure 3.46: Comparison of the same code snippet shown in a plain text editor (a) and the Protégé editor (b).

The concepts are defined as owl:class. The OEO uses numerical identifiers for classes. This leads to the necessity for an additional annotation for the human-readable class name. This name is added with the *rdfs:label* annotation property. Similar, the definitions are added with the *rdfs:definition* annotation. So called *term tracker items*, which link to issues and pull requests where changes to the concept were discussed, are added with the *oeo:term-tracker-item* annotation. Other annotations that might occur are *belongs-to-module* (to denote the module/file of the OEO the concept is stored in), *rdfs:alternative-label* (for labels that can be used as synonyms), *bfo:editor-note* (for notes about the usage of the concept or other important remarks) and *rdfs:comment* (for general comments). Table 3.32 summarizes the OWL expressions and annotations most commonly used in the OEO and shows their purpose.

For the relations, special OWL keywords come into play. For the subclass relation this is *SubClassOf* and for the equivalence relation the keyword is *EquivalentTo*. There are also keywords for logical set operations and quantifiers, these are *and,*

expression	purpose
owl:class	Definition of a new class
rdfs:label	Definition of the human-readable class name
definition	(Human readable) Definition of the concept expressed by this class
oeo-term-tracker-items	Provides links to GitHUb issues and pull requests for facilitated tracing and understanding of changes

Table 3.32: Most common OWL expressions in the OEO and their usage.

or, some, min. In Protégé, logical operators are color-coded in blue, quantifiers in pink. The axioms in the previous sections use the same color-coding. For relations with own semantics so called *object properties* are used. Analog to the classes above, they have an annotation for their name (*rdfs:label*) and an annotation for their semantics (*definition*). The label of the object property can then be used as a keyword in the definition of a relation. The *data properties* are barely used in the OEO and are not relevant for implementation part of this thesis. Table 3.33 summarizes keywords and properties used for the definition of relations.

keywords / properties	purpose
SubClassOf	Denotes that a class is a subclass of another class.
EquivalentTo	Denotes that a class is equivalent to a certain set of other classes.
and	Denotes a logical and
or	Denotes a logical or
not	Denotes a logical negation
some	Denotes the existential quantifier
min	Denotes a minimum quantifier
max	Denotes a maximum quantifier
Object property	Used to define own relations between classes.
rdfs:label of Object property	Used in the definition of relations.
Data property	Used to define relations between classes and data.

Table 3.33: Most common keywords and properties in OWL.

For the actual implementation of the concepts, the reader is referred to GitHub, where the entire OEO code can be retrieved. For single concepts, the provided links to the pull requests in the previous section lead to the code implementing the respective concept. The implementation adds no changes with regard to contents, and with the explanations in this section, it should be understandable. Hence, there is no reason to discuss the implementation of each concept.

Chapter 4

Possible Application Fields of the Ontology

4.1 Purpose of the application examples

There are many different applications possible for an ontology, such as inference, consistency checking, automated comparison or integration of data. All of them have in common, that they need annotated data to work with. Therefore, the first application example will be the annotation of data sets. The second example is the generation of scenario assumptions from text. Predicting the future means to make assumptions about the future on which the predictions are made. Those assumptions are usually written in plain text, making it difficult to compare them to the assumptions of other scenarios. Using the ontology as a basis for comparison, that is, to collect the assumptions for a scenario in a formalized manner and annotating them with ontology concepts, should facilitate this process. This possibility is examined by the second example.

Beneath showcasing the application of the ontology, the examples have further purposes. The first purpose, thought of when the idea for the application example was created, is to check the usefulness of the so far proposed concepts. It turned out fast that this is not a good motivation. Even just logical thinking reveals that "usefulness" is a difficult quality to measure. Assume that a concept in the OEO is useful as soon as it is used once for the annotation of a data set or the creation of a knowledge graph. That is a reasonably definition for usefulness in this context, because it is the very purpose of a concept to be used in that way, that is, to depict a particular notion of information. Then there might be concepts that are not used in the examples and thus would be considered useless. But they could be used in the future by a data set that simply hasn't been considered yet, which in turn would make the concept useful. This means, that it is not possible to tell about the usefulness of a concept by looking at only a small amount of data sets.

With the first reason for the application example turning out irrelevant, the second reason remains to check for suitable additions of concepts. This is indeed a valid motivation. Data that cannot be annotated by the terms in the OEO as of the state before implementing the application example should receive a new corresponding concept unless that concept would be too far away from the energy domain or denote only a neglectable, subtle notion of difference to an existing concept.

In consequence, this chapter aims at identifying new concepts. Additionally, the process of annotating data is documented, highlighting difficulties or problems and proposing solutions where possible. This provides a good overview over the possibilities and barriers to overcome in order for the OEO (and the OEP) to reach their goal of facilitated data exchange. Furthermore, the transfer of assumptions from text to a data table shows how more advanced data exchange could look like and which difficulties are to overcome.

4.2 Annotation of data sets

In order to test the annotation capability of the OEO, three data sets have been annotated. The first one is `quetzal_germany`[1], which contains model data about the transport performance in Germany [109]. The second one is `iTEM harmonized_dataset` [110] which contains many different measurements from various sources. The third data set is `Laos TED`[111], which contains several data tables about the energy and transport situation in Laos. The choice of the these data sets was influenced by the limited public accessibility of data sets about the transport domain. Furthermore, they are very distinct from each other. More specific, `quetzal_germany` is the result of a model and covers only the industrial country Germany, `iTEM harmonized_dataset` unifies data from various sources across the globe, and `Laos TED` contains data about a developing country in Asia.

For the annotation, the column headers, that is, the name or heading of the column, and text values of some columns, that is, textual entries in the column, are mapped to OEO concepts. The logical mapping can be done in a simple table. For a proper annotation according to the OEP metadata structure[2], the OEMetabuilder tool can be used. The most important features for this application example are the distinction between column header (in the OEMetabuilder it is simply called name) and values, and the linking of the column header to a unit, which is representing the unit of all values in the considered column. As of writing, the unit cannot be annotated with a unit concept from the OEO using the OEMetabuilder, but there is the intention to change that. In consequence, any unit, independent of the OEO, could be chosen.

Furthermore, the data should be in a format that follows the OEP guidelines[3]. That is not only for a consistent layout and possible further usage through the OEP, but also to avoid some problems with the annotation. One example is a year (e.g. 2022) as column header for a column that contains only numbers (e.g. 10). Since only the column header would be annotated, the corresponding OEO concept would be

[1] Data set retrieved from `https://github.com/marlinarnz/quetzal_germany/releases/tag/v1.2.0`.

[2] See `https://github.com/OpenEnergyPlatform/oemetadata`.

[3] See `https://openenergy-platform.org/tutorials/7/`.

scenario year. But the value, in this example the 10, is certainly not a year.

In the following examples, the mapping for the column headers and values, where applicable, is shown. Since the focus is on the feasibility of the mapping rather than the formally correct and OEP-conform annotation, the mapping avoids redundancies and may consider multiple data tables in one mapping where suitable. A "+" between two OEO concepts means that both concepts would be necessary to depict the notion of the column header.

4.2.1 quetzal_germany

The `quetzal_germany` data set as a whole consists of two files, `pkm.csv`, which holds the pkm per region and mode, and `results_agg.xlsx`, which contains four data tables about passenger kilometer per NUTS 1[4] region and transport mode, about vehicle kilometer, about greenhouse gas emissions, and about travel time respectively. Additionally, there are some extra calculations outside the actual data tables, which are included nonetheless, because it is a good opportunity to test the annotation capability of the OEO.

Column header	**OEO concept(s)**	**Unit**
origin	study subregion	
mode	transport mode	
pkm	transport performance value	passenger-kilometre

Table 4.1: Mapping for `pkm.csv`.

One general difficulty in annotation is the choice of the correct concept. This requires thorough thinking about the definitions of the OEO concepts and the semantics of column that is annotated. In this example, the correct type of spatial region in tables 4.1 and 4.2 was a case that was not trivial to solve. Another difficulty was to determine, whether *emission quantity value* is needed in addition to *carbon dioxide equivalent quantity* for emission values (see table 4.2). This issue is reinforced because of their placement and relation in the OEO, that is, *carbon dioxide equivalent quantity* relates to *emission quantity value*, which in turn relates to a unit. Since *carbon dioxide equivalent quantity* is understandable from a human point and relating it to a unit does not contradict the axioms in the OEO, it seems sufficient to omit *emission quantity value* for this annotation.

The biggest challenge with the annotation of this data set is the correct portray of the *inner* and *inter* terms. In the tables they form a row together with a NUTS 1 region and a transport mode. The *inner* and *inter* refer to NUTS 3 regions, that is, whether the boundary of that NUTS 3 region is crossed *inter* or not *inner* during a transport process. The results from those NUTS 3 regions are then aggregated for the NUTS 1 regions. Note that NUTS 3 regions are subregions of NUTS 1 regions. This means that data in the *inter* column includes data from transport processes that did not cross the NUTS 1 region boundary but only the boundary of a NUTS 3

[4] NUTS: Nomenclature of territorial units for statistics, developed by the European Union. See `https://ec.europa.eu/eurostat/web/nuts/nuts-maps`.

Column header	OEO concept(s)	Unit
NUTS1	study subregion	
route_type	transport mode	
pkm_inter	transport performance value + inter	passenger-kilometre
pkm_inner	transport performance value + inner	passenger-kilometre
pkm	transport performance value	passenger-kilometre
inter pkm share	transport performance value + inter	fraction value
inner pkm share	transport performance value + inner	fraction value
vkm_inter	transport performance value + inter	vehicle-kilometre
vkm_inner	transport performance value + inner	vehicle-kilometre
vkm	transport performance value	vehicle-kilometre
tCO2eq	carbon dioxide equivalent quantity	metric ton
inner emissions	carbon dioxide equivalent quantity + inner	metric ton
inter emissions	carbon dioxide equivalent quantity + inter	metric ton
time_inter	time span + inter	hour
time_inner	time span + inner	hour
time	time span	hour

Table 4.2: Mapping for the `pkm`, `car_vkm`, `emissions`, and `time` tables within `results_agg.xlsx`. Column header includes other terms that were used in the data set although not used as a column header.

Value	OEO concept(s)
air	national public air transport
bus	local public transport
car	private transport
coach	long distance bus transport
rail_long	long distance train transport
rail_short	regional train transport
walking	micromobility

Table 4.3: Mapping for the values in the `mode` and `route_type` columns within `pkm.csv` and `results_agg.xlsx` respectively.

region. This notion is so unique that no further terms for the OEO have been suggested. Instead, a possible solution would be to add a general remark about that specialty in the metadata, or to restructure the data in a more suitable way.

As a consequence of annotating this data set, *vehicle-kilometre* and concepts for spatial context information like *inner* and *inter* were suggested as additions to the OEO. The values from table 4.3 were taken into consideration for a further refinement in the, at this time, ongoing discussion about *transport mode*. For the implemented or suggested definitions, see chapter 3.

4.2.2 iTEM harmonized_dataset

The `iTEM harmonized_dataset` integrates data from various sources into one data set as explained in an accompanying rule book [110]. Unfortunately, it contains little information on the semantics of the used terms. The data is stored in the `iTEM harmonized_dataset.csv` file. It has the previously mentioned problem of years as column headers. For this exemplary annotation, the data layout was not changed, and thus the year columns can not be annotated and are therefore neglected. For a OEP conform layout the year columns would be substituted by a single *Year* column and new rows would be added for each non-empty year column. Furthermore, since there is an extra column for the unit of the variable in the row, that is, every value in the row can have its own unit, there are no units mapped to single columns.

Column header	OEO concept(s)	Unit
Source	dc:source	
Country	study subregion	
ISO Code	symbol	
Region	study subregion	
Variable	variable	
Unit	unit of measurement	
Service	transport	
Mode	transport	
Vehicle Type	vehicle	
Technology	vehicle	
Fuel	fuel	
ID	dc:identifier + data set	

Table 4.4: Mapping for `iTEM harmonized_dataset.csv`.

There were a couple of difficulties and problems when annotating this data set. The first one is again the right choice of a spatial region concept. Especially, if both *Country* and *Region* are mapped to the same type of region this could lead to irritations or problems for subsequent users of the annotated data set. Then there is the mapping of *Source* to *dc:source*, which caused difficulties in so far as *dc:source* is imported without definition into the OEO and thus required to look up the definition externally[5]. The same difficulty occurred for *dc:identifier*[6]. Next, the mapping of *ISO code* to *symbol* is a bit generic, but there is an ongoing discussion about importing geography related terms into the OEO[7]. Both *service* and *mode* refer to transport concepts. Similar, *Vehicle Type* and *Technology* are both mapped to *vehicle*. Actually, *Vehicle Type* refers to the vehicle design (e.g. car, bus, ship etc.) whereas *Technology* refers to the propulsion type (e.g. electrical, combustion etc.). But there is no suitable way to integrate that notion into the annotation and, therefore, both are mapped to *vehicle*.

[5] Definition at `https://www.dublincore.org/specifications/dublin-core/dcmi-terms/terms/source/`.

