Sebastian Gunnestad Evans

casEV - Modelling smart power grids with V2G charging as complex systems within an urban context

Master's thesis in Computer Science
Supervisor: Sobah Abbas Petersen
July 2020

Master's thesis

NTNU
Norwegian University of Science and Technology
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Kunnskap for en bedre verden

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Abstract

This thesis sets out to investigate how the use of complex systems modelling can be utilized to see how the flow of people and traffic can have an effect on the energy consumption within an urban area. A framework for smart grid architecture with vehicle-to-grid charging, that was proposed by the author as part of a research project last year, is implemented into an existing model *CitySim*. *CitySim* simulates the traffic and movement of people with the help of agent-based modelling. A literature review of topics related to complex systems, agent based modelling and smart power grids was conducted to give an overview and understanding of the subjects most central to the thesis. Three experiments were carried out by running simulations with the model, in order to demonstrate examples of how such a model can be utilized. As well as aiding in the validation of the framework implemented. The results of the simulations are then viewed and discussed in relation to the thesis' goal and research questions. The model proposed in this thesis is titled casEV and the source code can be found here.

Sammendrag

Denne oppgaven tar sikte på å undersøke hvordan bruk av kompleks systemmodellering kan benyttes til å se hvordan flyten av mennesker og trafikk kan ha en effekt på energiforbruket i et urbant område. Et rammeverk for "smart grid" arkitektur med tilbakeladning av strøm fra elektriske biler til kraftnettet, som ble foreslått av forfatteren som en del av et forskningsprosjekt i fjor, implementeres i en eksisterende modell *CitySim*. *CitySim* simulerer trafikk og bevegelse av mennesker ved hjelp av agentbasert modellering. En litteraturgjennomgang av emner relatert til komplekse systemer, agentbasert modellering og smarte kraftnett ble gjennomført for å gi en oversikt og forståelse av temaene som er mest sentrale i oppgaven. Tre eksperimenter ble utført ved å kjøre simuleringer med modellen for å demonstrere eksempler på hvordan en slik modell kan brukes. I tillegg til å hjelpe til med validering av det implementerte rammeverket. Resultatene fra simuleringene blir deretter sett på og diskutert i forhold til oppgavens mål og forskningsspørsmål. Modellen som er foreslått i denne oppgaven har tittelen casEV, og kildekoden finnes her.

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List of abbreviations

ABM	Agent-based Modelling
AI	Artificial intelligence
AMS	Advanced Metering System
EUC	European Commission
EV	Electric Vehicle
GUI	Graphical user interface
ICT	Information and communications technology
OECD	The Organisation for Economic Co-operation and Development
kWh	Kilowatt-hour
PEV	Plug-in electric vehicle
SETIS	Strategic Energy Technologies Information System

1 Introduction

This chapter aims to present the overview and background of this thesis, its problem statements & research questions, as well as providing the aim, objectives, scope and structure of the thesis as a whole.

1.1 Overview

The majority of the current global population are living in cities and urban areas, and the number is expected to continue increasing in the foreseeable future [1]. At the same time, the different needs and demands for energy in the world's urban areas will continue to grow alongside their increasing populations. This anticipated growth of energy demand will require new and innovative solutions for the subsequent problems and challenges that will arise [2].

As the people in cities and urban areas are living their normal, everyday life, the overall trends and pattern in the demand for energy are evident and clear to see. The patterns tend towards a high demand in the working areas during the morning rush hours, while the same can be seen in the living areas during wake-up hours and immediately after people come home from work [3]. When one considers the difference in energy demand over time, it's often beneficial to view it with regards to its peaks and valleys. A sudden increase in energy demand will produce a peak in consumption, while a sudden decrease in demand will produce a valley. To handle these sudden increases and decreases in demand is one of the biggest challenges for the electric utility companies [4]. The infrastructure has to be constructed in order to handle the highest peaks, which comes with high economic costs and continuous maintenance. Providing solutions for reducing the gaps between these peaks and valleys could prove to be quite beneficial. Not only for the utility companies and the general consumer, but for the whole environment as well.

The last two to three decades have seen huge increases in the attention directed towards the globe's environment and the challenges associated to it. Governments around the world are giving incentives and dedicates large parts of their national budgets to encourage the research and development of solutions to improve the globe's emission levels [5]. These efforts do seem to have some of desired effects, even though there is a long way to go and plenty of challenges that lie ahead [6]. One of the crucial steps towards a cleaner future is the encouragement of thrift, as well as the reduction of excessive consumption. One way to aid in this could be to ensure that the utilization of the available energy is maximized, by avoiding superfluous usage and providing solutions for giving redundant power back to where it's needed. The power grids of the future, also know as as *Smart Grids*, aims to assist in these goals of modernizing energy management [7].

Smart grids, as a concept, is fairly new. The definition isn't set in stone, and will often vary depending on who one asks. However, EUC's SETIS defines smart grids as [8]:

Electricity networks that can intelligently integrate the behaviour and actions of all users connected to it - generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies.

Smart grids are seen as an exciting and vital tool in handling many of the problems we face regarding grid optimization and maintenance. The research and interest surrounding the field of smart grids is ever-increasing. One of the most notable innovations that has emerged as a result of this is Vehicle-to-Grid charging (V2G). This technology aims to enable electric vehicles (EVs) to charge redundant power back to the grid when connected to a charger [9]. By achieving this, the effects could benefit in reducing the aforementioned gap between the peak and valley in grid load. Current studies on the related topics are mostly conceptual ones, and not yet implemented in the real world. It's hard to see the specific benefits of the different anticipated smart grid technologies. One approach is to model them as parts of complex adaptive systems, in order to view the emergent trends and patterns as a result of the implementation of the different smart grid technologies.

1.2 Background of study, problem statement & research questions

1.2.1 Background of study

The concept of complex adaptive systems has been around for a long time. However, during the last decades, the interest and science behind it has escalated quite a lot. Especially proportionally together with the advancements of computer science, mathematics, physics and AI, among others. These, relatively speaking, recent advancements in these fields, increases the applicability of complex systems modelling [10]. This is possible through having computational power and other technology that has not been available to utilize before now. At the most basic level, complex systems are often described in terms of their examples from biology and nature. Like ant colonies, flocks of birds, river networks, and more. These examples can, in many ways, also be related to cities and urban areas, where the behaviour of the different parts of the system is difficult to identify and model, while the system as a whole presents us with some emerging patterns and recognizable trends. As a result of this, the use of complexity science and complex modelling is gaining traction as one way to model and understand cities and the different parts that consist of. For example, power grids, transport and other important parts of urban infrastructure.

Last year, Fosvold wrote a Master's thesis that explored how the use of agent-based, complex systems modelling could aid in understanding the emergent traffic patterns in a city and how it mutually affects other aspects within. A complex model was proposed, by using the popular, open-sourced, library Repast Simphony [12]. The model set out to be able to simulate the transportation of people within an urban area, and is titled *CitySim* [4.2].

1.2.2 Problem statement & research questions

In this thesis, a conceptual high-level framework for modelling parts of smart power grids, that was introduced as a part of the author‘s specialization project last year [13], will be implemented into the existing model *CitySim* [4.2]. The thesis' problem statement can be stated as the following:

- *To implement a framework for modelling aspects of smart power grids as parts of a larger, agent-based, urban complex systems model. Where the emphasis will be on V2G charging, the movement of people and how they mutually affect the supply and demand of energy.*

Accordingly, the following research questions are explored in this thesis:

Q1: *How can complex modelling be used as a tool to see the flow of energy in relation to the movement of people?*

Here lies one of the central research gaps addressed by this thesis. To be able to see how the energy demands of a city is related to the movement of the people in it and how it's infrastructure is laid out. Through the use of complex systems modelling the thesis will study how it can be used as a tool to aid in the analysis of the correlation between how people and traffic move in a city, and the supply and demand of energy.

Q2: *In what way can a smart power grids with V2G charging be modelled as a complex system within a city?*

This thesis will look at potential ways smart power grids, with V2G charging, could be modelled as a part of a larger, complex adaptive system. Different existing literature will be reviewed, as well as existing models and techniques that have been developed during the recent years. The different approaches will be compared and discussed, in relation to their applicability and contribution to the domain of smart grid modelling.

Q3: *What are some of the benefits of having a complex systems model with regards to smart power grids with V2G charging?*

Another area of investigation in this thesis discusses and reflects around some of the potential benefits of having a complex system model with the intent to model smart power grids and their relation to urban transportation. The author looks at how this type of modelling could aid in understanding the flow of energy consumption with regards to other aspects of a city. I.e. the flow of people and traffic, pricing schemes for V2G charging and the cities infrastructure as a whole. The aim is to show how the model can be utilized as a tool for aiding in optimization and decision-making related to smart grids and V2G charging, as well as giving a holistic view of the the system and its parts.

Q4: ***What emergent patterns will arise from the system in relation to power-grid load distribution?***

The idea of *peak shaving* is believed to be one of the main benefits of V2G charging. Through three different experiments, the thesis will attempt to view different emergent patterns that will emerge as a result of running a number of simulations with varying input parameters. This is done to show the applicability of such a model, in the domain of smart power grids and V2G charging.

1.3 Aim

This thesis aims to provide a complex systems model that can give a clear picture of how the power load-distribution within an urban area is effected by the introduction of V2G charging and the movement of people. While also considering new and innovative technologies related to smart power grids.

1.4 Objectives

The objectives of this thesis are to provide a solution to the problem statement, as well as attempting to provide answers to the four research questions stated.

1.5 Scope of study

The scope of this study will be limited to looking at the V2G aspect of smart power grids and its potential benefits on grid load distribution, in relation to the transportation of people in electric vehicles in an urban context. This will be done by implementing a framework for modelling smart power grids with the existing complex systems model *CitySim*, and using it to conduct experiments by running different simulations.

1.6 Structure

Chapter 1 introduced the research to be examined in this thesis. The problem statement and research questions were stated. Chapter 2 presents a review of the literature and background information on the themes and topics most central to this thesis. Chapter 3 lays out the methodological approach taken during the completion of this thesis. Chapter 4 presents the design and implementation of the framework and interface of the model casEV. Chapter 5 demonstrates three different experiments, where the model is used to run different simulations. The results of these simulations are displayed and explained briefly. Chapter 6 discusses the the results of the simulations with regards to the problem statement and research questions. Lastly, Chapter 7 presents some of the limitations of the work done in this thesis as well as some potential future work that can be done on casEV. A section at the end of the chapter concludes the thesis.

2 Literature review

This chapter will review prior literature on complex systems and complexity science. The topics are discussed in relation to smart power grids and urban transportation. ABM and V2G charging is also explained and reviewed in order to provide broader context to the topics covered in this thesis. A separate subsection is dedicated to reviewing some of the existing work that can be related to the problem statement and research questions mentioned in section 1.2.2.

2.1 Complex systems and complexity science

Complex systems are systems who's behaviour is difficult to represent due to the interactions and dependencies of all the different components that make up the system. These components make up networks that interplay with each other, most often in a nonlinear fashion. Complex systems will, in many cases, arise and evolve through self-organization, making them part regular and part random, which allows for the emergence of different patterns related to the system's behaviour at a macroscopic level [14]. There are many examples of complex systems in today's world, both natural and man-made ones. These examples include everything from ant colonies to power grid infrastructure. Complex adaptive systems are a subset of complex systems, where the system is adaptable and able to change and learn based on experience and feedback.

When discussing complex adaptive systems, it's imperative to have an understanding of the systems different layers and these layers' interactions across each other. The act of creating a realistic model of real life phenomena requires a correct interpretation of the components and behaviours that are a part of them. Some of these components will be lower level ones, like the simple interactions between entities in the system. While other components will be at a higher level. By having such an approach to modelling, the need for choosing the critical components, and only the critical ones, arises. Complex adaptive systems are often computationally expensive to run, and to pick and chose which components to include needs to be done sparingly to avoid a bloated model that attempts to include more than what is really deemed necessary.

Emergence is a key word that is often recited when researching complex systems and complexity science. The definition of emergence could be explained as *the fact of something becoming known or starting to exist* [15]. This is the very essence of what complexity science is about. The behaviours and patterns of the system are seldom apparent from the system's subsystems and components in isolation, but rather from the dependencies and interactions between them. Sayama discusses emergence in relation to the system's properties at different scales [14]. This is emphasized by explaining how emergence is observing properties at a macroscopic scale that are fundamentally different than one would intuitively expect from rules at a more microscopic level. In short, emergence is the nontrivial relationship between a system's properties at different scales and levels.

With the recent advancements in computer science and increase in computational power, more and more scenarios where complex systems modelling is applicable has appeared. The potential for modelling real-world systems is one of complexity science's biggest selling points. In multiple fields, complex system modelling is being utilized for various different purposes. In the domain of power grids, there is already a great deal of interest in complex modelling and its potential with regards to power grid modelling.

Two of the major contributors to the field of complex systems and complexity science are *Santa Fe Institute* [16] and *New England Complex Systems Institute* (NECSI) [17]. They are both independent research institutes that are heavily involved in the research and development of complex systems science and its application. Both institutes are also tightly linked to academia, and have affiliates from MIT, Harvard and a number of other internationally recognized universities.

2.2 Power grids as complex systems

Power grids are arguably some of the most complex systems made by humans, ever [18]. They're also technologically evolving by the day, and as a result the structure of them is changing as well. The addition of new features will create an increase in interactions between the different involved parts. The behaviour of power grids is an emergent one, due to it arising from the interactions of multiple different parts [18]. But it is, in many ways, different from the complex systems found in biology. Like bee colonies or flocks of birds. Unlike these, the behaviour of power grids arises as a result of the central control of a decision maker, making them in many ways systems that are part complex and part deterministic. Power grids has ways of reinforcing their own stability. The elements of the grids are so tightly connected, that they will exert force on one another. If one or more of the elements become unstable, the others can compensate. On the other hand, this form of self regulation could destabilize a system as well. Anomalies and incorrect feedback could amplify an already unstable system to the point of destruction. Power grids, like many other human made complex systems, need some sort of human control to ensure that they operate correctly [Blumsack[18]].

Aspects like the weather, economics and technological innovation are the driving forces behind the behaviour of power grids, and these external powers can be seen in relation with the patterns that emerge from it. The EUC states that the complexity of the future power grids (smart grids) will rest on the multiplicity of interacting players that operate with, and within, a defined environment as independent decision-makers, with autonomous behaviours, goals and attitudes [19]. And this is where the essence of the relationship between power grids and complexity science lies. Complex adaptive systems are, in essence, systems whose behaviour is difficult to model and explain as a whole, due to the interactions, dependencies and non-linear behaviour of the involved parts. This can also be applied when explaining the behaviour and interactions that go on within a power grid and the elements that it interacts with.

The EUC believes that at this early stage in the development of the next generation of power grids and energy systems, some emergent properties can already be anticipated from them [19]. Nonetheless, they note that there is complexity and emergent patterns that remain unforeseen yet, and will not be visible before the actual implementation of the technology. The hypothesis they support, is the one where the introduction of complexity science can help identify the techniques and tools needed for the optimal decision making with regards to things like regulatory design, planning and investments, and real time operations. The usage of complexity science can provide foundations for models and guidelines for the future development of power grids, and for recognizing the emergent behaviours of them, states the EUC [19].

Plenty of research has been done on power grids and their relation to complex systems, as well as the functionality of the future smart grids. The grids are themselves parts of larger systems, described as a part in a "systems of systems". Therefore, the complexity is not merely an attribute of the power grids, but also of the systems they interact with [19]. Like the behaviour of the consumers of the grid, or the complex and varying behaviour of the weather and climate. The fact that the behaviour of power grids can not be isolated and abstracted without looking at the other systems that they interact with, means that their modelling and understanding is difficult to comprehend. Here is where the use of complexity science can aid in providing a alternative way to look at the power grids and their behaviour.

2.3 Smart grids and V2G charging

Smart grids is a collective term for the next generation of technology used in the energy systems of the world. A demand for new and innovative solutions for handling the energy-needs of an evermore energy-dependent world paves way for new and exciting technologies related to the grids and their infrastructure. The energy systems of the future will see the flow of energy going both to and from the prosumers and other smaller-scale producers [20]. Smart grids utilizes ICT-systems in grid-related infrastructure, which has laid path for intelligent solutions that uses state of the art technology from the fields of optimization and automation [21]. The EUC has stated a goal of replacing 80% of electricity meters within its borders with smart meters by the year 2020, given that it is economically viable to do so [22]. Smart meters are one of the most promising and low-entry additions to the smart grid systems and the implementation of them could potentially reduce emissions by a sizable amount [22].

V2G is a fairly new concept, which has emerged as a result of the recent influx of electric vehicles in large parts of the world. In short, it's the ability for plug-in electric vehicles to charge back their stored energy to the power grids while

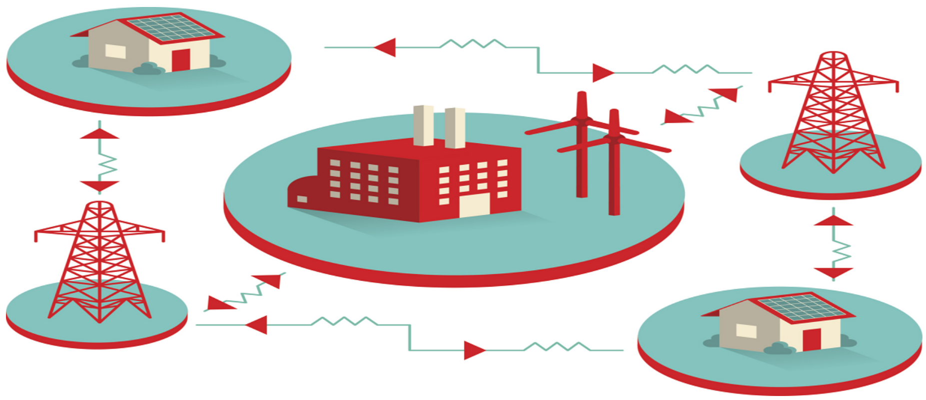


Fig. 2.1. A simple illustration demonstrating the bidirectional power flow of smart grids [23].

connected to a charger. This is done by implementing automatic mechanisms that determines the constant supply and demand of energy, which in turn decides whether or not the vehicle charges from the power grid or back to it [24]. These mechanisms are what is considered the smart component of the concept, and is also why V2G lies within the problem space of smart grids. The ability to provide constant energy at an as-needed basis is one of V2G's strongest selling points, as well as being seen as a promising tool in reducing the peak-valley gaps in energy consumption from the power grids.

Big power banks, in the form of batteries, are becoming more and more common. And at the same time, the improvement in battery-technology has made them better than ever. The available energy storage capacity has risen greatly during the last decades, which in turn has done such that the possibilities for their utilization has also increased [25]. When buildings, like houses or offices, has access to high-capacity batteries, they can take advantage of this available power to balance out energy production and consumption in the grids they're connected to [26]. The fact that electric-vehicles are mobile units means that their stored power is available to be taken advantage of, in theory, wherever they are. As long as they're connected to a bi-directional charger and has redundant power stored.

V2G charging, in most cases, will involve scenarios where the vehicles charges power from the grid, and ones where they charge power back to the grid, at alternating intervals. Calculations and decisions need to be made in order to determine the supply & demand of electric energy from both the EVs and the buildings (or other entities) their V2G charger is connected to. From the EVs perspective, the decisions will be based on factors like available stored energy, distance from home, battery deterioration, among many others. On the other hand, the entities that the EVs' chargers are connected to will decide its needs based on different factors. Like the time of day or the weather. To name a few. On both sides, there will be economic elements that weigh heavily in the decision making. One can imagine scenarios where a building's demand for energy is at its peak, and will therefore, at that particular moment, offer more for connected EV's stored power than it would at other, less demanding, moments. The opposite will also be a likely scenario. Where the buildings will offer little or nothing for the power of its connected EVs, due to the immediate demand being low. These decisions are based on factors that are rapidly changing, and some degree of automation needs to be implemented to accommodate for the changing variables.

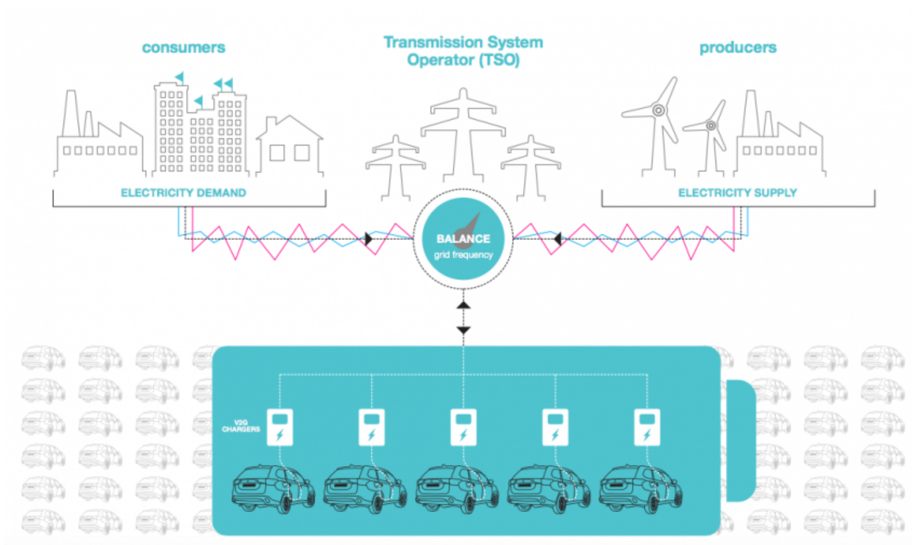


Fig. 2.2. A simple overview of V2G technology and how the power flows both to and from the vehicles [27].

2.4 Agent-based modelling

Agent-based models are a class of models that are classified as *models for simulating the actions and interactions of autonomous agents with a view to assessing their effects on the system of the whole* [28]. ABM combines different elements from complexity science, game theory, evolutionary programming, among others.

ABM is typically used in cases where the system, or scenario, being modelled involves entities that are able to make autonomous decisions based on how they perceive and react to the environment they operate in, as well as how they interact with the other agents of the system. The agents are often modelled at a microscopic scale, with simplified rules and functions to govern their behaviour.

This can give insight into emergent trends and patterns in the system at a more macroscopic scale. The book by Sayama lists these which are typical properties associated with agents in an agent-based system [14, p. 429]:.

- Agents are discrete entities.
- Agents may have internal states.
- Agents may be spatially localized.
- Agents may perceive and interact with the environment.
- Agents may behave based on predefined rules.
- Agents may be able to learn and adapt.
- Agents may interact with other agents.
- ABMs often lack central supervisors/controllers.
- ABMs may produce nontrivial "collective behavior" as a whole.

ABM is an approach often used when modelling and simulating complex adaptive systems. It has been used in a number of different disciplines to simulate the dynamical and parallel behaviour of systems that are made up of a large number of entities [14, p. 427]. Models like this allows for the simulation and analysis of various scenarios related to urban transportation and smart power grids. They could also aid as a tool in acquiring a greater understanding of how these two concepts are related and how they have a mutual effect on each other.

2.5 Existing research & work

This section will attempt to give a brief overview of some of the related work that has been done in the fields relevant to the problem statement and research questions of this thesis. Their contributions will be discussed briefly. Table 2.1 gives an overview of some of the relevant work done identified by the author.

The work done by Rylatt et al. in 2013 & 2015 provided a framework, titled *The Complex Adaptive Systems, Cognitive Agents and Distributed Energy* (CASCADE) [29]. The framework is utilized to both gain policy and industry relevant insights into the smart grid concept itself and as a platform to design and test distributed ICT solutions for smart grid based business entities. This framework uses ABM to capture different behaviours that influence the smart grids. Ranging from social, economic and technical actors. They model the actors as agents that are either *Prosumers* or *Aggregators* at various scales, from larger energy generators down to individuals. The authors of the paper state that the framework yielded some interesting results, indicating that it is possible for a mediating agent (*Aggregator*) to achieve flattening of the demand for electric energy across groups of households installed with smart energy control and communications technology. The findings also indicated that small changes in the demand could give big changes in the supply profile. The authors do state that integrating the framework with the transport sector is something to be addressed through future research. The framework for smart power grids proposed in section 4 is heavily influenced by the structure and organization of the CASCADE framework.

"Modelling elements of Smart Grids - Enhancing the OSeMOSYS (Open Source Energy Modelling System) code" expands on the existing Open Source Energy Modelling System (OSeMOSYS) to add aspects of smart grids [31]. The paper describes how different blocks of functionality can be added to represent the variability in electricity generation, as well as the shifting demand and difference in storage options. The authors of the paper state that the peak demand for electricity may be reduced by shifting certain demand types within predefined intervals at costs increasing with the delay of meeting a demand. They also found indications that higher electricity prices could force some of the consumers to reduce their consumption, based on simulations ran with their proposed model framework. However, the authors state that their proposed model only covers a subset of issues related to smart grids, and has been modelled using well-known linear programming methods. The paper does *not* attempt to list a full suite of other important modelling tasks related to smart grids, which they list as the focus of future work. For example, their role in frequency and voltage control.