[6] Definition at `https://www.dublincore.org/specifications/dublin-core/dcmi-terms/elements11/identifier/`.

[7] See `https://github.com/OpenEnergyPlatform/ontology/issues/1336`.

While the annotation of this data set showed a lot of difficulties worth to discuss in more depth in the next chapter, the only new term it inspired is *pipeline transport*.

4.2.3 Laos TED

The third data set that was annotated, `Laos TED`, contains several data tables in a spreadsheet. They have quite a variety of topics they cover. Not all of them are relevant for energy system modeling, but those can still contribute to identify challenges for the annotation. One drawback of this data set is the lack of additional information that could explain the meaning of the terms in the data set.

Column header	**OEO concept(s)**	**Unit**
ID	dc:identifier	
Items	written name	
Area	sector	
Type		
Year introduced	scenario year	
Target year	scenario year	
Status	modus	
Summary	textual entity	
Link	reference	

Table 4.5: Mapping for the `Policies` table in `Laos TED.xlsx`.

One problem with this table is the mapping of *Type*, which has values *Strategy*, *Policy*, *Regulation*, *Project*, *Action Plan*, or no value at all. The only suitable options in the OEO are *policy*, *project*, and *plan specification*. The main problem remains the unclear meaning of the values used in the data set. Therefore, the mapping cannot be completed. A smaller difficulty poses the choice of an OEO concept for *Year introduced* and *Target year*. The definitions in the OEO make it difficult to decide between *typical year* and *scenario year*.

There are a few gaps in the mapping table 4.6. *Fuel Oil* cannot be mapped, because the definition and the distinction to the other oil based terms in the table is not clear. *Other Petroleum Products* and *Others* cannot be mapped, because there is no simple way of expressing the notion of "other" with OEO concepts.

Another difficulty is highlighted through the mapping in table 4.7. Unit magnitudes such as "thousand" or "million" can either be added as a second concept or added to the unit. In the latter case it might even be converted into a prefix such as "k-" or "M-". The follow-up discussion suggests to add this kind of information with a prefix, where it is common, and to create a composed concept, if necessary[8].

The data tables mapped in table 4.8 use a more fine-grained distinction of car types than the OEO. In consequence, these are all mapped to *car*. It is worth to note, that also *3 Wheeler* satisfies the definition of the OEO concept *car*. In addition, it should

[8] See `https://github.com/OpenEnergyPlatform/ontology/issues/1402` and links therein.

Column header	OEO concept(s)	Unit
Year	scenario year	
Coal	coal	kilo ton of oil equivalent
Petroleum Products	mineral oil	kilo ton of oil equivalent
Motor Gasoline	motor gasoline	kilo ton of oil equivalent
Jet Fuel	jet fuel	kilo ton of oil equivalent
Gas/Diesel Oil	gas diesel oil	kilo ton of oil equivalent
Fuel Oil		kilo ton of oil equivalent
LPG	liquefied petroleum gas	kilo ton of oil equivalent
Other Petroleum Products		kilo ton of oil equivalent
Others		kilo ton of oil equivalent
Electricity	electrical energy	kilo ton of oil equivalent
Total	Integral	kilo ton of oil equivalent

Table 4.6: Mapping for the `Demand by Fuel` table in `Laos TED.xlsx`.

Column header	OEO concept(s)	Unit
Year	scenario year	
passenger (Thousand)	passenger	count unit + kilo
pkm (Million)	energy service demand for pkm	pkm + mega
ton (Thousand)	good	metric ton + kilo
tkm (Million)	energy service demand for tkm	tkm + mega

Table 4.7: Mapping for the `Transport Demand` table in `Laos TED.xlsx`.

Column header	OEO concept(s)	Unit
Year	scenario year	
2 Wheelers	motorcycle	count unit
3 Wheelers	car	count unit
Small car - Sedan	car	count unit
Small car - SUVs	car	count unit
Large car - Van	car	count unit
Large car - Pick up	car	count unit
Truck	truck	count unit
Bus	bus	count unit

Table 4.8: Mapping for the `Vehicle Fleet Data` and `New Registrations By Year` tables in `Laos TED.xlsx`.

be noted, that it is not clear whether the vehicles are used for the type of transport that is intended by the OEO.

For the mapping in table 4.9, the biggest problem is the meaning of *domestic*. It could refer to the national level or it could refer to households as opposed to other buildings. The meaning is not clear, which makes the mapping of *Domestic Supply* and *Domestic Consumption* incomplete. A smaller issue the concept choice for *Generation*. Without context information, both *net electricity generation* and *gross*

Column header	OEO concept(s)	Unit
Year	scenario year	
Percentage of population with access to electricity	population + electrical energy	percent
Generation	net electricity generation	GWh
Export	electricity export value	GWh
Domestic Supply	electrical energy amount value	GWh
Import	electricity import value	GWh
Domestic Consumption	energy consumption value + electrical energy	GWh
Average Price in Domestic	electricity price + arithmetic mean	US cent / kWh

Table 4.9: Mapping for the `Electricity Demand and Supply` table in `Laos TED.xlsx`.

electricity generation would be possible. The former is chosen, because it would be the more interesting measure, but it cannot be said, if that is correct. Lastly, the *access* part of *Percentage of population with access to electricity* has no corresponding OEO concept and thus is omitted. An *access* concept has not been suggested yet, because it is no specialty to the energy or transport domain and is not easy to define due to its abstractness.

Column header	OEO concept(s)	Unit
Year	scenario year	
Hydro	hydroelectric energy transformation	GWh
Coal	coal + electricity generation process	GWh
Solar	photovoltaic energy transformation	GWh
Biomass	biomass + electricity generation process	GWh

Table 4.10: Mapping for the `Electricity Generation Mix` table in `Laos TED.xlsx`.

The mapping in table 4.10 shows no problems. In table 4.11, there is again no problem, but for the *Plan Develop 2021-2030* it can only be assumed that length values are given. Furthermore, this is a good example to remark that the general subject of the data, in this case the *electricity grid*, should be annotated in a more general field in the metadata like subject[9].

The mappings in table 4.12 are comparably easy. LAK is the abbreviation for "Lao kip" which is the currency of Laos. Single currencies are not included in the OEO and out of the scope this thesis, because they are not strongly related to the energy or transport domain. Furthermore, if currencies should be included in the OEO, it would probably be easier to integrate them in a systematic manner, for example, with the integration of a currency ontology, than to define them all from scratch. The

[9] See `https://github.com/OpenEnergyPlatform/oeplatform/discussions/1107#discussioncomment-4147087`.

Column header	**OEO concept(s)**	**Unit**
No.	dc:identifier	
Transmission	electrical energy transfer	volt
Length	length value	km
Plan Develop 2021-2030	length value	km

Table 4.11: Mapping for the `Electricity System` table in `Laos TED.xlsx`.

Column header	**OEO concept(s)**	**Unit** (`Fuel Supply`)	**Unit** (`Fuel Price`)
Year	scenario year		
Diesel	diesel	kiloliter	LAK / liter
Gasoline	gasoline	kiloliter	LAK / liter

Table 4.12: Mapping for the `Fuel Supply` and `Fuel Price` tables in `Laos TED.xlsx`.

specific units are again an example why composed concepts should be added to the OEO.

Column header	**OEO concept(s)**	**Unit**
Year	scenario year	
2 Wheelers	motorcycle	count unit
3 Wheelers	car	count unit
Taxi	car + public transport	count unit
Public Bus	bus	count unit
Bus	bus	count unit

Table 4.13: Mapping for the `Public Service Vehicle Licenses` table in `Laos TED.xlsx`.

The last table of the `Laos TED` data set, mapped in table 4.13, has again problems with ambiguity and distinction. In this case, the difference between *Public Bus* and *Bus*. It is not clear, where the difference is between them, and thus they are both mapped to the *bus* concept. For *Taxi*, the concept *public transport* is added in addition to *car* to indicate that it is a car used for public transport.

Overall, the `Laos TED` data set brought a lot of insights about the annotation limits that are further discussed in the next chapter. Furthermore, it lead to the suggestion of these concepts: specific values for cost and energy consumption, electricity cost, ton of oil equivalent, and electricity and fuel demand.

4.3 Generating scenario assumption data from studies

Many studies about energy systems in a larger scale, e.g. nation-wide, differentiate between different scenarios. This could be as simple as an optimistic compared to a pessimistic scenario. But it could also include assumptions about the spread of certain technology or the development of social and economical factors. For a comparison of such scenarios and their results, the assumptions that were made for each scenario need to be captured in a structured way. For this purpose, the OEP uses scenario factsheets[10], which are currently in an overhaul process.

In the current state, a scenario factsheet of the OEP allows to attribute certain parameters with values. The available parameters may be insufficient to describe a scenario, which is why some parameters link to a table with parameters. The layout of these parameter tables is not uniform and can be chosen freely. For the examples in the following subsections, a minimum viable layout is chosen containing the following columns: ID, Parameter, Value, Unit, Year, and Base Year. In other words, it depicts that a uniquely identifiable parameter will have a certain value with a certain unit in a certain year in comparison to a certain base year. The base year is deemed necessary, because many parameters do not provide absolute values but relative changes. Furthermore, it is easily mapped to OEO concepts as table 4.14 shows. The limitations of this minimal layout are discussed in the next chapter. All assumptions are put into that table scheme first, then it is checked, whether they can directly be inserted into the scenario factsheet.

Column header	**OEO concept(s)**	**Unit**
ID	dc:identifier	
Parameter	(needs individual mapping)	
Value	quantity value	
Unit	unit of measurement	
Year	scenario year	
Base Year	scenario year	

Table 4.14: Mapping for the the columns in the minimal viable table layout. There is no mapping to units, because of the separate unit column (header). Parameter needs to be mapped individually to OEO concepts?

The two data studies used for the exemplary assumption extraction are "EU road vehicle energy consumption and CO2 emissions by 2050 – Expert-based scenarios" [112] and "Deutschland auf dem Weg zur Klimaneutralität 2045 - Szenarien und Pfade im Modellvergleich" [3], from the latter specifically chapters 1 and 2. The first study was chosen arbitrarily from the results of a new literature search with keywords "transport", "energy", and "scenario". This way, there was no previous information on how well structured or detailed the assumptions are. This would likely be the case in any real world application, or at least, there would be no influence on the structure. The second example, on the other hand, was already known from the literature review in chapter 2. It was also known, that it contains nicely structured assumptions presented on-block rather than dispersed throughout the document. This allowed to compare the success of the extractions and to examine, whether the structure is important for that.

[10] See `https://openenergy-platform.org/factsheets/scenarios/`

4.3.1 Arbitrary study

The study "EU road vehicle energy consumption and CO2 emissions by 2050 – Expert-based scenarios" [112] specifies the three scenarios *High Electrification*, *High Electrification plus Hydrogen* and *Mixed*. For each scenario the energy consumption and CO_2 emissions by 2050 are modeled based on certain assumptions. The paper presents some of these assumptions dispersed throughout the text, while other parameter assumptions are collected in tables. Specifically, tables 7 and 9 of the paper show such assumptions. These were adapted to the minimal table layout. The resulting parameter tables are shown in tables 4.15 and 4.16. In the text itself, five assumptions were identified. They are shown in table 4.17.

From these assumptions, only two could be inserted directly into the scenario factsheet. These are entry 4 from table 4.17 as *emission_reductions* and entry 2 from the same table as *share_RE_mobility*. The former assumption is made for both electrification scenarios, the latter assumption for all three scenarios. The others need to remain in linked data tables.

The immediate issue present in that paper is the difficulty to identify assumptions in the first place. There is no dedicated section for assumptions and not all tables indicated clearly whether the data is a result from the model or assumption-based input data. Due to that, there is a chance that not all assumptions in this paper were identified. In a similar fashion, the year and especially the base year of the parameters are not always clear. Sometimes they need to be assumed themselves. As another result, fitting the assumptions into the minimal parameter table layout showed that it could be necessary to extend that layout. This is mainly because of the great length of the parameter names as can be seen in all three tables 4.15, 4.16 and 4.17. Ideas for a better layout are discussed in the next chapter. Also, the depiction of completeness or coherence to guidelines such as entry 1 in table 4.17 poses a problem, but is likely not solved by another table layout. Furthermore, the layout of the scenario factsheets seems to be insufficient as only two assumptions could be inserted directly. Because of issues like that, the scenario factsheets are being reworked right now.

The identification of assumptions in this study lead to the suggestion of the following concepts as additions to the OEO: efficiency for well-to-wheel, well-to-tank, and tank-to-wheel; energy consumption value for well-to-wheel, well-to-tank, and tank-to-wheel; emission value for well-to-wheel, well-to-tank, tank-to-wheel; battery efficiency; load of vehicles. Furthermore, some shortcomings and difficulties with the current scenario factsheets of the OEP and formalizing assumptions in general are briefly discussed in the next chapter.

ID	Parameter	Value	Unit	Year	Base Year
1	reduction in activity per vehicle for 2-Wheelers and S/M cars because of 'Reduced urban parking search traffic' (pessimistic)	4	%	2050	2015
2	reduction in activity per vehicle for 2-Wheelers and S/M cars because of 'Reduced urban parking search traffic' (optimistic)	10	%	2050	2015
3	reduction in activity per vehicle for L cars, SUVs, LCVs, Vans < 7,5 t because of 'Reduced urban parking search traffic' (pessimistic)	2	%	2050	2015
4	reduction in activity per vehicle for L cars, SUVs, LCVs, Vans < 7,5 t because of 'Reduced urban parking search traffic' (optimistic)	6	%	2050	2015
5	reduction in activity per vehicle for city buses and trucks < 12 t because of 'Reduced urban parking search traffic' (pessimistic)	0	%	2050	2015
6	reduction in activity per vehicle for city buses and trucks < 12 t because of 'Reduced urban parking search traffic' (optimistic)	2	%	2050	2015
7	reduction in activity per vehicle for trucks >7,5 t and long distance buses because of 'Reduced urban parking search traffic' (pessimistic)	0	%	2050	2015
8	reduction in activity per vehicle for trucks >7,5 t and long distance buses because of 'Reduced urban parking search traffic' (optimistic)	0	%	2050	2015
9	reduction in number of trucks >7,5 t and long distance buses because of 'Intermodality of freight' (pessimistic)	2	%	2050	2015
10	reduction in number of trucks >7,5 t and long distance buses because of 'Intermodality of freight' (optimistic)	5	%	2050	2015
11	reduction in activity per vehicle for city buses and trucks < 12 t because of 'Coordination systems for freight (logistics)' (pessimistic)	5	%	2050	2015
12	reduction in activity per vehicle for city buses and trucks < 12 t because of 'Coordination systems for freight (logistics)' (optimistic)	10	%	2050	2015
13	reduction in activity per vehicle for trucks >7,5 t and long distance buses because of 'Coordination systems for freight (logistics)' (pessimistic)	5	%	2050	2015
14	reduction in activity per vehicle for trucks >7,5 t and long distance buses because of 'Coordination systems for freight (logistics)' (optimistic)	10	%	2050	2015
15	reduction in number of trucks >7,5 t and long distance buses because of 'Increased truck capacity' (pessimistic)	5	%	2050	2015
16	reduction in number of trucks >7,5 t and long distance buses because of 'Increased truck capacity' (optimistic)	10	%	2050	2015

Table 4.15: Mapping for the parameters in table 7 in [112].

ID	Parameter	Value	Unit	Year	Base Year
1	grid efficiency for BEV 2015, Range 250 km	95	%	2050	2015
2	grid efficiency for BEV 2050+, Range 600 km	96	%	2050	2015
3	inverter AC/DC efficiency for BEV 2015, Range 250 km	95	%	2050	2015
4	inverter AC/DC efficiency for BEV 2050+, Range 600 km	96	%	2050	2015
5	battery efficiency (fast charge) for BEV 2015, Range 250 km	92	%	2050	2015
6	battery efficiency (fast charge) for BEV 2050+, Range 600 km	93	%	2050	2015
7	power electronics efficiency (DC/DC DC-AC) for BEV 2015, Range 250 km	91	%	2050	2015
8	power electronics efficiency (DC/DC DC-AC) for BEV 2050+, Range 600 km	92	%	2050	2015
9	min. motor to wheel efficiency (WLTP) for BEV 2015, Range 250 km	86	%	2050	2015
10	max. motor to wheel efficiency (WLTP) for BEV 2015, Range 250 km	91	%	2050	2015
11	min. motor to wheel efficiency (WLTP) for BEV 2050+, Range 600 km	87	%	2050	2015
12	max. motor to wheel efficiency (WLTP) for BEV 2050+, Range 600 km	92	%	2050	2015
13	min. grid to wheel efficiency for BEV 2015, Range 250 km	65	%	2050	2015
14	max. grid to wheel efficiency for BEV 2015, Range 250 km	69	%	2050	2015
15	min. grid to wheel efficiency for BEV 2050+, Range 600 km	69	%	2050	2015
16	max. grid to wheel efficiency for BEV 2050+, Range 600 km	73	%	2050	2015

Table 4.16: Mapping for the parameters in table 9 in [112].

ID	Parameter	Value	Unit	Year	Base Year
1	EU greenhouse gas and renewable energy targets for 2020	100	%	2020	2016
2	vehicle green fuel consumption	100	%	2050	2015
3	vehicle electricity consumption	100	%	2050	2019
4	urban transport emissions in the high electrification and high electrification plus hydrogen scenarios (EC transport white paper)	0	ton	2050	2019
5	air pollutant emissions from combustion engines (probably only in the high electrification and high electrification plus hydrogen scenarios)	0	ton	2050	2019

Table 4.17: Mapping for the parameters from the text in [112].

4.3.2 Well-structured study

The other study taken as an example for assumption extraction is "Deutschland auf dem Weg zur Klimaneutralität 2045 - Szenarien und Pfade im Modellvergleich"[3], already introduced in chapter 2. In the study, several energy related sectors are being investigated, among others the transport sector. The study distinguishes between general assumptions that are valid for all sectors and scenarios therein, and specific assumptions that concern all or some scenarios of a specific sector only. The former are introduced in a table in the first chapter, the latter in text form at the beginning of each chapter about the sector they are addressing. Since this thesis is interested primarily in the intersection of energy and transport, only the chapter for transport is considered for sector-specific assumptions. Again, the assumptions were filled into minimal parameter tables and the result is shown in tables 4.18 and 4.19.

The direct insertion of assumptions into a scenario factsheet was problematic again. Only assumption 2 in table 4.18 about the greenhouse gas emission could be filled in properly. The others need to be kept in parameter tables. Not even the intermediate value, assumption 1 in table 4.18, could be included.

Two new difficulties were identified in that process. The first one, in the factsheets it is not possible to denote intermediate values. A simple example in this paper are the assumptions for greenhouse gas reductions until 2030 and 2045 in comparison to 1990. In the scenario factsheet, it is not possible to include both values. A

ID	Parameter	Value	Unit	Year	Base Year
1	GHG reduction targets	65	%	2030	1990
2	GHG reduction targets	100	%	2045	1990
3	limit for kumulated CO2 emissions (excl. international aviation and shipping) (minimum)	7300	MtCO2	2045	2020
4	limit for kumulated CO2 emissions (excl. international aviation and shipping) (maximum)	7700	MtCO2	2045	2020
5	limit for biomass usage (primary energy)	410	TWh		
6	limit for geological storage of CO2 (incl. Industrial processes and fossil emissions)	50	MtCO2/year		
7	realised potential of CO2 withdrawal (incl. Depressions) (minimum)	44	MtCO2/year		
8	realised potential of CO2 withdrawal (incl. Depressions) (maximum)	60	MtCO2/year		
9	Increase of the BIP (minimum)	78	%	2050	2019
10	Increase of the BIP (maximum)	85	%	2050	2019
11	population (minimum)	80	Million	2050	2021
12	population (maximum)	83	Million	2050	2021

Table 4.18: Mapping for the general assumptions in table 1.2 in [3].

ID	Parameter	Value	Unit	Year	Base Year
1	CO2 cost	100	EURO/tCO2	2025	2021
2	CO2 cost	200	EURO/tCO2	2030	2021
3	CO2 cost	500	EURO/tCO2	2045	2021
4	reduction of fleet limits for CO2 for cars	50	%	2030	2021
5	reduction of fleet limits for CO2 for trucks	31	%	2030	2021
6	cost reduction for battery technology (electrification scenario)	55	%	2030	2021
7	expansion/completion of charging infrastructure (electrification scenario)	100	%	2030	2021
8	reduction of real electricity cost (electrification scenario)	20	%	2045	2021
9	cost reduction for fuel cells (hydrogen scenario)	80	%	2030	2021
10	expansion/completion of hydrogen filling station infrastructure (hydrogen scenario)	100	%	2035	2021
11	blending quota of E-fuels to normal fuels (E-fuels scenario)	10	%	2030	2021
12	blending quota of E-fuels to normal fuels (E-fuels scenario)	90	%	2040	2021

Table 4.19: Mapping for the assumptions in chapter 2, *Verkehr*, in [3].

similar issue, but not only problematic for the scenario factsheets but also for a normal parameter table is the representation of allowed value ranges. As an example from the paper, the *limit for kumulated CO2 emissions* is assumed as 7500 +/- 200 MtCO2 in the year 2045. That information is stored in two rows in table 4.18, one with value 7300 and one with value 7700. Other possibilities to handle this problem with a different parameter table layout are discussed in the next chapter. Furthermore, some of the previously mentioned difficulties are present as well, such as missing information about year and comparison year like for entries 5 to 8 in table 4.18, and the depiction of completeness like in entries 7 and 10 in table 4.19.

The only new concepts inspired by this application is the fuel blending quota. Other terms that are used in the example are either already included in the OEO or too abstract as to be addressed as part of this thesis. Examples for the latter are limit, reduction, expansion, or completion.

Chapter 5

Discussion

5.1 Difficulties

A number of difficulties occurred during the development of this thesis.

The definition of axioms is oftentimes challenging. The major reason for that is the lack of time constraints for OWL axioms. That means there is no information on when the proposed axiom should be valid. In consequence, only axioms that are valid all the time should be included. However, that is not as easy as it sounds. As an example, axioms that apply the object property 'uses' to connect two concepts A and B state that concept A uses concept B all the time. If it really is true, it means that during A's entire existence A uses B. In reality that is seldom the case. Instead, "all the time" often refers to the time in operation. That is acceptable, as long as this is clear from the definition of the respective concepts and no ambiguities are introduced. The definitions of *gas vehicle* and its subclasses in section 3.3.2 are good examples for this. In conclusion, axioms should be defined carefully as they are generally valid without explicit time restrictions.

Another difficulty that arises from OWL and its limitations, is the depicting of a starting location that is different from an ending location. In OWL, it is not possible to formulate that. In turn, the discussion about concepts for boundary-crossing processes becomes more difficult. It might be possible to include that information in a human-readable way but without machine-readable axiom. Since not even the basic prerequisites for implementation (e.g. implement as class or as object property) have been decided, it would be purely speculative to discuss this more in depth, and therefore, it is not done here.

In the previous chapter, a couple of general difficulties during the annotation process were identified. The first one is to determine which terms are sufficient. In the `quetzal_germany` example, *carbon dioxide equivalent quantity* was used for annotation, specifically without the addition of *emission quantity value*. In the OEO, *carbon dioxide equivalent quantity* is a process attribute and related to *emission quantity value*, which is a quantity value, via the axiom `'has quantity value' some 'emission quantity value'`. From a logical perspective, this requires an emission quantity value to exist, which is referenced by the *carbon dioxide equivalent quan-*

tity. However, this distinction is more relevant for the creation of a knowledge graph based on the annotation than it is for the annotation itself. Hence, the choice of only adding *carbon dioxide equivalent quantity* to the annotation is acceptable and even beneficial in terms of conciseness. A reader who reads the data set and the meta data will know the meaning of the data, which is the main goal of the annotation.

Another difficulty for annotation pose distinctions that are made in a data set, but not in the OEO. An example is the division of vehicles into design types (e.g. car, truck etc.) and propulsion types (e.g. combustion of diesel/gasoline, combustion of gas, electric etc.). While the OEO distinguishes different design and propulsion types from each other, there are no classes that cover all vehicles characterized by design or all vehicles characterized by propulsion. This would correspond to one class containing aircraft, land vehicle, watercraft and one class containing electric vehicle, gas turbine vehicle, internal combustion vehicle, and plug-in hybrid vehicle, respectively. Since these two classes cannot have definitions that are good enough for the OEO (they share a common view, but not a common characteristic as required for a proper concept definition), they won't be included. As a result, the corresponding columns are both mapped to the general vehicle concept (see table 4.4). In a similar manner, this problem occurs at other places such as the distinction of small and large cars. Again, these are mapped to the general car concept (see table 4.8). Whether that is a problem, depends on the further usage of the metadata containing the annotations.

Not only in cases, where no exact OEO concept is available, but also in cases, where the available OEO concepts are quite similar, the choice for the annotation was difficult. One example for this is *scenario year* and *typical year*. They both describe a year with the main difference that a *scenario year* is a time step and related to a scenario horizon, whereas a *typical year* is a time series. In the definition of *typical year* it says "It doesn't refer to a real date"[1], which is why *scenario year* is chosen for the mappings in this thesis. However, a clearer distinction of these two concepts in the OEO would be beneficial. On a side note, there is also simply *year* in the OEO, but it is a time unit and hence is not suitable for annotating single years like 2022, 2023 and so on.

For the formalization of assumptions in chapter 4, a minimal parameter table layout was introduced. It showed that it has several short comings during application such as too long parameter names and the need to add extra rows for values with deviation ranges. In order to reduce the length of the parameter names, common characteristics could be collected in additional rows. For example, a parameter type to indicate whether the value denotes an absolute value or an increase or decrease in comparison to the base year. The possibility to add a scope in another column would also be helpful to distinguish parameters with the same name that apply for different objects or spatial regions. The alternative would be to add that information to the parameter name, like it has been done in chapter 4, but again that should be avoided. For example, efficiency values that refer to the same process but executed by different machines. Another useful addition could be a column that contains the

[1] See definition at `http://openenergy-platform.org/ontology/oeo/OEO_00020089`.