Title	Year	Author(s)
Modelling elements of Smart Grids - Enhancing the OSeMOSYS code	2012	Manuel Welsch et al.
A Complex System Approach for Smart Grid Analysis and Modeling	2012	Guillaume Guérard, Soufian Ben Amor, and Alain Bui.
Modelling and simulation of large scale power grids	2014	Jan Zabojnik and Michal Dvoraky.
Modeling Smart Grids as Complex Systems through the Implementation of Intelligent Hubs	2010	Jose Gonzalez de Durana et al.
CitySim: A modular Agent-Based simulation system for Modeling Cities as Complex Systems	2019	André Fosvold
Complexity and emergence in city systems: implications for urban planning	2009	Michael Batty

Table 2.1. Overview of some of the relevant work done on modelling and analysis of smart grids through complex systems.

Guérard, Ben Amor, and Bui proposed a state of the art on smart grids, to clarify the concept and to identify different issues of importance in "Survey on smart grid modelling" [33]. They also provide an overview and analysis of the similar characteristics between smart grids and complex systems, to gain the knowledge on how to design a reliable and efficient smart grid [32]. In the paper, they state that most of the modelling and simulations done in the domain of smart grids has been based on multi-agent systems, and that they mostly deal with microgrids. The authors believe that modelling smart grids as complex systems opens new opportunities and perspectives, especially concerning the scaling and behaviour at different levels of the grids.

SINTEF, and independent research organization located in Norway, has done multiple experiments and projects regarding the modelling of power grids, some with an emphasis on the *smart* parts of the grids as well. A relevant study is the one they have from 2016, titled *SmartPower* [34]. The project set out to demonstrate the usefulness of modern optimisation methods for demand response applications in energy markets. They developed a prototype for optimised power matching/load balancing in large scale Smart Grids. The same organization has also developed the software *Power Grid Optimiser* [35]. This is a software service for computing the optimal configuration of a power grid. I.e. how to use switches and other grid components to optimise reliability, loss, balance, power quality and so on.

KogniGrid [36] is a joint research project from SINTEF and Kongsberg Digital that aims to develop information systems for grid operations that will give the grid-operators tools for implementing more automated processes to a greater extent than what they are able to do today. Another project worth mentioning is *ENERGYTICS*, which aims to demonstrate how machine learning and artificial intelligence can raise the utility of the smart power meter (AMS) that the power companies are installing in Norwegian households [37]. This is a joint venture between a mixture of different organizations and companies related to power grids in Norway, including Hafslund Nett, SINTEF Digital and The Norwegian Smartgrid Centre.

As shown, there has been quite a bit of work done in the interconnecting fields of smart power grids and complex systems modelling. However, most of it seems to view the grids as partly isolated systems, where their characteristics are analysed in relation to their affinity to complex systems. Not taking other sub-systems into account, and thus not really treating the smart grids as part of a larger *system of systems*. There is little research and work done on the use of ABM and complex systems to view power grids and energy flow in relation to the transportation and movement of people in urban contexts, and how they have mutual effects on each other.

2.6 Chapter summary

This chapter has reviewed prior literature on complex systems and complexity science. Other topics relevant to the thesis has been discussed in relation to complex systems. The last section gave an overview of some of previous work done in the same domain as this thesis, while also stating their contributions.

3 Methodology

This chapter presents the methodological approach taken when writing this thesis. The process behind the collection of relevant background literature and data will be described, as well as an overview of the external expert opinions that were taken into account when designing and implementing the framework of the model. A separate section is dedicated to the validation and confirmation of the model and its output data. The methods used when analyzing the output data and performance of the model is also discussed.

3.1 Methodological approach

The research methods in this thesis consisted of a background study and literature review of topics relevant to the problem statement and research questions. Like complex systems, ABM, smart grids, V2G charging, among others. The model presented in section 4 is built upon the existing model *CitySim* [4.2], and the modelling library *Repast Simphony* [4.1]. The problem statement [1.2.2] came about after discussion with the author's supervisor and co-supervisor, as well as being a continuation of the work done in specialization-project of last year, where the framework for the casEV model was presented by the author [13]. The research questions [1.2.2] were formed in a way that could help in tying the ideas of complex adaptive systems, urban transportation and smart grid technology together. This is where the main research gap addressed by the thesis lies; to use complex systems modelling to see the patterns that emerges when looking at energy flow as a result of the movement and transportation of people.

To gain an understanding of the different topics discussed in sector 2, various sources needed to be reviewed and examined. Many of the topics and technologies discussed, like smart grids and V2G charging, are also quite new, relatively speaking. The sources reviewed included research papers, as well as articles and various other resources found on the internet. Conducting research this way calls for extra caution and consideration when searching, selecting and evaluating the different sources. Thus, the methods used in the background study and literature review could described as qualitative in nature. The research was done in order to understand the central concepts and thoughts involved, while also gathering in-depth insight into the research being done in the fields of complex systems modelling and smart grid development. To validate the ideas and design of the model framework proposed in section 4, the author consulted and held conversations with experts in fields relevant to thesis' theme of complex adaptive systems and power grid modelling. Their information is shown in table 3.1. The author gained an understanding of the existing model *CitySim* [4.2] and the modelling library *Repast Simphony* [4.1] by reading their documentation, as well as by playing around with the source code to better comprehend the design and logic behind each of them.

There were also elements of quantitative research methods utilized when designing parts of the casEV, as well as when conducting parts of the necessary validation. The thesis is heavily involved with the day-to-day and hourly changes in demand for energy within a given geographical area. In addition to the changes in traffic going in and out of cities. This created a need for quantitative values that could serve as a benchmarks for the performance of the model. Relevant data was collected from government websites, and used during the design and validation of the model. As shown in section 3.2.2.

3.2 Data collection

The collection of data that went into creating this thesis can be described in two parts:

- Qualitative and quantitative information needed when designing the model and agents' behaviour.
- Quantitative data gathered from the simulation runs from the experiments conducted in section 5.

The first part was the validation of the author's ideas and proposed methods, through qualitative research from the literature review. As well as through more in-depth conversations with various experts within the fields relevant to the thesis. The quantitative collection of data and statistics related to electricity demand and traffic was also a part of the information needed to design the model and its framework. The second part was was the data gathered during the simulations from the experiments presented in section 5. This data was later used for the analysis and validation of the model's performance, as well as giving valuable information during the iterative testing and adjustments done when developing the model.

3.2.1 Experts consulted

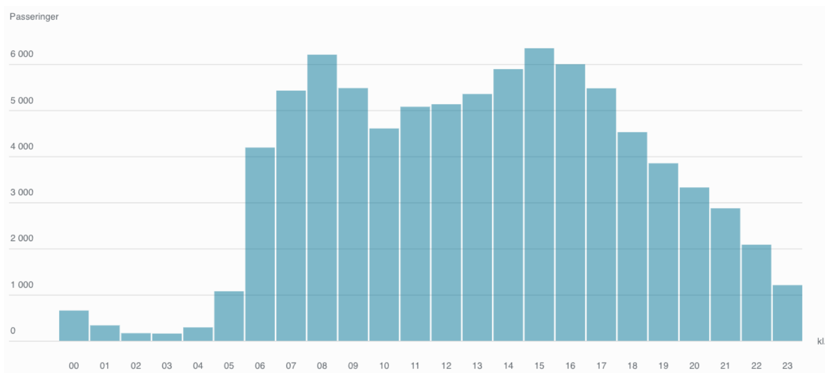
In table 3.1 the experts consulted during the development of casEV are listed, with their relevant background information. The experts were selected based on recommendations from the author's supervisor, as well as due to their relevancy to the topics underlying this thesis. The information gathered from the conversations has been used in the design and development of the model proposed in section 4.

Name	Institution	Role	Field
Idar Petersen	SINTEF Energy	Research scientist	Energy systems.
Keith L. Downing	NTNU	Professor	AI, Cognitive Science, Computational Neuroscience.
Gunnar Tufte	NTNU	Professor	Computer science, complex systems science.

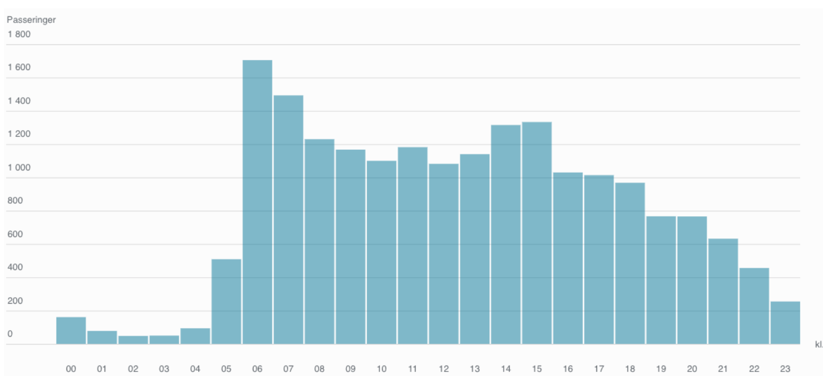
Table 3.1. An overview of the experts that were consulted during design of the model framework.

3.2.2 Real-world data; energy and transportation profiles

There is a need for real-world data when attempting to model real-world scenarios. So that one can compare the performance of the model up against some sort of benchmark. In the case of this thesis, the real-world data needed was that of energy profiles of a specific area over a set period of time, as well as an overview over the traffic going in and out of cities. When collecting this data, the author relied on research papers and statistics related to energy demand forecasting and urban transportation. Figure 3.1 gives the amount of passages through two of the most popular toll stations going into Oslo, Norway during an average weekday. Figure 3.2 depicts the daily average energy usage across the secondary and tertiary sectors of the Norwegian economy. The framework presented in section 4 supports parameters for adjusting the average load (kWh) per agent and other electric entities, as well as the option for adjusting the traffic-load going into the city throughout the day. The information in figures 3.1 and 3.2 is used as a base case for the simulations in section 5, and when analysing and validating the performance of the model, as discussed in section 3.3.

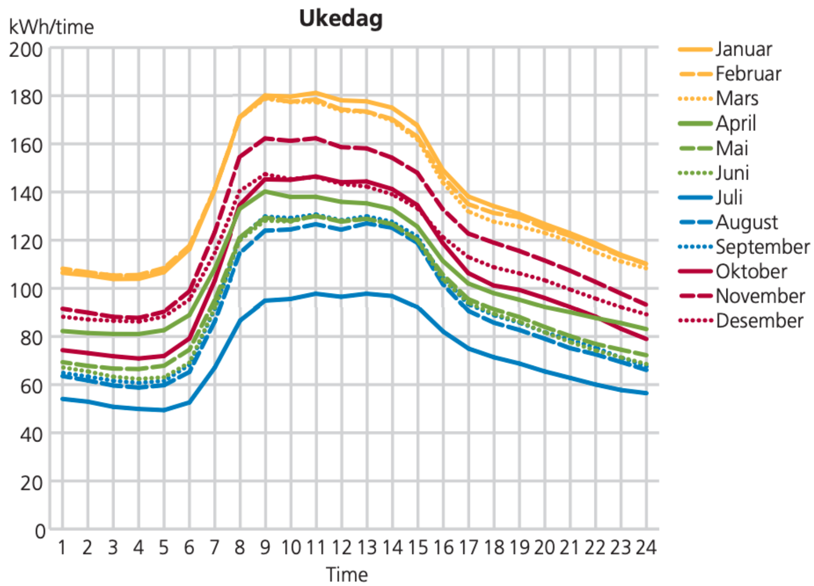


(a) E18 Maritim 24 hour transportation profile [38].