ID	Parameter	Parameter Type	Scope	Cause	Value Type	Value	Unit	Year	Base Year

Table 5.1: Example for a uniform parameter table layout using the value type option.

cause of a given parameter. Such a cause could be a political decision, social or technological development, among others. This is particularly helpful, when multiple reasons lead to a certain parameter assumption like in table 4.15. For the depiction of values with deviation range, multiple alternatives are possible. The first one is to add a column value type that indicates whether the value is a minimum, maximum, sum, average etc. The second possibility is to have two columns for value instead of one that store minimum and maximum value respectively. As third option, a column with the value range could be added indicating the allowed deviation from the given value. While options two and three would allow to capture a value range in one row, option one provides more possibilities to add information. Table 5.1 shows how a parameter table with these suggestions would look like.

Regarding the development of this thesis, a couple of more general challenges were faced. The first one is the scope of the thesis. As the intersection of transport and energy domain is not small and there are many aspects that could be considered, only a subset of the most important concepts could be investigated and included in the OEO. This leads to difficulties to determine what should be included or not. An example for that are pipelines. They were initially not included in closer consideration, because they do not have an energy demand on the same scale and are in many ways different from vehicles. During the annotation of the `iTEM harmonized_dataset`, however, pipeline transport became a necessary concept, and was therefore suggested as well. In a similar manner, vehicle concepts only referring to vehicle shape, size, purpose etc. like car, truck, bus, and so on, were neglected at the beginning, because they do not include any information about energy aspects. As it turned out during the annotations, these concepts that were anyway introduced to the OEO in the meantime are indeed a valuable addition.

Another challenge was the dependency on other OEO developers. This could lead to some suggestions being uncommented for several weeks. As a result, some discussions took a long time and in some cases it was necessary to wait for a previous discussion to conclude before new concepts could be introduced.

Finding suitable data sets for the annotation was another difficulty. There are not many openly available data sets that cover energy and transport domain. Via recommendation the `quetzal_germany` data set with a strong focus on the transport domain was found. The other two data sets `iTEM harmonized_dataset` and `Laos TED` were found via internet search. They contain more elements from the energy domain, but lack a thorough description, which is not ideal. The advantage of this group of data sets is their diversity, which prevented narrowness and repetition during annotation.

On the technical side, there were a couple of issues that occurred when working with Protégé. These had no influence on the content and, therefore, need no discussion. Instead, the difficulties and their solutions are presented in part A of the appendix.

5.2 Limitations and Restrictions

As already mentioned in the difficulties, not all concepts from the intersection of transport and energy domain can be included. There are too many aspects to these areas and each user of the OEO may have a different need for concepts. As manifold as the models are, as different are the terms and distinctions they use. That is the very reason to build such an ontology in the first place. A specific restriction herein are the relations to other domains such as finances or politics. They influence energy and transport domain, but are not a central part of it. Therefore, only few concepts that considered those aspects were suggested. Similarly, infrastructural elements were not further investigated with respect to energetic aspects like construction or maintenance but only included as functionally important parts of the transport domain. The same argumentation may also hold for other concepts.

As mentioned above, vehicle types such as car, truck, ship etc. were neglected at the beginning. Instead, equivalence classes like gasoline road vehicle, diesel watercraft etc. were suggested. After discussion, the equivalence classes were altered a bit and only introduced for cars and trucks. The reason, why these additions were limited to the car and truck concepts, is simply that these two are the most commonly used concepts for further distinction. The other way round, airplanes and ships are rather seldom distinguished by their fuel. For the cases, where this is necessary, concepts from the OEO can be combined to achieve the same result. The equivalence classes are, however, more convenient and prevent misinterpretation. As mentioned at other places in this thesis, there is the discussion about an easy addition of compound concepts to the OEO. That would also allow to add other equivalence classes for vehicles in any desired way.

Another limit, related to the previous ones, is the level of detail at which concepts are included in the OEO. Some limits are rather obvious like brands and colors of cars, or operators of filling stations. These are not relevant for energy system modeling and thus are not integrated in the OEO. On a side note, if a data set would contain such information, it would still be possible to annotate the data set in a slightly more general manner. More challenging is the level of detail for technical aspects that actually influence energy consumption. An example is internal combustion engine and its subclasses. These are currently distinguished by the fuel they use. However, there is no distinction or reference with respect to performance determining components such as the number or volume of combustion chambers, the type of gearbox and similar. These aspects are primarily interesting when looking at single cars. For energy modeling on a larger scale, they are not necessary to have as explicit concepts.

In the application scenario, it was mentioned that the scenario factsheet that the OEO uses is being reworked currently. There are good reasons for that. As the two examples showed, only little information about scenario parameters could be inserted directly. This has multiple causes. First, the separation of parameters by sector is only done for some of them like the share of renewable energies. For others, like emission reduction, this is not done. Second, only one value per parameter can be inserted. That means that not both intermediate and final values (e.g. intermediate value until 2030, final value until 2045) can be placed in the factsheet.

Then, there are some notes to make about the literature research. It was as systematic as suitable and as described in chapter 2. However, some literature was found later on, that is, after the initial two cycles of the first three steps of the approach, using different keywords. Furthermore, at few occasions, the access to possibly relevant literature was not given. In addition, the selection of literature from the search results was based on personal assessment regarding the relevance for this thesis. Following the characterization and explanation by [113], this makes it a narrative literature review, which can miss relevant literature, may be biased, or may rely too much on single publications.

Lastly, there is to note that the work on the OEO continues which means that any addition presented in this thesis may be altered in the future. This could already be the case at the time of closure of this thesis. I, the author, did my best to present up-to-date content herein, but I cannot guarantee this for all parts. Especially references to older OEO terms could be updated in any way without my knowledge. This poses no problem for the scientific work done in this thesis, but should be taken into account by the interested reader.

5.3 Assumptions

A major assumption for the annotation of data sets like in chapter 4 is about the meaning of multiple concepts that are used to annotate a column header. It is assumed that these concepts are connected with a logical AND. It seems intuitive, but is not formally defined anywhere. Furthermore, it is assumed that the logical combination of these concepts yield the correct meaning, although that cannot be guaranteed. It is at least humanly understandable. For a well defined meaning, a single concept would be necessary, which may be defined as a compound concept, once the discussion about these has led to a solution.

Another assumption is that the subject field in the OEMetadata is actually used. In many cases this adds a crucial part of information. For example, whether a certain amount of energy is a demand, a consumption, a generation, or a storage value. Another example is table 4.11, where the length values for an electricity system are given. Without electricity system as a subject, ideally depicted through OEO concepts itself, these values are arbitrarily interpretable.

At some places during annotation or assumption extraction minor assumptions were necessary. Usually, because information from context was not sufficient. In general, the used terms were literally interpreted. If another assumption was necessary, it is explained at the corresponding places in the text. The most prominent case is the unclear year or base year for a parameter. If it could not be assumed from the context, the publishing year was taken.

5.4 Evaluation of integrated concepts in comparison to initial concept collections

5.4.1 Comparison to concepts without explicit energy perspective

As a result of the first cycle of the approach, central elements for the transport domain were identified (see section 3.2.1). With the exception of measurement values, they were further refined with possible concepts. Figures 5.1 to 5.6 illustrate which of these initial concepts ideas became a part of the OEO (in green with green border), are still in discussion (green with red border), are not included but still presentable with a combination of concepts (red with green border), are neither included nor in discussion (red with red border) or were already present in the OEO (blue).

From the vehicle types, the basic types water, ground, rail, and air vehicle have been included (see figure 5.1). For water vehicles, passenger ships and freight ships with its subclasses are now included. A further distinction for passenger ships was not necessary from an energy perspective. The same holds for utility ships and private water vehicles. These categorizations showed to be too detailed and too far away from an energy perspective. For the ground vehicles, several important vehicles types have been included. Less important classes like scooter or utility vehicles were omitted. The distinction wheeled against tracked vehicles was not useful for the energy perspective. From the rail vehicles, only trains have been included. Its subclasses are representable through the combination with transport subclasses. The other rail vehicles occurred not often enough in literature to be relevant. Lastly, airplanes and helicopters have been included in the OEO from the air vehicles. A jet airplane could be depicted with the combination of airplane with jet fuel turbine or jet fuel vehicle. The other concepts were again not relevant enough.

For the transport types, most concepts are still in discussion (see figure 5.2). The concepts related to utility transport showed to be unnecessary for an energy perspective. The only remaining concept that is not in discussion is passenger cars. It can still be represented through the combination of the concepts private transport and car.

For infrastructure, most of the concept ideas have been included in the OEO (see figure 5.3). A pure connection concept was not necessary, instead, rails, roads, and canals are included. With the tunnel and bridge concepts, the depiction of rails or roads through tunnels or on bridges is also possible. Concepts for special rails or water gates were not necessary from an energy perspective. A place concept has been included in form of the transport hub. A range extension concept and garages

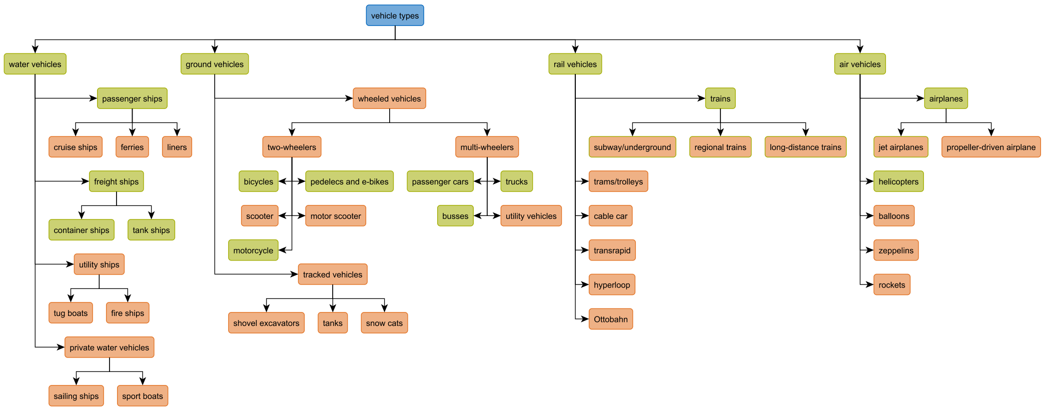


Figure 5.1: Inclusion of vehicle types without energy perspective.

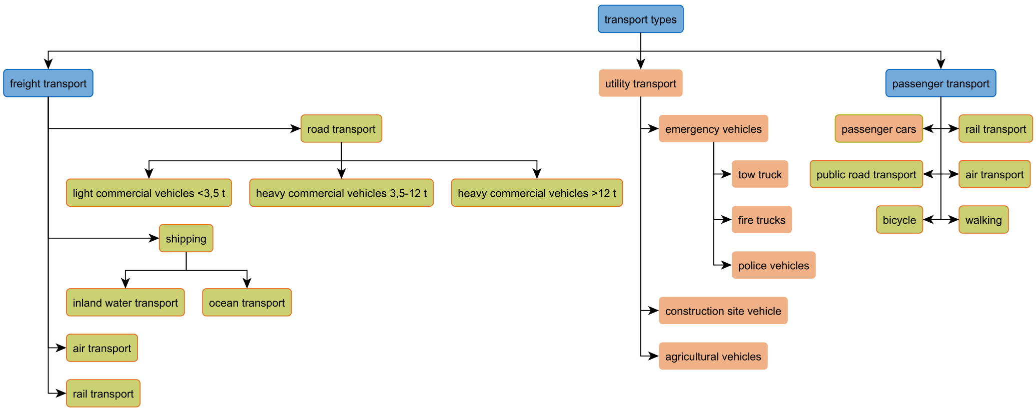


Figure 5.2: Inclusion of transport types without energy perspective.

where again not necessary for the energy perspective. The remaining subclasses of places have been included at various points in the OEO.

The operational environment showed to be not important for a detailed consideration. A pure concept for it was deemed unnecessary, because both vehicle types and transport types inherently demand a certain environment. Furthermore, the concepts water and air, both previously included in the OEO, and the additions road network and rail network cover the operational environment sufficiently. Any more fine grained distinctions are not necessary for energy considerations. For cycling, a cycle network could be represented with the combination of the concepts transport network and cycling or bicycle.

As expected, the energy carriers were already well covered in the OEO (see figure 5.5). The distinction between induction and power line electricity supply was not relevant enough for the energy perspective. From the natural energy carriers, the direct conversion of solar energy, thermodynamic currents, and muscle power showed to be not relevant enough for energy modeling. Muscle power is of course a requirement for walking or cycling, but it is usually not explicitly modeled.