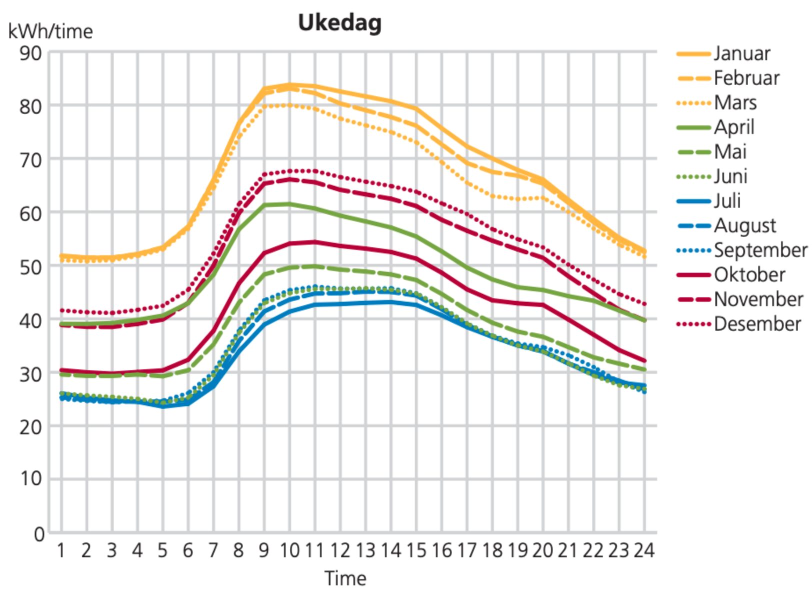


(b) E6 Alnabru 24 hour transportation profile [38].

Fig. 3.1. Two graphs depicting the rate of traffic trough two of the most frequented toll stations leading in to Oslo.



(a) 24 hour energy profile for the secondary sector of the economy in Norway [39].



(b) 24 hour energy profile for the tertiary sector of the economy in Norway [39].

Fig. 3.2. Two graphs depicting the 24 hour energy profile for the secondary and tertiary sector of the Norwegian economy.

3.2.3 Simulation data gathered

During the simulations that were ran as part of the experiments in section 5, data was generated and logged after each run. The *Repast Simphony* framework [4.1] allows for real-time logging of simulations, both in terms of raw data and more polished graphs, as shown in figure 4.3. Table 3.2 show some of the variables gathered from the simulation runs. The data logged from the runs aided in giving an understanding of the model and how it performed, was used during the experiments presented in section 5, while also giving a basis for the validation and comparisons against the real-world data that was collected.

Variable	**Description**
Peak grid load (kWh)	A measure of the highest electric load recorded during a simulation.
Bottom grid load (kWh)	A measure of the lowest electric load recorded during a simulation.
V2G connected	Real-time measure of the amounts of EVs connected to V2G chargers.
Average travel time	A measure of the time it takes for an agent from entering the city to parking.
Average travel distance	A measure of the distance an agent travels from entering the city to parking.
Average kWh price	A measure of average price of electricity during a run.
Car percentage	How many % of the agents rode cars during the simulation. Given as 100 - busPercentage.
Bus percentage	How many % of the agents rode buses during the simulation. Given as 100 - carPercentage.

Table 3.2. Overview of some of the data gathered from each simulation run.

3.3 Methods of analysis and validation

The data collected during the experiments in section 5 was a continuous real-time log of the simulations, stemming from the behaviour of the agents and the system as a whole. The values being logged were programmatically set, so that the data could be pivoted automatically. The analysis and validation of the data stemming from the simulations could be described in three parts:

- Comparing the results to real-world data.
- Analysing the results of edge case runs to assess and validate model performance.
- Comparing the results from different simulations up against each other.

This thesis sets out to model a real-life setting, and a logical way to try to validate such a model, would be to compare the results of the simulations with real world data. No model will ever be perfect, but such a comparison could give insight into areas that needs to be worked on and improved further. The data detailed in section 3.2.2 was used initially when designing and implementing the framework for the model. The behaviour of the agents and the system was based on the data gathered. For example when setting the traffic load during different time of the day, or when detailing an entities power usage over a set period of time. The data was also used when trying to assess the model's performance after each simulation run. By trying to view the system's overall behaviour up against actual data from the real world. By comparing the results against the data, a more holistic assessment of the system could be made.

The use of edge cases provided insight into the model's performance and agents' behaviour during the testing and development phases. The iterative approach taken during these phases created the need for simple tests to make sure the system behaved as expected after doing modifications to the source code. In the case of this thesis, such a test could for example be to see how the agents behave with an unlikely high price for parking. If the agents decision to park is not affected by such a high price, it might indicate that there is something that needs to be addressed with regards to the agents' decision making related to parking. The model parameters detailed in section 5.0.1 were set to unexpectedly high and low values, before simple simulation runs were carried out as tests after each major modification to the code.

By comparing the results of the different simulation runs from the experiments in section 5 up against each other, a more qualitative analysis of the system could be done. This analysis was based on the knowledge and information obtained during the literature review and background study in section 2. The data gathered from the different simulations gave valuable information that aided in providing answers to the problem statement and research questions from section 1.2.2. An insight into the agent's behavioural patterns was also given from the data gathered from the simulations.

3.4 Chapter summary

This chapter has presented the methodological approaches taken during the course of this thesis. First, the overall strategy of research was given. Later, the steps that went into the data collection was discussed. And lastly, the approaches taken for during the validation and analysis of the results was presented.

4 Design and implementation

This chapter presents the design and implementation of a complex adaptive systems model, that aims to show the cross connection between transportation and smart power grids in an urban context. The model is titles casEV. The existing model *CitySim* and the agent-based modelling library *Repast Simphony*, which are both integral to design and implementation of casEV, is also presented and discussed briefly. A description of the proposed model framework is presented, and the overall system will be introduced and discussed. The user interface of casEV is explained in short in its own section at the end. This chapter aims to answer RQ2; *In what way can a smart power grids with V2G charging be modelled as a complex system within a city?*

4.1 Repast Simphony

Repast Simphony is a richly interactive Java-based modelling system, and part of The Repast Suite. The Repast Suite is a family of advanced, free, and open source agent-based modelling and simulation platforms that have been under continuous development for 15 years [12]. The modelling system is compatible with Windows, macOS, and also most linux variants. Making it readily available for everyone who wishes to use it. As shown in figures 4.1 and 4.2, the software provides a simple GUI that can display the simulation going on, as well as input fields for specific variables entered before runtime. Specified graphs can also be displayed and updated as the simulations are running. As shown in figure 4.3.

The decision to implement the model using Repast Simphony was twofold. Firstly, CitySim was built upon it. Secondly, it fills the needs of what the model in this thesis aims to do. Providing a stable environment for developing complex adaptive systems that allows for the implementation of ABM.

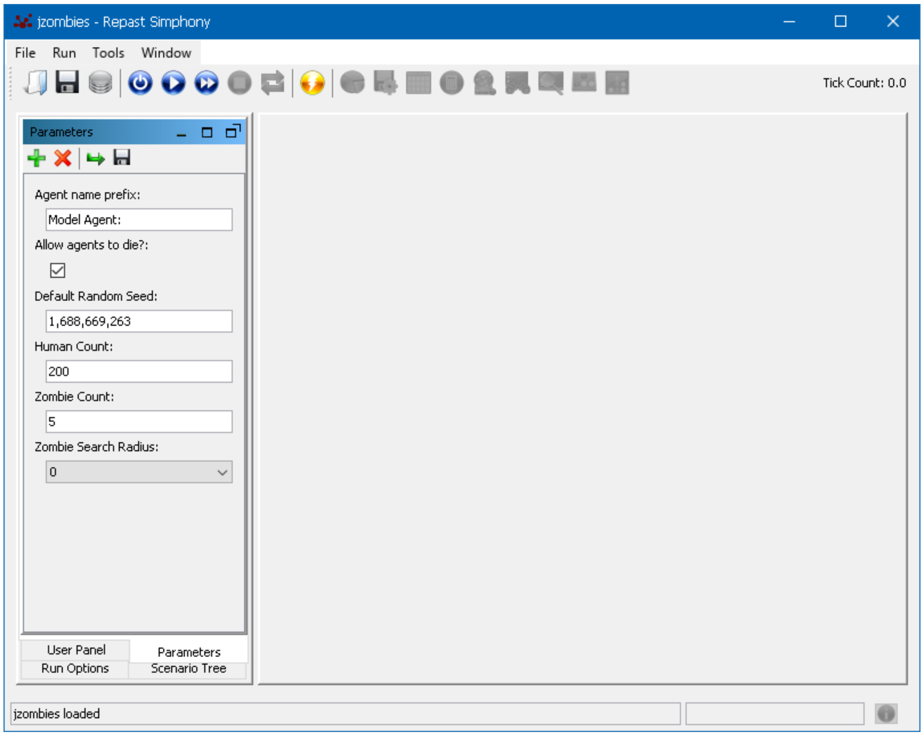


Fig. 4.1. A basic view of the GUI included in Repast Simphony [12].

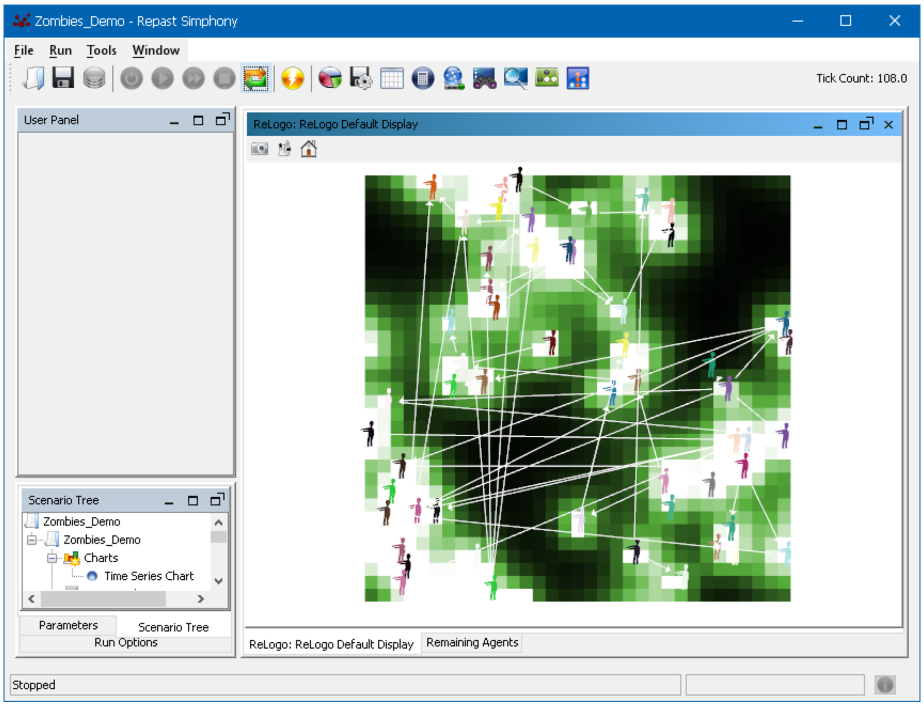


Fig. 4.2. A view of an example simulation ran using Repast Simphony [12].

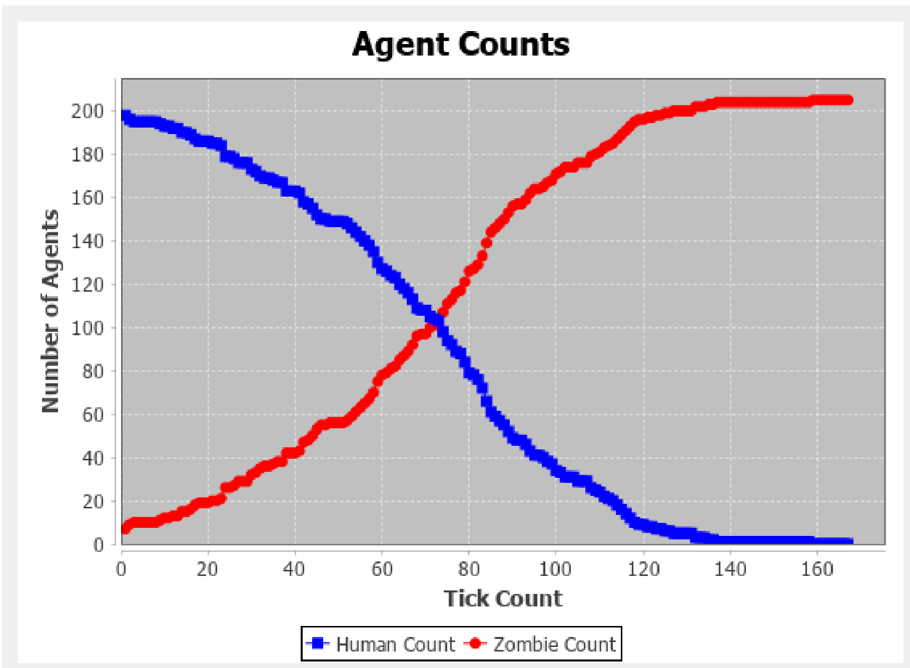


Fig. 4.3. A view of a chart from an example simulation ran using Repast Simphony [12].