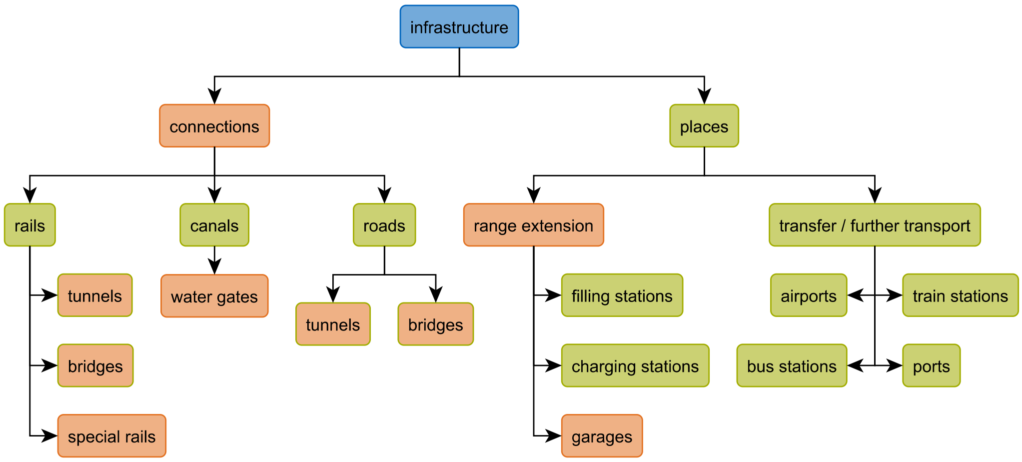


Figure 5.3: Inclusion of infrastructure without energy perspective.

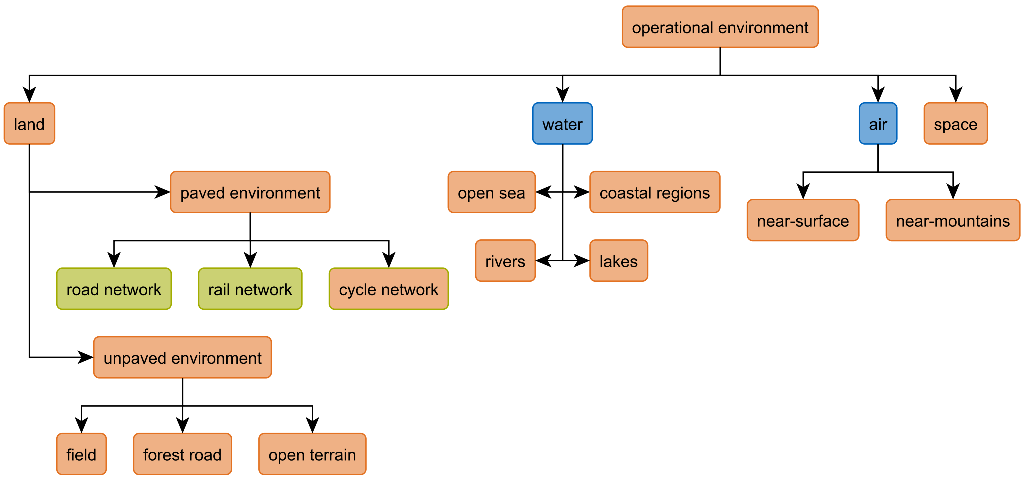


Figure 5.4: Inclusion of operational environment without energy perspective.

For the operational mode, only a general concept has been included. Given, that it is usually not considered in energy modeling literature, it was deemed sufficient to include a general concept.

In a similar manner, figure 5.7 shows the relations between the elements and measurement values. There were already concepts in the OEO for the consumption process and its measurement values emissions and consumption amount. For the size of a network, an axiom was introduced to link a length value to a network. Charging and filling stations where introduced as well and can be connected to a count unit. For transport performance a value with different units has been included. For modal split and related terms, definitions have been agreed upon in the discussion, but wait for the agreement on transport subclasses to be implemented. Similarly, some cost values have been suggested and are still in suggestion. From

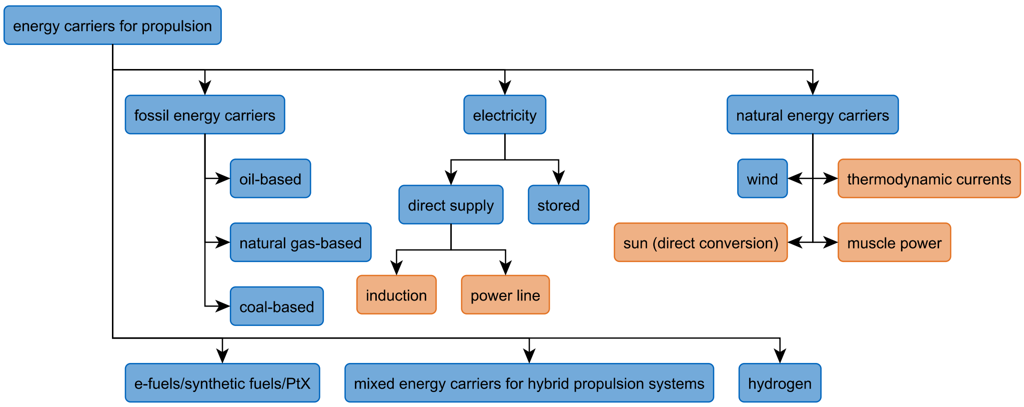


Figure 5.5: Inclusion of energy carriers.

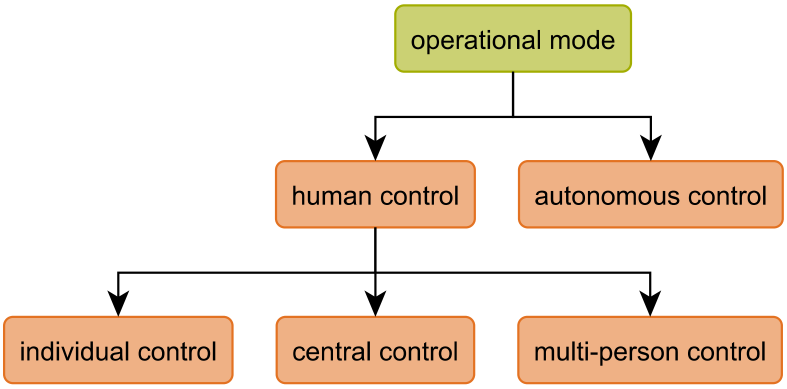


Figure 5.6: Inclusion of operational mode without energy perspective.

the relations in the figure, not all have been implemented, because that could cause involuntary restrictions. As an example, energy carriers can exist in nature without using infrastructure. Because subclasses can have additional axioms to their parent classes, it would be to tedious to discuss all relations. For the implemented axioms, section 3.3 in the approach chapter should be considered. As an additional overview, figure B.1 in the appendix provides an overview over the relations between the new concepts.

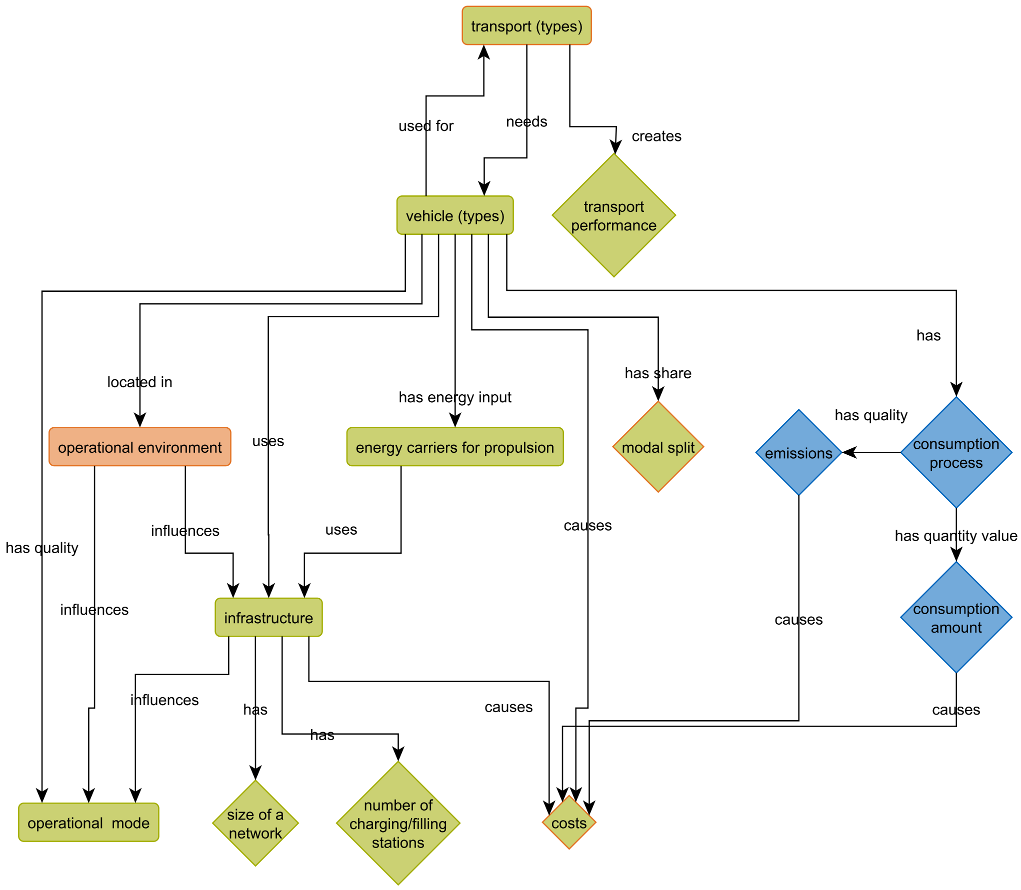


Figure 5.7: Inclusion of the relations between the elements.

5.4.2 Comparison to concepts considering energy aspects

Analogously to the previous section, figures 5.8 and 5.9 show the evaluation of the concepts from the energy perspective adaption step (see section 3.2.2). As in that step, the combined graph is again shown in the appendix (see figure B.3). The color coding is the same as before.

For passenger transport, concepts for land, air, and water transport are still in discussion. Road and rail transport are in discussion as well, but the corresponding vehicles are already integrated in the OEO. Concepts for e-bikes, busses, and cars with all suggested subclasses have been implemented as well. For busses, the characterization by energy carrier is not included, but can still be depicted with a combination of concepts. Scooter and motor scooter are not relevant enough to be included. Passenger train is included and it can be further refined through a combination with an energy carrier. Other types of trains are not separately considered in literature and hence have not been integrated. Passenger airplanes and the kerosene using subclass can be depicted through combinations. Analogously, the subclasses of passenger ships can be represented that way.

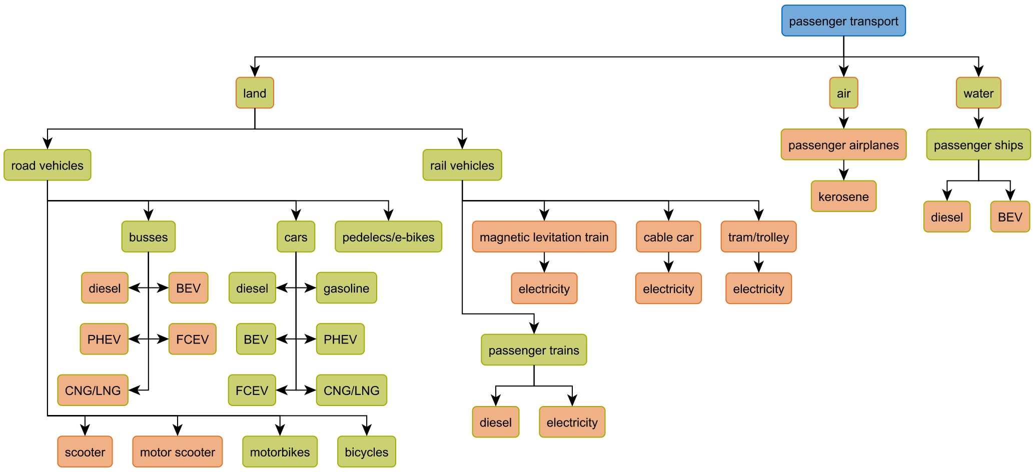


Figure 5.8: Inclusion of passenger transport from an energy perspective.

Like before, concepts for land, air, and water freight transport are still in discussion. Most concepts have been added to the OEO: truck as a road vehicle with its subclasses, freight trains as rail vehicles, and tank ships and cargo ships as cargo ships. Quite analogously to concepts about passenger transport, the missing concepts can be depicted with a simple combination of other terms in the OEO.

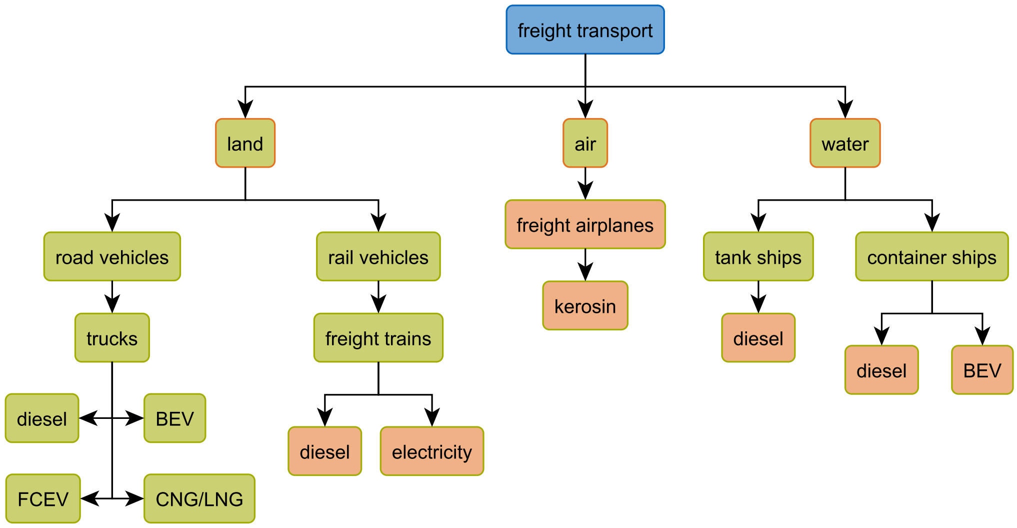


Figure 5.9: Inclusion of freight transport from an energy perspective.

Summarizing this comparison, a lot of the concepts have been added to the OEO or are at least in discussion. From the elements without energy perspective, significantly less made it to the discussion or integration compared to the concepts in the condensed energy perspective. This is not surprising but shows the advantage of getting from a broader scope to a narrow one. Furthermore, a lot more concepts can be depicted by combining two other concepts.

5.5 Evaluation of the Research Questions

5.5.1 Representation of the transport sector in literature

The aim of the first research question, *How is the transport sector represented in scientific literature?*, was to gain an understanding of the transport sector by identifying literature that addresses the transport sector and how it is represented therein. To achieve that goal, several subquestions were formulated.

The first subquestion was *Which terms and classifications are used to describe the transport sector?* The literature research for the transport domain in section 2.4 highlights important aspects for that. In the approach, section 3.2.1, these led to an initial collection of terms in a categorized manner. Therefore, it can be said, that this question has been answered.

The second subquestion, *Which measurements are used to describe the transport sector?*, is answered alongside the first one. Literature showed important aspects, which were used in the first cycle of the approach. However, the manifold of possible measures, especially when looking at specific values, makes it impossible to collect them all. Figure 3.8 shows some of the most important ones. As far as possible, this question has been answered.

The third and last subquestion was *Which models are used to describe the transport sector?* As the literature showed, there is a high variety of models and underlying modeling frameworks. In some studies, it is not even clear on which models the results are based. Also, the focus of the models can be very different. Energy consumption, carbon dioxide emissions, fleet size etc. are considered only by some models. One commonality seems to be a value for transport demand or performance like pkm, tkm, or vkm. There is, however, not the *one* model that describes the transport sector entirely or best. Instead, it depends on the specific use case which model or framework is chosen. Therefore, no list of models can be given as an answer.

Given that all these subquestions have been answered as far as possible, it can be concluded that the first research question has been sufficiently answered in this thesis.

5.5.2 Coverage of the transport sector in an ontology from an energy perspective

The second research question *How can the transport sector be captured in an ontology from an energy perspective?* aimed at finding a suitable way to add concepts from the transport domain to an energy ontology. Several subquestions helped at gaining the desired insight.

Which concepts are relevant for capturing the transport sector from an energy perspective? was the first subquestion and it is answered primarily through the second cycle in the approach. In addition, the application examples helped to fill in the gaps. The result are the concepts presented in section 3.4 together with some previous concepts from the OEO. The most important ones from the latter are shown in section 3.2.3. In the sections above, some difficulties and restrictions are discussed.

The second subquestion, *Which relations are relevant for capturing the transport sector from an energy perspective?*, is again answered primarily through the first two cycles in the approach. Figure 3.8 shows some of the fundamental relations. The resulting axioms are shown together with the concepts they belong to in section 3.3. Furthermore, in the section above is explained, why not all relations were implemented as axioms.

Next, the subquestion *How can concepts and relations be defined such that they are consistent with existing terminology?* was answered through the adaption step of the approach. New concepts need to be consistent with existing terminology in order to be added to the OEO, which was achieved through the adaption and secured through the discussion process. As a result, the concepts and relations presented in this thesis are consistent with existing terminology.

Which level of detail is suitable for modeling the transport sector from an energy perspective? was another subquestion and it is answered in the discussion above. There is no short and concluding answer to this as every application has its own desired level of detail.

The intention of the subquestion *How can different views on the same entity be modeled?* was to make sure that the energy perspective is the dominant view. For one part, this is implicitly achieved by looking at concepts from an energy perspective like in previous questions demanded. This also led to prior neglect of concepts that take another view, but turned out useful later on, as described in the discussion above. For the other part, the definitions of the concepts in section 3.3 are formulated so that they concentrate on energy aspects wherever possible. To fully answer this question, if multiple views on the same concepts should be modeled, it would be best to define two concepts based on the characteristic that is highlighted by each view. Then, an equivalence class that is exactly the union of those two classes could be added. An example for that are the definitions in table 3.13.

The subquestion *How can ontologies help with the representation of complex dependencies?* is related to the example in the previous one, as equivalence classes, an important feature of ontologies, can be used to depict more complex relations of concepts. General class axioms or disjoint unions are other ontology features that can be helpful, but were not needed in this thesis. Other than that, the simple nesting and combining of relations in one axiom can be used for non-trivial relations. On of the most complex relations in the OEO is depicted in the second axiom in listing 3.13.

As shown, all subquestions have been answered in this thesis, and therefore, this research question is answered as well.

Chapter 6

Summary and Outlook

6.1 Summary

In this thesis, the transport sector was investigated with respect to its structure and terminology, and how this can be captured in concepts. These concepts were checked for their relevance for energy system modeling and, if relevant, included in the Open Energy Ontology. This was done in a way that preserves consistency with other concepts in the OEO. Through these procedures, the research gap of a common knowledge basis for energy systems and transport systems has been sufficiently closed. As explained in the discussion, there is always the possibility for improvement in terms of level of detail and a broader scope. Furthermore, this thesis tested the applicability of the OEO as a reference for data annotations. As an advanced example, the translation of scenario assumptions into an OEO-conform scheme was investigated.

A central insight is that many concepts in transport domain are concepts regarding the view on certain parts of transport processes. The best example is the mode of transport for which numerous aspects exist. It seems as almost every author uses their own set of modes and distinguishes them by other criteria. But also the type of vehicles is distinguished in different ways. Sometimes, it is only focused on road vehicles in general or cars in particular, other times at freight vehicles in general or trucks in particular, and occasionally there are completely different distinctions like the `Laos TED` data set shows. More or less fine grained concepts, as well as the combination of multiple criteria in one concept, e.g. battery electric car, show the necessity to combine concepts in a compound concept like it is discussed in the OEO development. Meanwhile the combination of other concepts are a possible solution.

During the approach, six elements beneath measurement values were identified that cover the central aspects of the transport domain. For all of these, particular classes were suggested and in many cases already implemented. The further approach also showed, that not all possible transport concepts are relevant for energy system modeling, and that sometimes concepts are only useful as part of another concept, like the operational environment, which needs no explicit definition. Those six elements were also related to each other and, where possible, these relations were added as axioms to the ontology. From the condensed energy view on the transport domain, most concepts were integrated in the OEO or are at least presentable with a combination of concepts. Only a few very specific vehicles were not integrated from those concepts.

This thesis showed difficulties and restrictions for the creation of OEO-conform concepts and axioms caused by the limits of OWL. Insights gained from the annotation process are difficulties to determine the "correct" annotation and to handle terms that are not or in another way handled in the OEO. Furthermore, feedback regarding the functionality of the OEMetabuilder was provided to the developers, although hardly mentioned in this thesis. The findings from the scenario assumptions examples were used to suggest an improved parameter table layout and to contribute to the rework of the OEP scenario factsheets. In addition, the insights from this thesis add to the ongoing discussions about compound concepts and specific values.

The scientific foundation for this thesis was presented in chapter 2. The approach with its results and the application examples were explained in chapters 3 and 4 respectively. Any difficulties, limits and restrictions, and assumptions were discussed in chapter 5. In that chapter, the early steps of the approach were evaluated, and the research questions, which served as a guide for the work on this thesis, were answered as well.

All in all, this thesis contributed to the overarching goal of facilitated data comparison, integration, and exchange at the intersection of energy and transport domains by enhancing an energy ontology with concepts from the transport sector.

6.2 Outlook

There are several ways in which the work of this thesis could be continued. Further additions to the OEO is one of them. The concepts that are currently under discussion and not yet implemented as of closure of this thesis are followed up to be implemented in the future. There are also other domains whose intersections to the energy domain are important and could be examined in a similar fashion as the transport sector. Examples for those are the building and construction industry or the waste and recycling management. Another way is to evaluate the usefulness of the proposed uniform parameter table layout. This relates also to the overhaul of the OEP scenario factsheets, which should be considered alongside.

A uniform layout for parameter tables would also open opportunities for automation. The translation of assumptions from a written text into a parameter table seems like a desirable goal. There are many difficulties to consider for this type of natural language processing, but it would be interesting to test the current possibilities. Another field for automation is the annotation of data tables. While the lack of machine-readability and universal understanding is the reason for annotation in the first place, it would be interesting to see how artificial intelligence-based methods would perform in such an annotation. A preliminary step, which could be automated as well, is the transformation of data sets into an OEP-conform layout.

Another possibility with regard to the OEO is to build a knowledge graph from an annotated data set and to test how well the inference mechanisms work, that is, how beneficial inferred knowledge is and how well the axioms work to detect inconsistencies. Even more experimental, but also interesting, would be to see how an integration of multiple data sets into one knowledge graph would work out.

This leaves several opportunities to leverage the work and findings of this thesis in future work.

Appendix A

Issues when working with Protégé

When opening the main ontology file (`oeo.omn`) from within Protégé, it can happen that the file doesn't open. The problem is solved by closing Protégé, selecting the file in the explorer, choosing option "open with" from the context menu, and finally selecting Protégé.

Another issue occurs, when saving the ontology from a sub-file like `oeo-physical.omn` instead of the main file. It causes Protégé to change the namespaces in the file and with that the unique IRIs of each concept. Since that should be avoided, the ontology should always be saved from the main file. In some cases, this problem also occurred when saving from the main file. In that case restarting Protégé solves the issue.

At some occasions, updates to the ontology files from merging different code branches were not shown in Protégé. Usually, Protégé detects external changes to files and asks whether it should reload the files. If that is not the case, Protégé needs to be restarted.

Appendix B

Additional figures

Figure B.1 shows all concepts that were suggested as additions to the OEO in this thesis. If a suggested concept has been implemented already, it is entirely green, while concepts that are still in discussion are green with a red border. Previous OEO concepts are blue. Relations that result from axioms between the concepts are depicted with orange arrows. The outgoing concept is where the axiom has been added to. Not all relations are visualized. In particular, axioms referring to previous OEO concepts that are not included in the figure are neglected. If these concepts and relations would have been visualized as well, the figure would be too chaotic to provide an useful overview - hence, the limit to all concepts, but not all relations.

Figure B.2 shows the complete hierarchy for the energy focus in section 3.2.2. In other words, it is the integration of graphs 3.9 (hierarchy for passenger transport from an energy perspective) and 3.10 (hierarchy for freight transport from an energy perspective) in one graph.

Analogously, figure B.3 shows the complete graph for the two evaluation graphs for the energy focus in section 5.4.2. It is the combination of figures 5.8 (inclusion of passenger transport from an energy perspective) and 5.9 (inclusion of freight transport from an energy perspective). It uses the same color-coding as the mentioned figures in section 5.4.2 and as described in the list of color-codes in the beginning of this thesis.

These figures, as well as most figures in this thesis, are scalable and allow for a close-up view in the pdf version of this thesis.

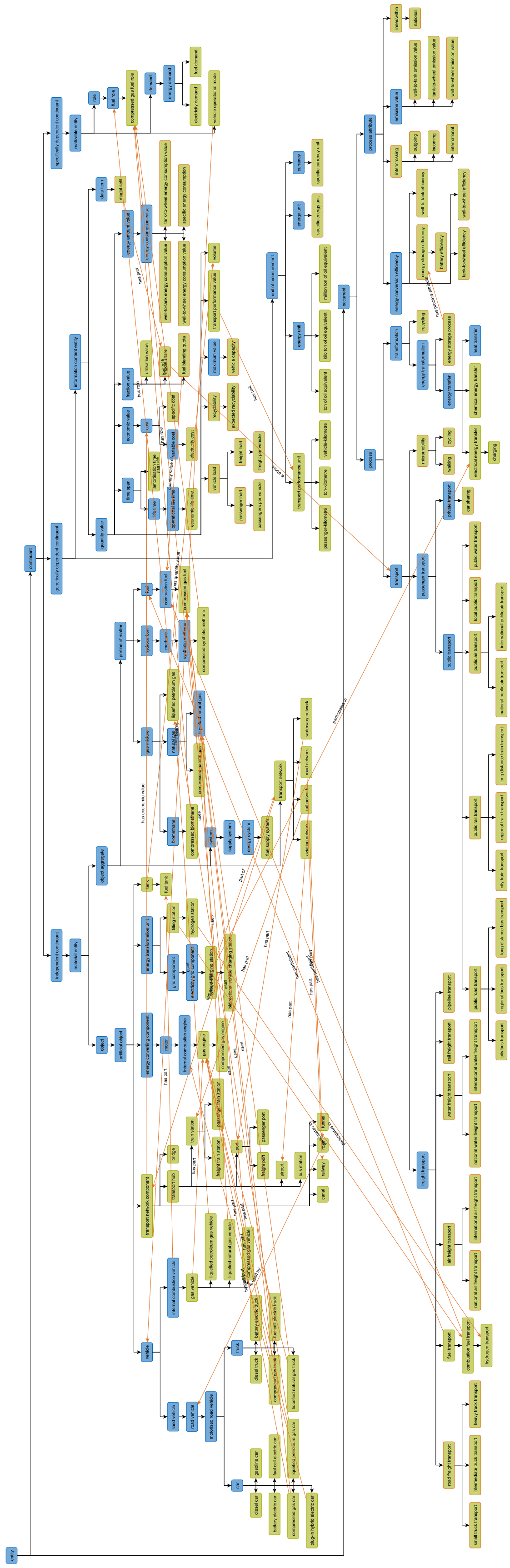


Figure B.1: Overview over all additions to the OEO.