4.2 CitySim

CiySim is a modular agent-based simulation system for modelling cities as complex systems. The model was created during a master's thesis in 2019 at the Department of Computer Science at NTNU. The thesis focused on creating a model that examined the use of agent-based, modular, micro simulator of a city as a complex system [11]. The thesis addressed how agent-based, complex systems could aid in understanding the emergent traffic patterns and their effect on other aspects of a city. CitySim was created with a modular approach, where parts of the system being modelled could be easily modified and swapped out, if needed.

Typical entities which make up the transportation and mobility in cities are modelled as agents, in an agent-based system. These are the buses, cars and people. A somewhat simplified version of reality. The agents interact with the city through the traffic system and make decisions based on their past experiences. The system is classified as a Complex Adaptive System, meaning that it's both complex and adaptive. A group of smaller agents forms a unified whole, and they adapt to the environment in which they are in. By running simulations, *CitySim* aims to show patterns that emerge from how these agents interact with their environment, and how the changes in the environment will impact the decision making of the agents. The environment is the city as a whole, which involves multiple levels of complexity.

4.2.1 Framework

CitySim is designed with a structure that separates the different parts of the model in four larger packages. These four are Environment, Agent, Structures and Utils, as shown in in figure 4.4.

Environment

The environment that is basis of the model is contained in its own package, and includes classes like roads, sidewalk, building, among others. The environment is created upon start-up by going through an image file pixel by pixel, and reading the different pixels to create the environment. Each class in the package is colour-coded, so the initialization algorithm creates the environment based on the pixels that match the different classes, similar to what is shown in figure 4.7. The different classes in the environment will have their own variables and methods. Like a road having a weight, a building having an electric-load, etc.

Agent

The agents of the model are the vehicles (cars and buses) and the people. They are bundled together under the agent package. The vehicles are goal-driven, in the sense that they follow a list of smaller-goals in order to reach their final goal (the destination in which they are going), using an A* pathfinding algorithm [40]. The people in *CitySim* also have goals and objectives which they follow, and their decision making is adaptive as its influenced by the results of past decisions.

Structures

The structure package of the framework is the package containing the data structures that are used in the different parts of the model.

Utils

Utils is the package for utilities and other tools that are used by all the parts of the model, like algorithms and other more general functions.

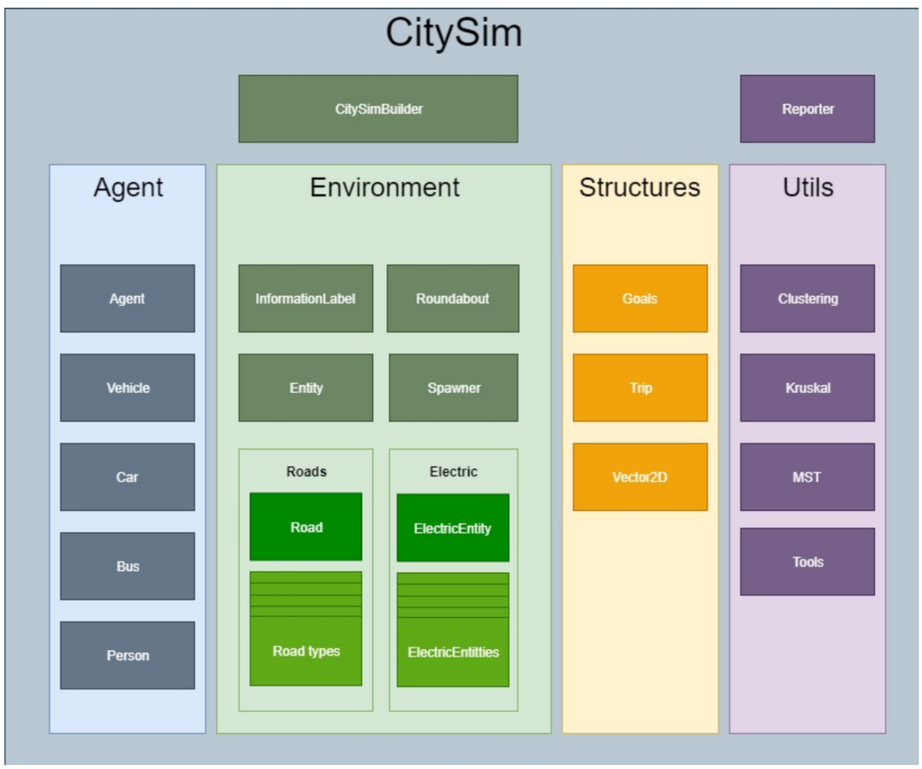


Fig. 4.4. An overview of the structure of CitySim. Showing the different packages and classes [11].

4.3 Proposed framework

The framework for casEV is constructed by implementing the components from the framework presented in the author's specialization project [13] into the existing model CitySim. The framework was highly influenced by the CASCADE framework [29], by borrowing the idea of having Prosumers and Aggregators to handle the trading of energy between the agents and the power grids. This resulted in a framework that is split into three smaller and relatable modules. These modules encapsulates the different components that make up the model and it's environment. Figure 4.5 details the flow of information between the different modules of the framework. Figure 4.6 gives a high-level overview of the different modules and classes included in the framework.

The framework for casEV is split into these three modules:

- The physical module
  - A module to represent the physical elements that make up the environment.
- The market module
  - A module that handles the buying and selling of electric energy within the environment.
- The agent module
  - A module that deals with the agents that operate and move within the environment.

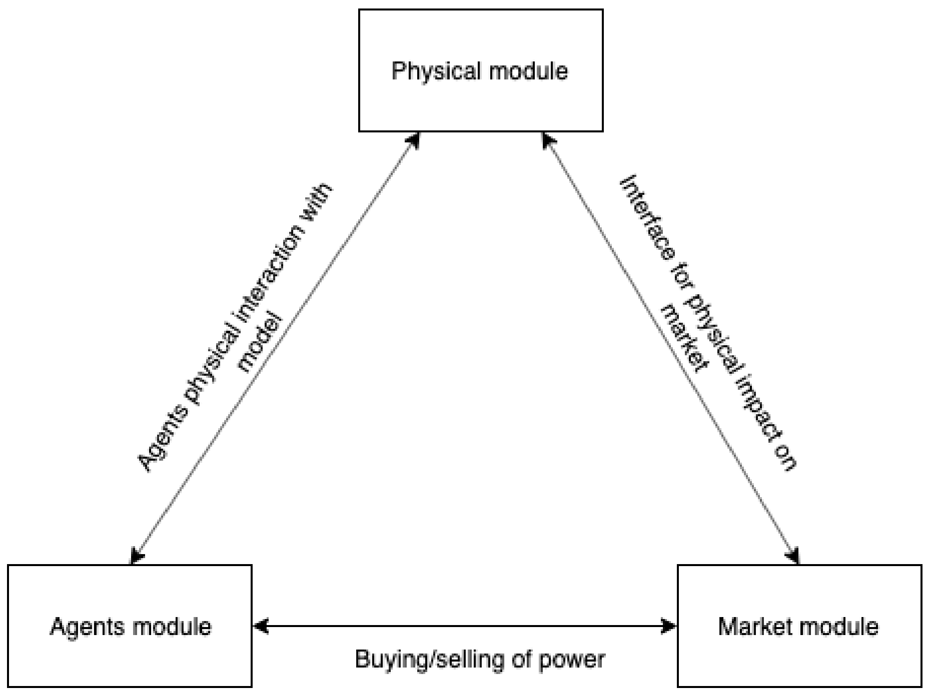


Fig. 4.5. A high level overview of information flow between the modules in the framework.

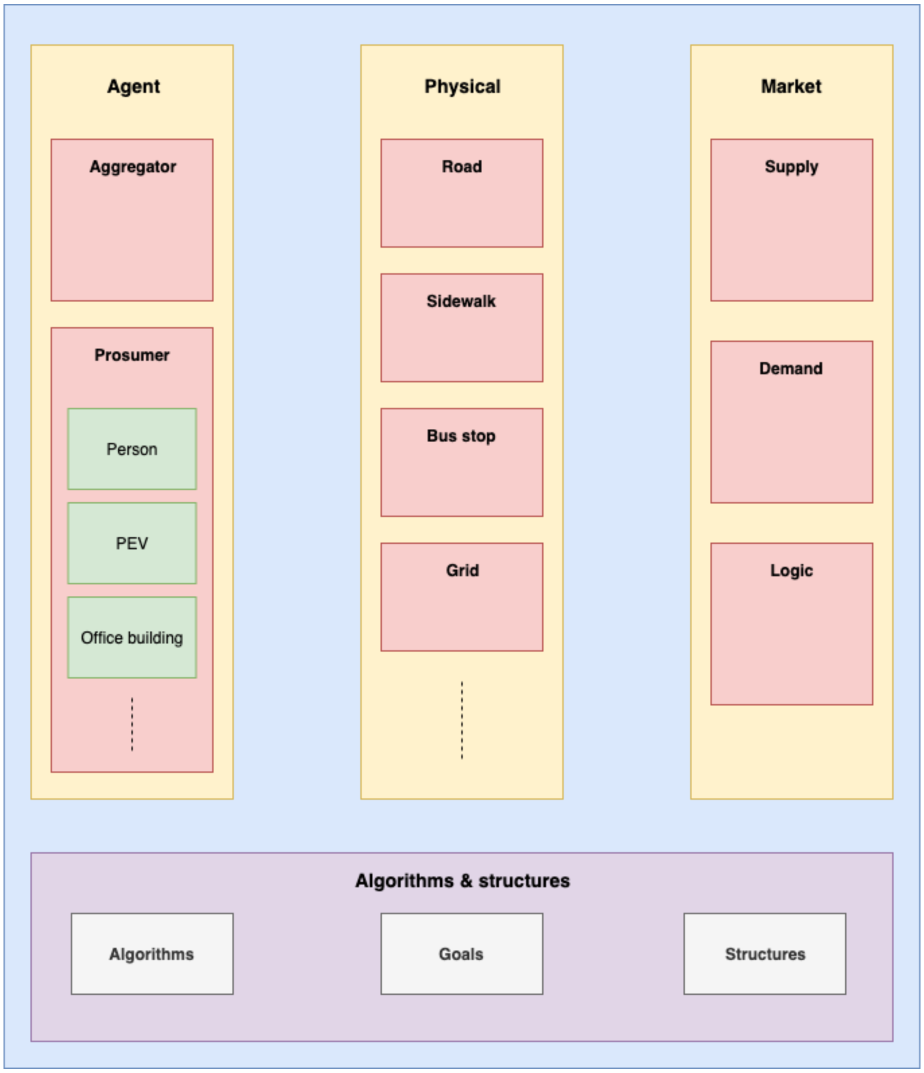


Fig. 4.6. A diagram of the framework proposed, showing the different modules and classes.

4.3.1 Physical module

The physical module is the one that represents all the physical elements that make up the city, which the agents interact with. Like the roads, roundabouts, parking spaces, and others. The motivation behind gathering these similar components into this one module is first and foremost due to their similarities. The entities represented here will have some common variables, like position, size, etc. There are also variables that are unique for the different parts of the entities. For example, a bus-stop class will have a variable for number of occupants, while the roundabout class will need it's own variable for driving direction. The physical module is very similar to the environment package from *CitySim* [4.2.1]. The difference is the electric entities, which in this case are part of the agent module as well.

4.3.2 Agent module

When modelling agents in a complex adaptive system, there is a need to accurately and simplistically capture the key elements of their goals, actions and behaviours, and identify how the three influence each other [14]. The goal isn't to create the most intelligent agents, per se. But rather agents that have abstracted the most vital parts of what they try to emulate, in order to keep the systems intricacy and computational costs as low as possible. All the agents share the common trait of having goals and a set of rules that affects their interaction with the environment [29].

In the model, the agents will either consume power, produce power or do both. They are divided into two main classes; Prosumers and Aggregators. With Prosumers representing all the smaller level electric entities that can physically connect to the electricity grid, and Aggregators being the larger entities, that trades electricity on behalf of groups of their connected Prosumers. This design is heavily influenced by the CASCADE framework and work done by Rylatt et al. [29]. This splitting of the agents will enable the model to capture their most crucial behaviour and actions, while simultaneously placing them in the larger context of the system. The Prosumers and Aggregators have the following relationship:

- The Prosumers can map to an Aggregator - in a many-to-one mapping function, f i.e. f: P $\rightarrow$A.
- Both Prosumers & Aggregators must publish a net supply & demand at given timesteps or on an interrupt basis.
- Each Aggregator's net supply & demand is the sum of the net supply & demand of the Prosumers mapped to it.

Prosumers

The term Prosumer is derived from the term *prosumption*. Meaning "production from consumers" [41]. In this case, it refers to something, or someone, that can consume and/or produce electric energy. In the smart grids of the future, and in parts the ones we have today, it's anticipated that many of the entities connected to the grid will have the capabilities for both consumption and production of electric energy. For example EVs or houses with solar-panel roofs. The production and consumption of electric energy can be done at the same time buy the Prosumers, and is not mutually exclusive.

The Prosumers' role, in relation to the electric grid, is to communicate their supply & demand of electric energy at given intervals or on an interrupt basis. This keeps the agents' behaviour simple and easily understandable. Different Prosumers will have their own specific rules and actions, also regarding their supply & demand of energy. The Prosumers in this framework will be on the lowest level of the agent-hierarchy. The Aggregators, who aggregate the Prosumers will acts as the "higher-level" agents. The framework highlights these common attributes for all Prosumers:

- Has the option to both produce and consume energy (doesn't necessarily have to do both).
- Has its own internal supply/demand profile that it publishes to the Aggregator it's connected to at given timesteps or on an interrupt basis.
- Has the option to connect and disconnect to Aggregators at its own will.
- Can perform simple data processing and evaluation, related to its internal energy profile.

Aggregators

Aggregators can be described as entities that represents a group of any number of Prosumers that are connected to them, by keeping track of their supply & demand of energy [30]. The relationship between the Prosumers and Aggregators gives the opportunity for a more decentralized approach to the trading of electric energy between the agents. The decisions regarding the buying and selling of electric energy is spread out to multiple smaller units, rather than having a centralized entity having all the control. This can also give the opportunity to provide more region specific measures with regards to the flow of electric energy in a specific geographical area that also handles the logic and communication with the overall grid.

The Aggregators can be suited to handle the needs of their connected Prosumers, by not having to communicate back and forth from Prosumer to grid. The framework highlights these common attributes for all Aggregators:

- Handles the communication between Aggregator-Prosumer and Aggregator-grid.
- Monitors the physical grid(s) it's connected to.
- Monitors the supply & demand of its connected Prosumers.

- Performs data processing and evaluation.
- Can act as local decision units.
- Smaller Aggregators can connected to larger ones.

4.3.3 Market module

The market module handles the logic and communication behind the transaction of electric energy between the Prosumers and Aggregators, at different levels across the model. This module connects the Prosumers in the model to their associated Aggregator. The Aggregators will communicate with the main grid, allowing for top-down and bottom-up communication between the grid and the agents in the model. The market module is designed to handle the bids to and from the agents with regards to buying and selling electricity, and will at all times have knowledge of the power grids total load. The price of electricity for the Prosumers will vary as a function of the number of entities connected and the real-time supply & demand.

4.4 casEV

As this thesis centres around the modelling of urban transportation and power grids, the model has to identify their central components, and how they interact with each other. Like how the traffic load effects energy consumption in an area, or how the price of energy effects the behaviour of people with regards to energy consumption. These scenarios are endless in complex systems such as cities, and the level of understanding of these will determine the robustness and accuracy of the model and its agents' behaviour.

The components that comprises the model needs to be essential to the behaviour of the system. There is always a trade-off when deciding what to include and what to ignore. As the complexity and variables increases, so does the computational costs. The agents uses an A* pathfinding algorithm implemented through *CitySim* to reach their goals, which occupies a large part of the computational resources. After having consulted with Keith Downing [3.1], a desired approach would include keeping the behaviour of each part as simple as possible. The more characteristics a component has, the more things will need to be tuned in the model. Which often results in bloated systems that are expensive to run, with regards to computational power. Thus, good, solid abstractions of the parts being modeled are important for the accuracy and applicability of the model.

The proposed framework was implemented into the existing model *CitySim*, resulting in a model titled casEV. This was done by deconstructing the packages and classes in *CitySim*, before implementing the framework as shown in section 4.3. In the model, V2G chargers are added across the city as electric entities, to act as access points for the Prosumers, which are the agents operating in the space. The V2G chargers are in turn connected to larger electric units, which will act as the Aggregators in casEV. These Aggregators communicate with the Market module, which handles the real-time supply & demand of the overall electric grid. As shown in figure 4.5. The electric grid records the constant load across the simulation, and can be viewed in relation to how the agents behave and operate in the environment. Input parameters determines how many of the agents' vehicles are EVs before each simulation run. The agents' behaviour and goal structure regarding movement and transportation is kept the same as in *CitySim*. The source code and detailed user guide for the casEV model can be found on the author's GitHub page [42].

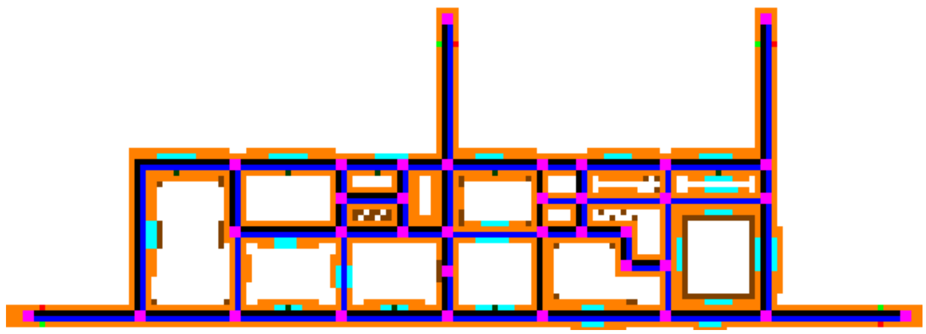
4.4.1 Environment design

The environment being modelled is made up of roads, bus-stops, parking spaces, V2G chargers, among others. Upon initialization, a `.png` image is iterated through, pixel by pixel, in order to add each element to the context of the model. The image is made by hand, drawing in each pixel to represent the objects. Figure 4.7 gives a more detailed view of the setting and the different elements. This is done in the same way as in CitySim [4.2]. The electric entities in the model are added as parts of the city's power grid, and will act as Aggregators or Prosumers, based on their classification.

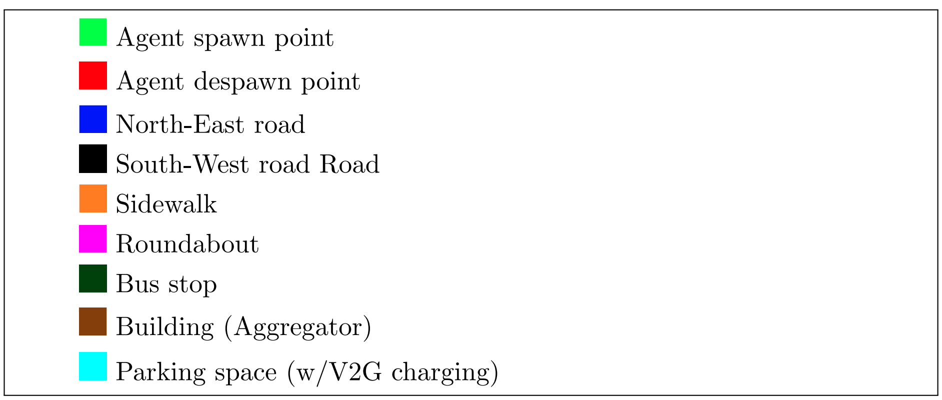
As shown in figure 4.7, the agents in the model are spawned and despawned into the environment in one of four access points. The agents move and operate in the space, and are moving to reach their goal. The parameters entered before each simulation determines the agent count and spawn frequency.

4.4.2 User interface

casEV runs simulations using the GUI provided by Repast Simphony [4.1]. This allows for a visual display of the agents' behaviour in the environment, as well as providing real time graphs of the data captured during the simulation runs. A typical simulation run is shown in figure 4.8. Parameters can be entered before each run, as shown on the left side of the top image in the figure. Other relevant information, like the total load registered and the time, is shown graphically during the runs as well. The GUI also allows for exporting simulation results as graphs after each run.

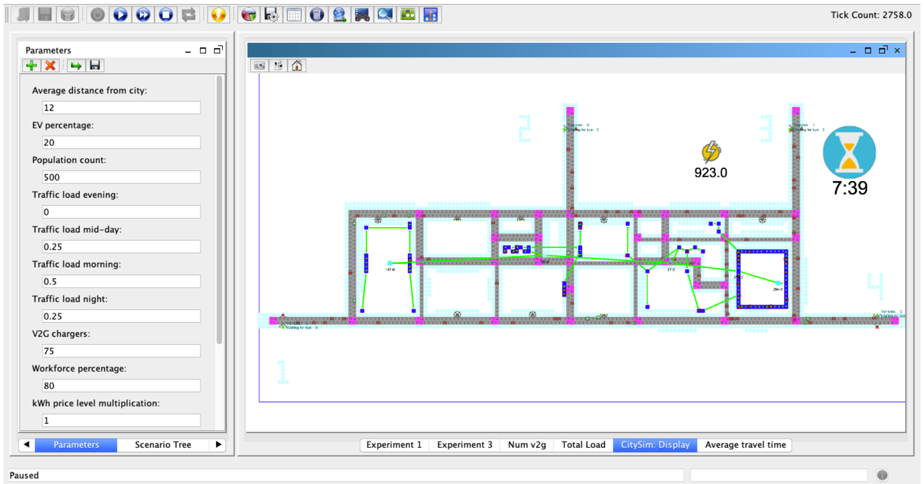


(a) An example of the city-environment being modelled, where each pixel depicts an entity.

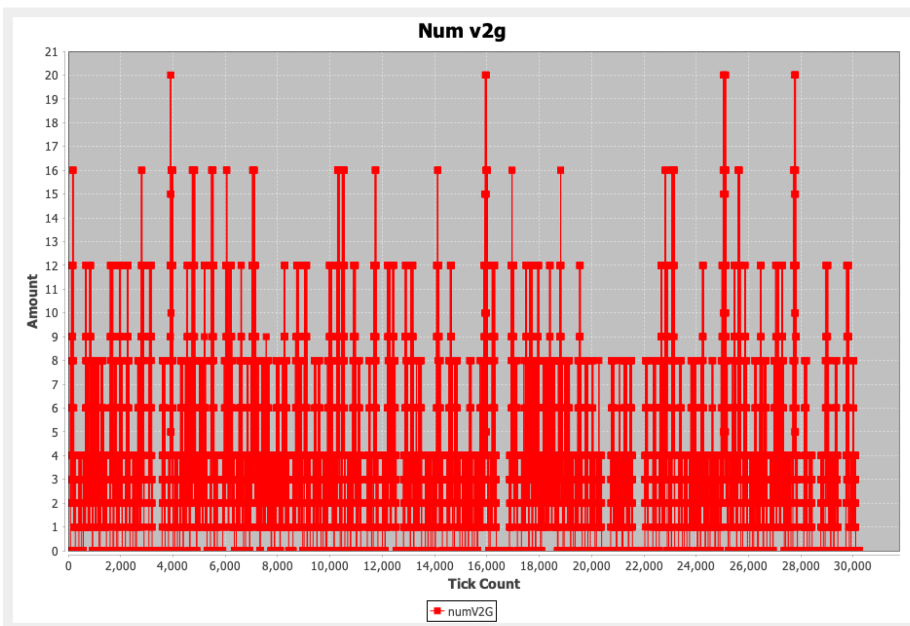


(b) An overview of the different pixels that make up the city-environment being model.

Fig. 4.7. Environment design



(a) A GUI view of the agents in the environment during a simulation run. The red agents are the personal vehicles, while the green ones are buses.



(b) A GUI view of a graph during a simulation run.

Fig. 4.8. View of the GUI of the model. Showing how the agents move around the environment and how information is displayed graphically.

4.5 Chapter summary

This chapter has presented the design and implementation of the framework for the model casEV. The different modules of the framework was explained. A brief introduction to the existing model *CitySim* and the modelling library *Repast Simphony* has been given to provide context.

5 Experiments and results

This chapter presents three separate experiments that have been carried out using the model casEV that was presented in section 4. The three experiments are explained in their own sections, where the results of the different simulations are discussed separately as well. An overview of the parameters that are given during initialisation of the model is also provided in this chapter. The author aims to see some emergent patterns that comes from the behaviour of the agents in the model and how they interacted with their surroundings. The experiments are done in order to demonstrate and assess the value of such a model, when considering how the flow of people and energy are related. As well as looking at how it could be used as a tool to aid in the implementation of smart grids and V2G charging in an urban setting.