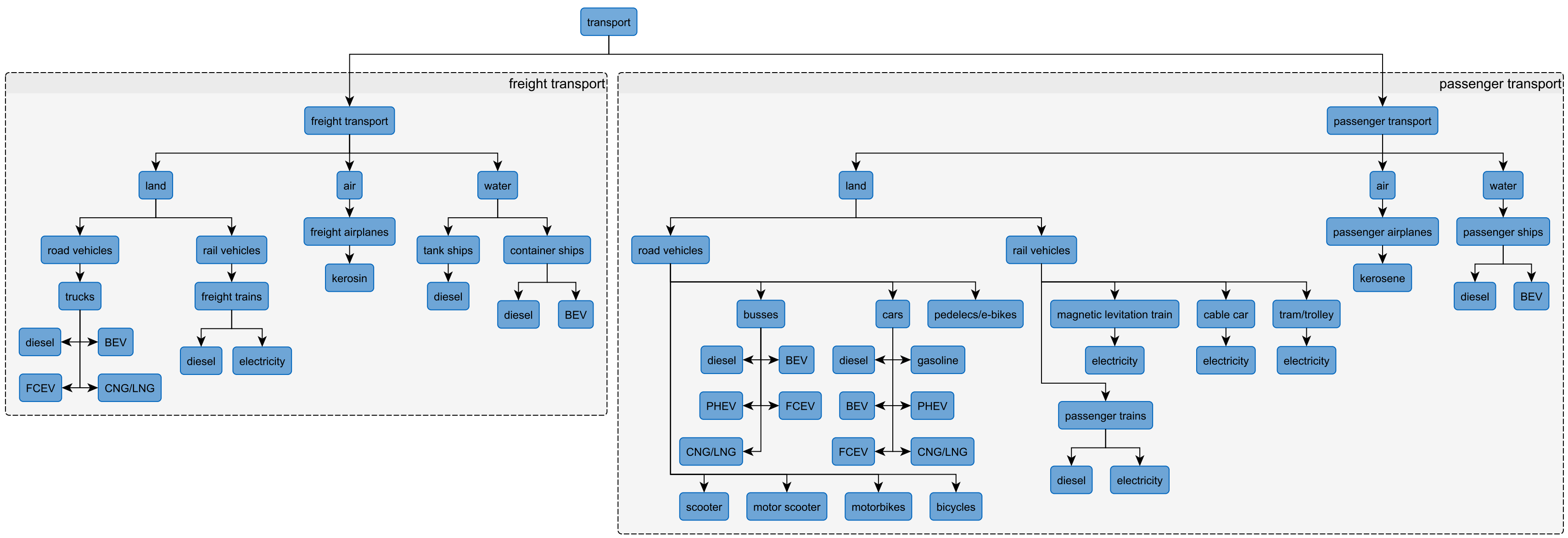


Figure B.2: Complete graph for the energy perspective.

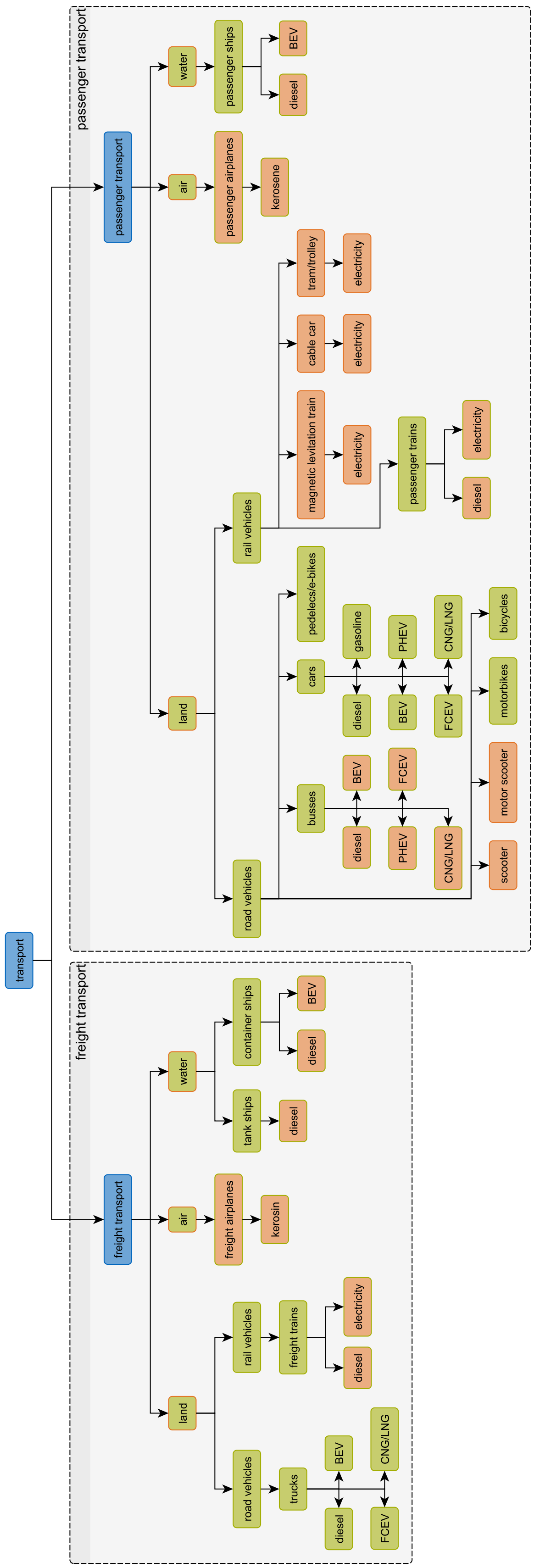


Figure B.3: Complete graph for the energy perspective - evaluated.

Appendix C

Lists of all concepts and axioms

Table C.1 lists all concepts that have been implemented.
Table C.2 lists all concepts that have been suggested.
Listing C.1 lists all axioms that have been implemented.
Listing C.2 lists all axioms that have been suggested.
The order in these lists is the order of appearance in this thesis.

Concept	**Definition**
transport performance value	A transport performance value is a quantity value that indicates the performance of a transport process in terms of its mileage and amount of transported people and/or goods.
transport performance unit	A transport performance unit is a unit of measurement for the accumulated transport distance of a number of people and/or amount of goods.
passenger-kilometre	Passenger-kilometre is a transport performance unit for the accumulated transport distance of people where one passenger-kilometre equals the transport distance of 1 km for one person.
ton-kilometre	Ton-kilometre is a transport performance unit for the accumulated transport distance of goods where one ton-kilometre equals the transport distance of 1 km for one ton of goods.
vehicle-kilometre	Vehicle-kilometre is a transport performance unit for the accumulated transport distance of the used vehicles themselves where one vehicle-kilometre equals the transport distance of 1 km for one vehicle.

Concept	**Definition**
gas vehicle	A gas vehicle is an internal combustion vehicle that has only a gas engine as a motor for propulsion.
liquefied petroleum gas vehicle	A liquefied petroleum gas vehicle is a gas vehicle that uses liquefied petroleum gas as fuel.
liquefied natural gas vehicle	A liquefied natural gas vehicle is a gas vehicle that uses liquefied natural gas as fuel.
compressed gas vehicle	A compressed gas vehicle is a gas vehicle that uses a compressed gas fuel.
gas engine	A gas engine is an internal combustion engine that uses a gaseous combustion fuel.
compressed gas engine	A compressed gas engine is a gas engine that uses a compressed gas fuel.
gas vehicle	A gas vehicle is an internal combustion vehicle that has only a gas engine as a motor for propulsion.
liquefied petroleum gas vehicle	A liquefied petroleum gas vehicle is a gas vehicle that uses liquefied petroleum gas as fuel.
liquefied natural gas vehicle	A liquefied natural gas vehicle is a gas vehicle that uses liquefied natural gas as fuel.
compressed gas vehicle	A compressed gas vehicle is a gas vehicle that uses a compressed gas fuel.
compressed gas fuel role	A compressed gas fuel role is a fuel role that expresses that a portion of matter can be used in a compressed gas engine.
transport network	A transport network is an object aggregate of transport network components that enables the transport of people and/or goods.
road network	A road network is a transport network that enables transport on roads.
rail network	A rail network is a transport network that enables transport on rails.
waterway network	A waterway network is a transport network that enables transport on water.
aviation network	An aviation network is a transport network that enables air transport.
transport network component	A transport network component is an artificial object that is part of a transport network.

Concept	Definition
road	A road is a transport network component with an artificial surface that allows transport for road vehicles.
bridge	A bridge is a transport network component that spans a physical obstacle without blocking the way underneath.
tunnel	A tunnel is a transport network component that is built through a certain environment (e.g. a mountain or water) and allows to pass through that environment.
railway	A railway is a transport network component that can only be used by trains.
canal	A canal is a transport network component that is an artificially created waterway.
transport hub	A transport hub is a transport network component that allows the exchange of people and/or goods.
train station	A train station is a transport hub for trains.
freight train station	A freight train station is a train station for the exchange of goods.
passenger train station	A passenger train station is a train station for the exchange of passengers.
bus station	A bus station is a transport hub for busses.
port	A port is a transport hub for ships.
freight port	A freight port is a port for the exchange of goods.
passenger port	A passenger port is a port for the exchange of passengers.
airport	An airport is a transport hub for airplanes.
electrical energy transfer	Electrical energy transfer is an energy transfer of electrical energy.
charging	Charging is an electrical energy transfer where the transferred energy is stored in a battery.
chemical energy transfer	Chemical energy transfer is an energy transfer of chemical energy.
fuel transport	Fuel transport is a transport of fuel.
combustion fuel transport	Combustion fuel transport is a fuel transport for combustion fuel.
heat transfer	Heat transfer is an energy transfer of thermal energy.

Concept	Definition
vehicle charging station	A vehicle charging station is an electricity grid component that transfers electrical energy into the traction battery of a battery electric vehicle.
bidirectional vehicle charging station	A bidirectional vehicle charging station is a vehicle charging station that can also feed electrical energy from the traction battery back into the electricity grid.
vehicle operational mode	A vehicle operational mode is a realizable entity that determines how a vehicle is operating.
fuel supply system	A fuel supply system is an energy system covering the distribution of fuels.
diesel truck	A diesel truck is a truck that has only a diesel engine as motor for propulsion and thus is also a diesel vehicle.
diesel car	A diesel car is a car that has only a diesel engine as motor for propulsion and thus is also a diesel vehicle.
gasoline car	A gasoline car is a car that has only a gasoline engine as motor for propulsion and thus is also a gasoline vehicle.
battery electric car	A battery electric car is a car that as an electric traction motor and a traction buttery and thus is also a battery electric vehicle.
fuel cell electric car	A fuel cell electric car is a car that has an electric traction motor and uses electrical energy from a fuel cell and thus is also a fuel cell electric vehicle.
compressed gas car	A compressed gas car is a car that uses compressed gas in a gas engine and thus is also a compressed gas vehicle.
liquefied petroleum gas car	A liquefied petroleum gas car is a car that uses liquefied petroleum gas in a gas engine and thus is also a liquefied petroleum gas vehicle.
plug-in hybrid electric car	A plug-in hybrid electric car is a car that can switch between an electric traction motor and an internal combustion engine for propulsion and thus is also a plug-in hybrid electric vehicle.

Concept	Definition
battery electric truck	A battery electric truck is a truck that has an electric traction motor and a traction battery and thus is also a battery electric vehicle.
fuel cell electric truck	A fuel cell electric truck is a truck that has an electric traction motor and uses electrical energy from a fuel cell and thus is also a fuel cell electric vehicle.
compressed gas truck	A compressed gas truck is a truck that uses compressed gas in a gas engine and thus is also a compressed gas vehicle.
liquefied natural gas truck	A liquefied natural gas truck is a truck that uses liquefied natural gas in a gas engine and thus is also a liquefied natural gas vehicle.
tank	A tank is an artificial object that stores a liquid or gaseous portion of matter.
fuel tank	A fuel tank is a tank that stores a combustion fuel.
volume	A volume is a quantity value indicating the size of a three-dimensional spatial region.
filling station	A filling station is an energy transformation unit that transfers fuel into the fuel tank of a vehicle.
hydrogen station	A hydrogen station is a filling station that transfers hydrogen.
hydrogen transport	Hydrogen transport is the combustion fuel transport of hydrogen.
electricity demand	Electricity demand is the energy demand for electricity.
fuel demand	Fuel demand is the energy demand for fuel.
ton of oil equivalent	A ton of oil equivalent is an energy unit which is equal to the amount of energy released by burning one metric ton of crude oil with a certain net calorific value. That is defined as 41.868 gigajoules or 11.63 megawatt-hours.
kilo ton of oil equivalent	A kilo ton of oil equivalent is an energy unit which is equal to 1,000 tons of oil equivalent.
million ton of oil equivalent	A million ton of oil equivalent is an energy unit which is equal to 1,000,000 tons of oil equivalent.