Multiple simulations were ran in each experiment, each based on different initialization parameters. Experiment 1 [5.1] studies how modifying the geographical placement of the V2G chargers would impact the flow of energy and movement of traffic within a city. Experiment 2 [5.2] attempts to analyze how different price levels for electricity will impact the agents' decision to charge back to the grid, based on varying prices offered for their EVs redundant power. Experiment 3 [5.3] assessed how different battery technologies in the EVs will influence their willingness and ability to charge back to the grid. Each of the three experiments are viewed in relation to the overall electric load recorded on the power grid.

The simulation time is measured in "ticks". The tick-count is incremented after each agent has completed their action for that particular step. One day is measured as 4 320 ticks. As a general rule, most simulations were ran over a period of seven days in the model, which measures to 30 240 ticks. This was chosen due to the simplicity with regards to weeks, while having a long enough period of days to be able to see emergent patterns and trends in the results. These simulations are quite computationally heavy, so there is a cut-off when it comes to how long the different simulations should run. After some initial testing the decision landed on seven days. There is nothing inhibiting running the model for as many days as wanted, as long as the computational power is strong enough. The experiments were designed in order to provide answers and solutions to the problem statement and research questions detailed in section 1.2.2.

5.0.1 Model initialization & variables

The simulations ran by casEV is based on a number of different parameters, and the modification of these will impact the systems behaviour. The model consists of different modules, which all requires their own variables and structures. Some of these variables are set when initializing the simulations and remain static throughout. Some, however, are dynamic and are changed based on the agents' interaction with the environment. Table 5.1 gives an explanation of some of the parameters set before each simulation.

Type	**Range**	**Explanation**
Population count	0-1000	Number of agents in the simulation
Traffic load	0-1	Sets the frequency of which the agents enter the city.
V2G chargers	0-100	Number of v2g chargers in the environment.
EV percentage	0-100	How many of the vehicles in the simulation are EVs?
Workforce percentage	0-100	Determines how many of the agents are workers. The remaining ones will be shoppers.
kWh price level	0-100	Price for electricity. Set on initialization, while also being affected by system behaviour.
Average distance from city	0-100	Average distance the agents live from the city.

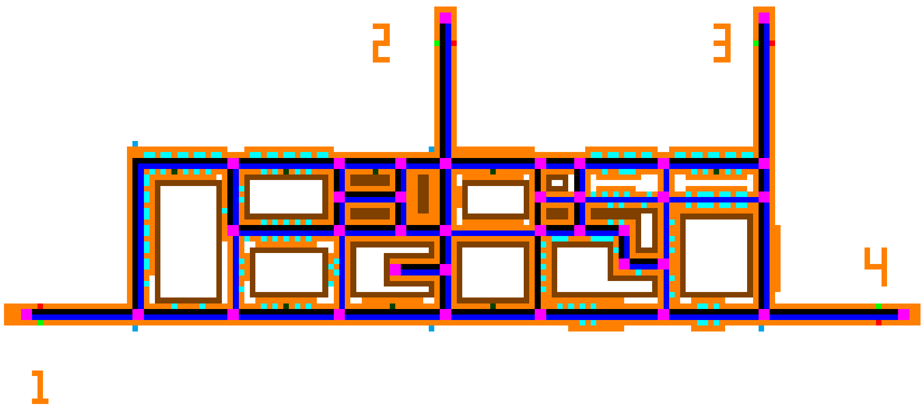
Table 5.1. The variables used by the model as parameters during the initialization before each simulation.

5.1 Experiment 1

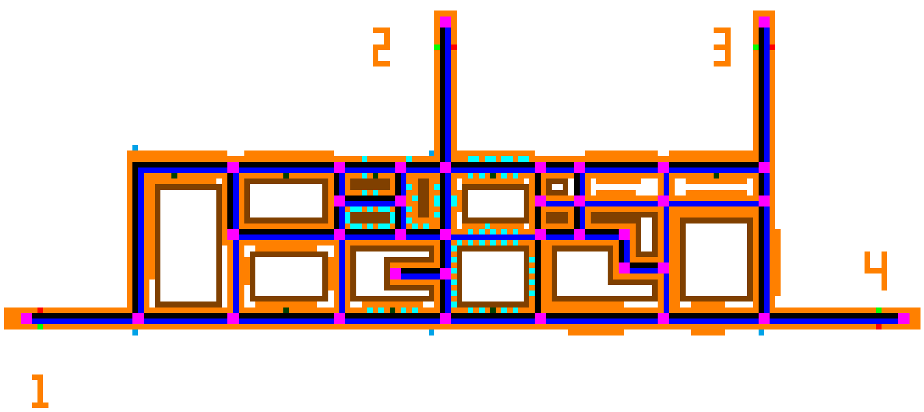
The first experiment aims to see how the different placement of V2G chargers around the city can have an effect on the flow of energy, and how the traffic flows as a result of this as well. Three placement strategies will be tested. These are:

- The chargers are evenly spread throughout the city
- The chargers are evenly spread throughout the city, *except* for the centre. No chargers are placed in the centre.
- The chargers are all evenly spread out *within* the city centre. No chargers are placed outside the centre.

While running this experiment, the model has two separate smaller sub-grids, as opposed to only one in the other two experiments (2 & 3). One for each of the geographical areas of the city; the centre and everywhere else. This is done in order to view the results of the two grid nodes separate of each other, so that a comparison could be done between different scenarios. This is in contrast to the two other experiments, where the load was seen in the perspective of the whole city. The simulation also provides the average travel time for the agents, from entering the city to reaching their destination. This is to see how and if the placement of chargers will affect the traffic congestion. Figure 5.1 shows how the parking spaces were spread out in the model, indicated by the light blue pixels. The aim of the experiment coincides with RQ1[1.2.2] and RQ4[1.2.2] especially. Due to it potentially showing how the flow of energy follows the movement and transportation of people. Each of the simulations had a agent population of 500 with an EV ratio of 0.2 to every 0.8 other vehicles.



(a) Environment where the V2G chargers placed outside the centre.



(b) Environment where the V2G chargers placed within the centre.

Fig. 5.1. The environment from the simulations ran in the first experiment. Showing the different geographical placement of the V2G chargers.

5.1.1 Results

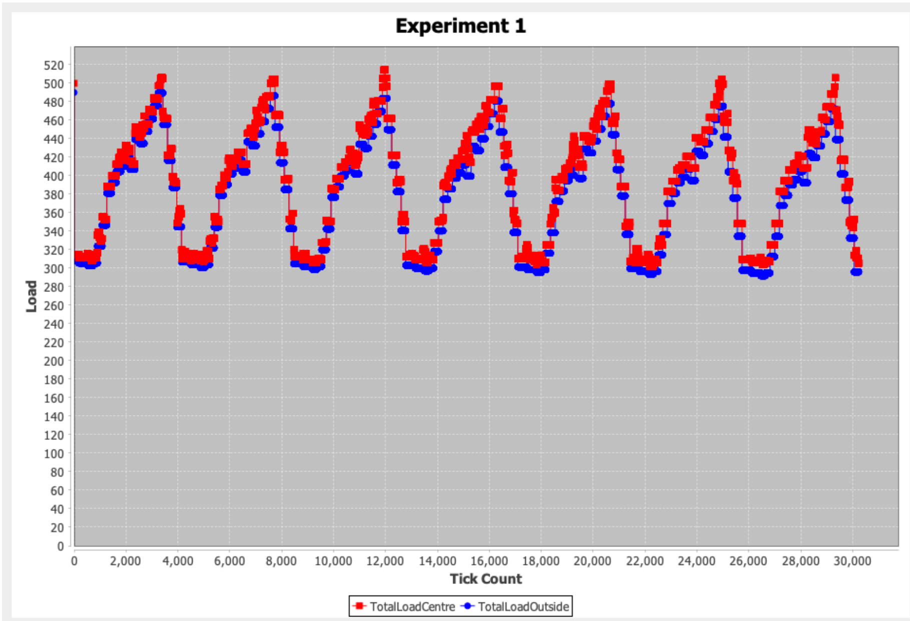
Experiment 1 results

Sim.	**RG-Centre peak load (kWh)**	**RG-Centre bottom load (kWh)**	**RG-Outside peak load (kWh)**	**RG-Outside bottom load (kWh)**	**Avg. agent travel time**
1	514	302	490	291	57
2	501	297	503	278	60
3	502	293	512	298	59

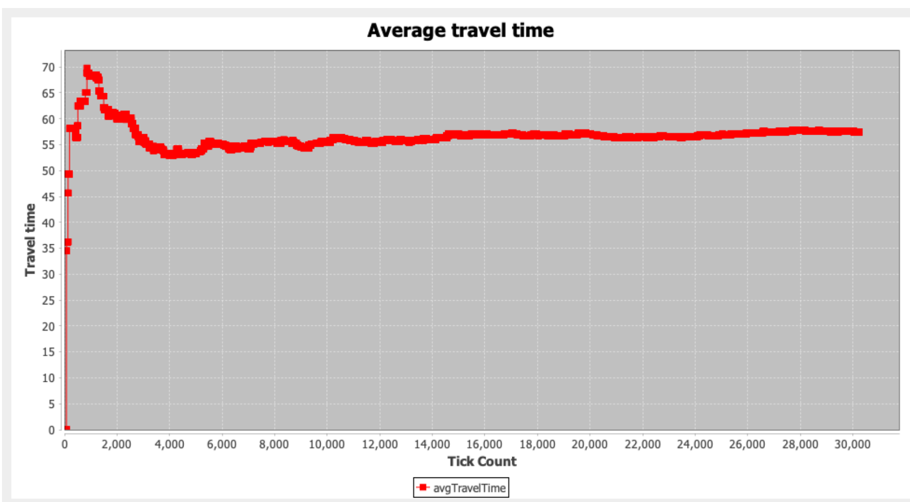
Table 5.2. The results from the three simulations ran during the first experiment. The table shows the different loads recorded at each regional grid node, as well as average travel time for the agents.

The results from each of the three simulations can be seen in table 5.2 and graphically in figure 5.2, 5.3 and 5.4. The top sub-figure of each of the figures shows the load distribution for *both* of the sub-grids; Centre (red) & Outside (blue). The bottom sub-figure gives the average travel time for the agents. From the first simulation, where both "areas" of the city had an even distribution of V2G chargers, displayed a fairly even distribution of load between the two areas. The graph [figure 5.2] shows that the two sub-grids share a similar profile over the period of the simulation.

The second simulation, where all the V2G chargers were placed everywhere *except* the centre, does indicate that the overall load recorded in the centre tends to be slightly higher than what is seen in the other parts of the city. The difference in recorded peaks in the two sub-grids increases as the simulation goes on. Where the centre sub-grid stays fairly even day-to day while the other sub-grid decreases somewhat, as seen in figure 5.3. However, the recorded peak in both of the areas are very similar (501 kWh & 503 kWh). The third simulation, where the V2G chargers are all placed within the centre, shows some of the same behaviour as the second simulation. The area where the chargers are placed shows *some*, reduction in the overall grid load compared to areas where there are no V2G chargers. Figure 5.4 shows that the variations in the recorded load is smaller than what was shown in the second simulation.

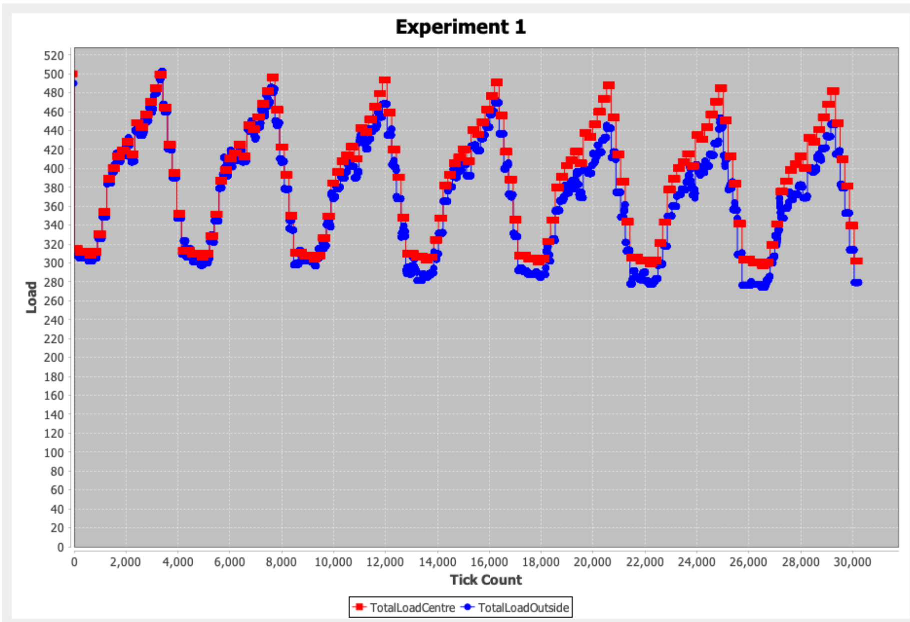


(a) Total load recorded by each of the two grid nodes during the first simulation from experiment 1.