Concept	Definition
amortisation time	An amortisation time is the time span in which the investment costs are refinanced from the annual profits and depreciation of the investment.
economic life time	An economic life time is the operational life time during which an artificial object is profitable to the owner.
utilisation value	A utilisation value is a fraction value that describes the instantaneous share of a maximum value that is utilised.

Table C.1: List of all implemented concepts.

Concept	Definition
modal split	A modal split is a data item that contains modal shares.
modal share	A modal share is a fraction value that describes the share of a transport mode.
micromobility	Micromobility is transport on short distances.
walking	Walking is micromobility without any vehicle.
cycling	Cycling is micromobility with a bicycle.
car sharing	Car sharing is the private transport where people share a car.
local public transport	Local public transport is public transport where the used transport networks cover a certain local area.
public road transport	Public road transport is public transport that takes place on roads.
city bus transport	City bus transport is public road transport for short distances.
regional bus transport	Regional bus transport is public road transport for medium distances.
long distance bus transport	Long distance bus transport is public road transport for long distances.
public rail transport	Public rail transport is public transport that takes place on rails.
city train transport	City train transport is public rail transport for short distances.

Concept	Definition
regional train transport	Regional train transport is public rail transport for medium distances.
long distance train transport	Long distance train transport is public rail transport for long distances.
public air transport	Public air transport is public transport that primarily takes place in the air.
national public air transport	National public air transport is public air transport that does not cross country borders.
international public air transport	International public air transport is public air transport that crosses the borders of one or more countries.
public water transport	Public water transport is public transport that takes place on water.
road freight transport	Road freight transport is freight transport that takes place on roads.
small truck transport	Small truck transport is the road freight transport with small trucks.
intermediate truck transport	Intermediate truck transport is the road freight transport with intermediate trucks.
heavy truck transport	Hevy truck transport is the road transport with heavy trucks.
rail freight transport	Rail freight transport is freight transport that takes place on rails.
air freight transport	Air freight transport is freight transport that primarily takes place in the air.
national air freight transport	National air freight transport is air freight transport that does not cross country borders.
international air freight transport	International air freight transport is air freight transport that crosses the borders of one or more countries.
water freight transport	Water freight transport is freight transport that takes place on water.
national water freight transport	National water freight transport is water freight transport that does not cross country borders.
international water freight transport	International water freight transport is water freight transport that crosses the borders of one or more countries.
pipeline transport	Pipeline transport is freight transport that uses pipelines.

Concept	Definition
electricity cost	An electricity cost is a variable cost that depends on electricity price and amount.
specific cost	A specific cost is a cost that is calculated by dividing the total considered costs through the quantity value of interest.
specific currency unit	A specific currency unit relates currency to another unit.
specific energy consumption	A specific energy consumption is an energy consumption value that is calculated by dividing the total considered energy consumption through the quantity value of interest.
specific energy unit	A specific energy unit relates an energy unit to another unit.
recycling	Recycling is a transformation that regains materials and/or energy from an artificial product or waste.
recyclability	Recyclability is a quantity value that indicates the percentage of materials that can be regained during a recycling process.
expected recyclability	Expected recyclability is the recyclability an artifical object is expected to have at the end of its operational life time.
inner/within	Inner/within is a process attribute that describes that a process takes entirely place within the same spatial region.
national	National is inner/within whereby the spatial region is a country.
inter/crossing	Inter/crossing is a process attribute that describes that a process crosses the boundaries of one or more spatial regions.
international	International is inter/crossing whereby the boundaries of the spatial regions are boundaries of countries.
outgoing	Outgoing is inter/crossing for processes that leave the spatial region of interest.
incoming	Incoming is inter/crossing for processes that arrive at the spatial region of interest.
vehicle load	A vehicle load is a quantity value indicating the magnitude of the load (passengers or goods) of a vehicle.
passenger load	A passenger load is a vehicle load that results from passengers.

Concept	Definition
passengers per vehicle	Passengers per vehicle is a passenger load averaged over a number of vehicles.
freight load	A freight load is a vehicle load that results from freight.
freight per vehicle	Freight per vehicle is a freight load averaged over a number of vehicles.
vehicle capacity	A vehicle capacity is a maximum value that indicates the maximum load of a vehicle.
fuel blending quota	A fuel blending quota is a fraction value that indicates the share of renewable fuel mixed into fossil fuel.
energy storage process	An energy storage process is an energy transformation that whereby input energy and output energy are of the same type, apart from energy losses.
energy storage efficiency	An energy storage efficiency is an energy conversion efficiency that describes the ratio between the input and the useful output of an energy storage process.
battery efficiency	A battery efficiency is the energy storage efficiency of a energy storage process in which a battery is used.
well-to-tank efficiency	A well-to-tank efficiency is the energy conversion efficiency of a series of energy transformation processes from the primary energy production to the storage in a tank or traction battery of a vehicle.
tank-to-wheel efficiency	A tank-to-wheel efficiency is the energy conversion efficiency of a series of energy transformation processes of the energy stored in a tank or traction battery of a vehicle until the conversion into kinetical energy for propulsion.
well-to-wheel efficiency	A well-to-wheel efficiency is the energy conversion efficiency of a series of energy transformation processes from the primary energy production to the conversion into kinetical energy for propulsion.
well-to-tank energy consumption value	A well-to-tank energy consumption value is the energy consumption value of a series of energy transformation processes from the primary energy production to the storage in a tank or traction battery of a vehicle.

Concept	Definition
tank-to-wheel energy consumption value	A tank-to-wheel energy consumption value is the energy consumption value of a series of energy transformation processes of the energy stored in a tank or traction battery of a vehicle until the conversion into kinetical energy for propulsion.
well-to-wheel energy consumption value	A well-to-wheel energy consumption value is the energy consumption value of a series of energy transformation processes from the primary energy production to the conversion into kinetical energy for propulsion.
well-to-tank emission value	A well-to-tank emission value is the emission value of a series of energy transformation processes from the primary energy production to the storage in a tank or traction battery of a vehicle.
tank-to-wheel emission value	A tank-to-wheel emission value is the emission value of a series of energy transformation processes of the energy stored in a tank or traction battery of a vehicle until the conversion into kinetical energy for propulsion.
well-to-wheel emission value	A well-to-wheel emission value is the emission value of a series of energy transformation processes from the primary energy production to the conversion into kinetical energy for propulsion.

Table C.2: List of all suggested concepts.

```
'transport performance value' 'has unit' some 'transport performance unit'

'gas vehicle' 'has part' some 'gas engine'
'gas vehicle' 'has part' only ('gas engine' or (not (motor)))
'gas vehicle' uses some 'gaseous combustion fuel'
'liquefied petroleum gas vehicle' uses some 'liquefied petroleum gas'
'liquefied natural gas vehicle' uses some 'liquefied natural gas'
'compressed gas vehicle' uses some 'compressed gas fuel'

'gas engine' uses some 'gaseous combustion fuel'
'compressed gas engine' uses some 'compressed gas fuel'

'liquefied petroleum gas' 'has state of matter' value liquid
'liquefied petroleum gas' 'has normal state of matter' value gaseous
'liquefied petroleum gas' 'has disposition' some 'combustible energy carrier disposition'
```

```
'liquefied petroleum gas' 'has role' some 'fuel role'
'compressed natural gas' 'has role' some 'compressed gas fuel role'
'compressed biomethane' 'has role' some 'compressed gas fuel role'
'compressed synthetic methane' 'has role' some 'compressed gas fuel role'
'compressed gas fuel' EquivalentTo: 'combustion fuel' and ('has role' some
    'compressed gas fuel role')

'transport network' 'has part' some 'transport network component'
'transport network' 'has quantity value' some 'length value'
'road network' 'has part' some 'road'
'rail network' 'has part' some 'railway'
'rail network' 'has part' some 'train station'
'waterway network' 'has part' some 'port'
'aviation network' 'has part' some 'airport'

'transport network component' equivalentTo 'artificial object' and ('part
    of' some 'transport network')
'transport network component' 'has economic value' some 'cost'
'road' 'is used by' some 'road vehicle'
'railway' 'is used by' some train

'train station' 'is used by' some train
'freight train station' 'is used by' some 'freight train'
'passenger train station' 'is used by' some 'passenger train'
'bus station' 'is used by' some bus
port 'is used by' some ship
'freight port' 'is used by' some 'cargo ship'
'passenger port' 'is used by' some 'passenger ship'
airport 'is used by' some aircraft

'electrical energy transfer' 'has energy input' some 'electrical energy'
'electrical energy transfer' 'has energy output' some 'electrical energy'
'chemical energy transfer' 'has energy input' some 'chemical energy'
'chemical energy transfer' 'has energy output' some 'chemical energy'
'fuel transport' 'has participant' some 'fuel'
'combustion fuel transport' 'has participant' some 'combustion fuel'
'combustion fuel transport' 'has energy input' some 'chemical energy'
'combustion fuel transport' 'has energy output' some 'chemical energy'
'fuel' 'has role' some 'good role'
'freight transport' 'has participant' some good

'vehicle charging station' 'participates in' some 'electrical energy
    transfer'
'vehicle charging station' 'part of' some 'transport network'

vehicle 'bearer of' some 'vehicle operational mode'
'vehicle operational mode' 'has bearer' some vehicle

'battery electric car' EquivalentTo car and ('has part' some 'traction
    battery') and ('has part' some 'electric traction motor')
'compressed gas car' EquivalentTo car and (uses some 'compressed gas fuel')
     and ('has part' some 'gas engine') and ('has part' only ('gas engine'
    or (not (motor))))
```

```
'diesel car' EquivalentTo car and ('has part' some 'diesel engine') and ('has part' only ('diesel engine' or (not (motor))))
'fuel cell electric car' EquivalentTo car and ('has part' some 'fuel cell') and ('has part' some 'electric traction motor')
'gasoline car' EquivalentTo car and ('has part' some 'gasoline engine') and ('has part' only ('gasoline engine' or (not (motor))))
'liquefied petroleum gas car' EquivalentTo car and (uses some 'liquefied petroleum gas') and ('has part' some 'gas engine') and ('has part' only ('gas engine' or (not (motor))))
'plug-in hybrid electric car' EquivalentTo car and ('has part' some 'electric traction motor') and ('has part' some ('internal combustion engine' and ('participates in' some propulsion)))
'battery electric truck' EquivalentTo truck and ('has part' some 'traction battery') and ('has part' some 'electric traction motor')
'compressed gas truck' EquivalentTo truck and (uses some 'compressed gas fuel') and ('has part' some 'gas engine') and ('has part' only ('gas engine' or (not (motor))))
'diesel truck' EquivalentTo truck and ('has part' some 'diesel engine') and ('has part' only ('diesel engine' or (not (motor))))
'fuel cell electric truck' EquivalentTo truck and ('has part' some 'fuel cell') and ('has part' some 'electric traction motor')
'liquefied natural gas truck' EquivalentTo truck and (uses some 'liquefied natural gas') and ('has part' some 'gas engine') and ('has part' only ('gas engine' or (not (motor))))

'tank' 'has quantity value' some volume
'fuel tank' 'has quantity value' some 'storage capacity'
'fuel tank' 'has function' some 'chemical energy storage function'
volume 'has unit' some 'volume unit'
volume 'quantity value of' some 'three-dimensional spatial region'

'internal combustion vehicle' 'has part' some 'fuel tank'
'plug-in hybrid electric vehicle' 'has part' some 'fuel tank'
'fuel cell electric vehicle' 'has part' some 'fuel tank'
'gas turbine vehicle' 'has part' some ''fuel tank'
'tank ship' 'has part' some 'tank'

'filling station' 'part of' some 'transport network'
'filling station' 'participates in' some ('combustion fuel transport' and ('has participant' some ('fuel tank' and ('part of' some vehicle))))
'hydrogen station' 'participates in' some 'hydrogen transport'
'hydrogen transport' 'has participant' some hydrogen
```

Listing C.1: List of all implemented axioms.

```
'modal split' 'has part' some 'modal share'
'modal share' 'is about' some 'transport'
'modal share' 'has unit' some 'percent'

'passenger load' 'has unit' some ('mass unit' or 'count unit')
'freight load' 'has unit' some ('mass unit')
'vehicle capacity' 'has unit' some ('mass unit' or 'count unit')

```

```
'fuel blending quota' 'quantity value of' some 'combustion fuel'

'energy storage process' 'has process attribute' some 'energy storage
    efficiency'
'energy storage process' 'has participant' some 'energy storage object'
```

Listing C.2: List of all suggested axioms.

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