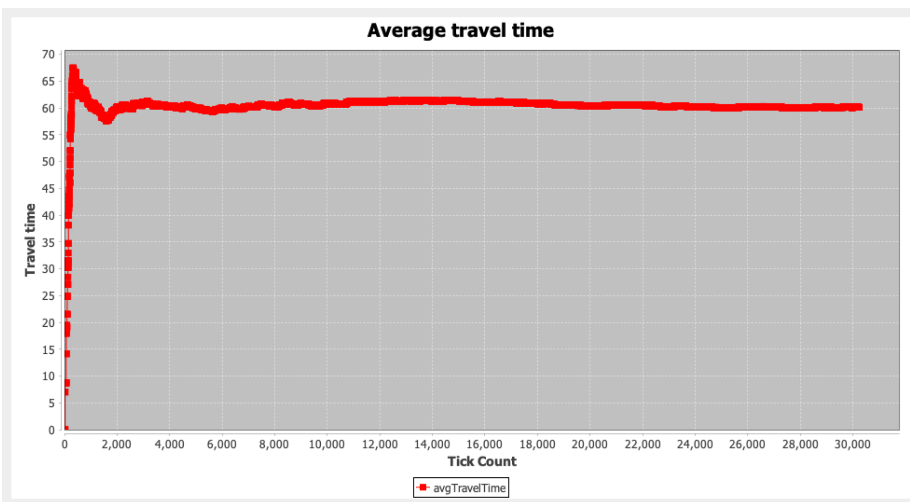


(b) Average travel time for the agents in the first simulation from experiment 1.

Fig. 5.2. The two graphs depicts the results from the first simulation from experiment 1.

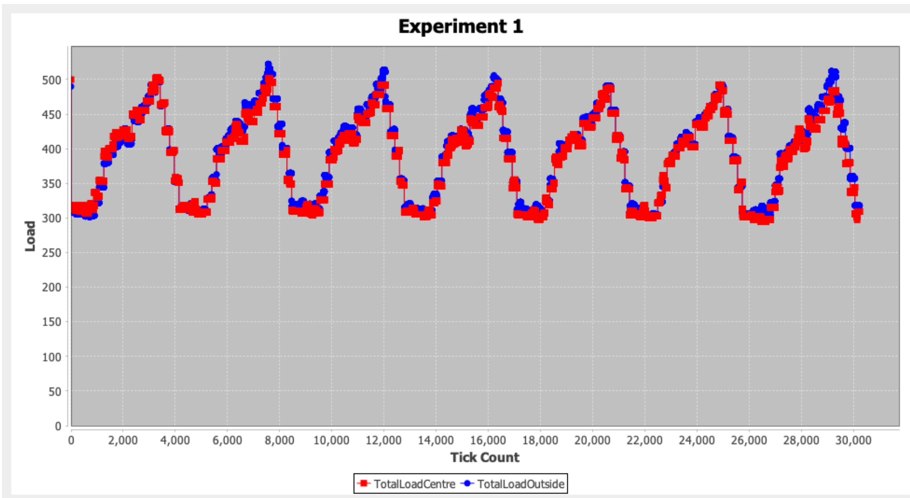


(a) Total load recorded by each of the two grid nodes during the second simulation from experiment 1.

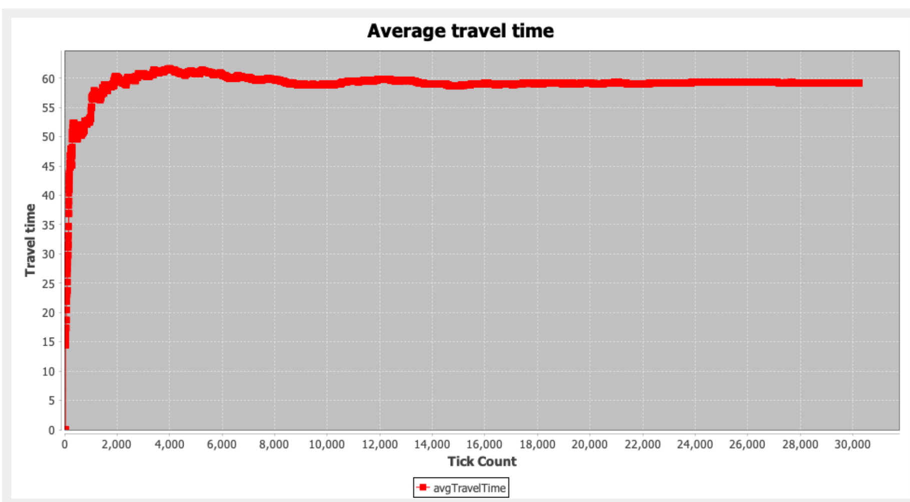


(b) Average travel time for the agents in the second simulation from experiment 1.

Fig. 5.3. The two graphs depicts the results from the second simulation from experiment 1.



(a) Total load recorded by each of the two grid nodes during the third simulation from experiment 1.



(b) Average travel time for the agents in the third simulation from experiment 1.

Fig. 5.4. The two graphs depicts the results from the third simulation from experiment 1.

5.2 Experiment 2

The aim of the second experiment is to see how different electricity price levels, offered from the Aggregators to the Prosumers, could affect the agents' (Prosumers) willingness to engage in V2G charging, and how this will have a mutual effect on the cities electricity load distribution as a whole. This experiment could be viewed in relation to RQ1 [1.2.2], RQ3 [1.2.2] and RQ4 [1.2.2]. The results could be used to analyse how agents move and operate based on the supply & demand of energy. The potential benefits regarding the balancing of the load distribution should also emerge, as a result of how much power is charged back to or from the grid based on the different price levels.

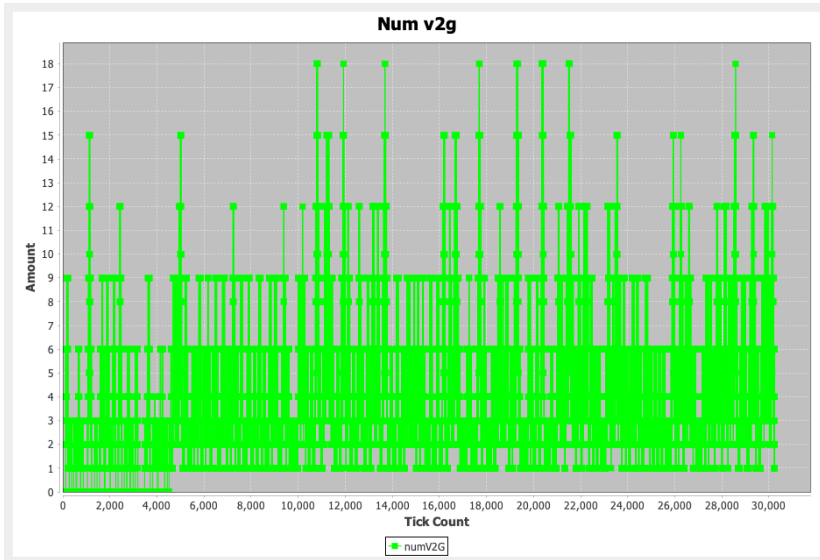
This experiment looked at different price levels for the kWh, seeing the willingness of the agents with EVs to sell it back at that particular price and its mutual effect on the load distribution as a whole. The price level of kWh offered from the market module was multiplied with incremented values, and taken into account by the Prosumers with EVs when making the decision on whether to charge back to the grid, charge from the grid, or neither. The range of multiplication of the kWh went from 1.0-2.0, while also testing edge cases on both sides of the spectrum. Running test with intervals of .1 gave the results shown in table 5.3. The multiplied price is given as a variable to the function that determines the Prosumer's decision on whether or not to charge back to the grid. Each of the simulations had a agent population of 500 with an EV ratio of 0.2 to every 0.8 other vehicles.

5.2.1 Results

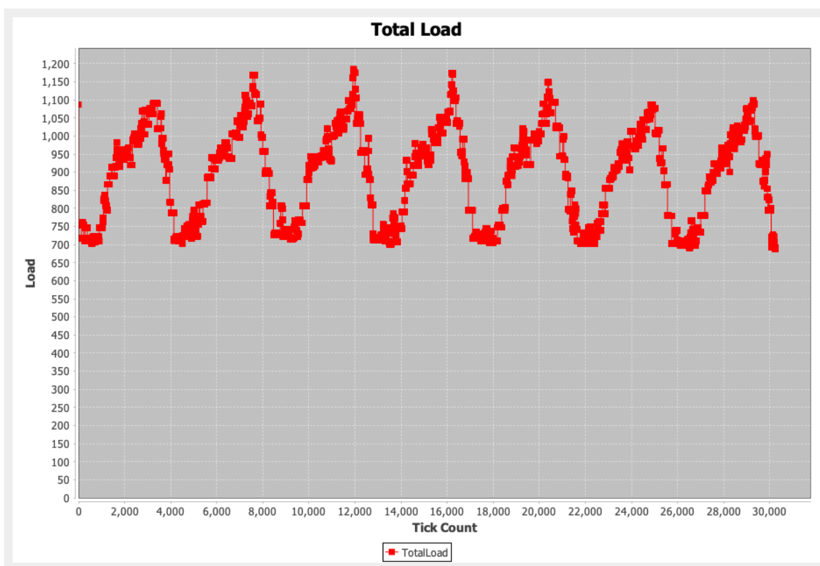
Table 5.3 gives the results after running the simulation for the ten different scenarios. Figures 5.5, 5.6 and 5.7 gives a graphical representation of three of the simulations. These are the ones with a price multiplication of 1.0, 1.5 and 2.0, respectively. The top sub-figure of each figure shows the number of EVs connected with the current price multiplication. The bottom sub-figure is its effect on the grid load over the same period of time. A slight trend could be seen with regards to the amount of connected EVs and their effect on the overall load distribution. A higher price level for kWh in the V2G chargers (both selling and buying) does seem to show some correlation to a higher amount of connected vehicles, which in turn provides *some* reduction in the peak load.

Price multiplication	**Peak num. of V2G**	**Peak load (kWh)**	**Bottom load (kWh)**
1.0	18	1184	688
1.1	17	1178	678
1.2	21	1189	702
1.3	20	1080	699
1.4	24	1052	704
1.5	25	1054	567
1.6	25	1022	689
1.7	28	1068	678
1.8	29	988	603
1.9	30	1025	589
2.0	30	978	607

Table 5.3. The results from the ten simulations ran during the second experiment. The table shows the peak number of EVs involved in V2G charging, as well as the peak and bottom loads recorded by the regional grid node from each simulation.

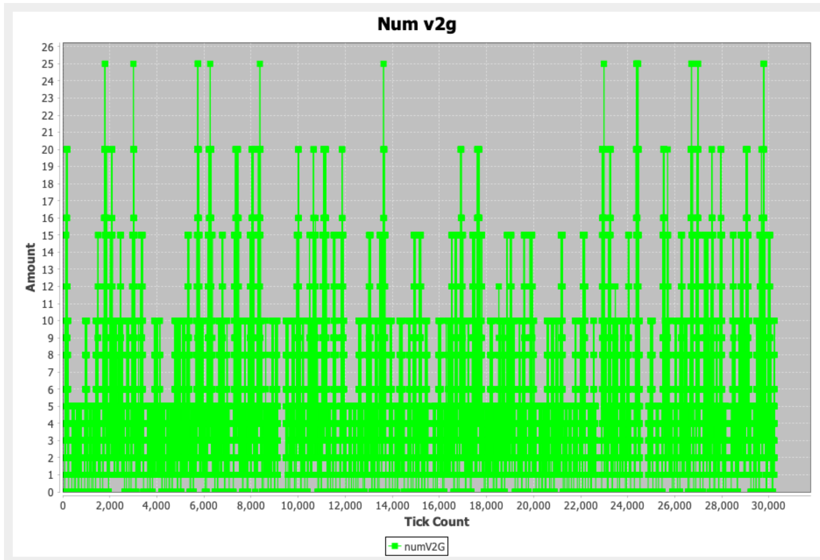


(a) Number of EVs involved in V2G charging throughout the first simulation of experiment 2.

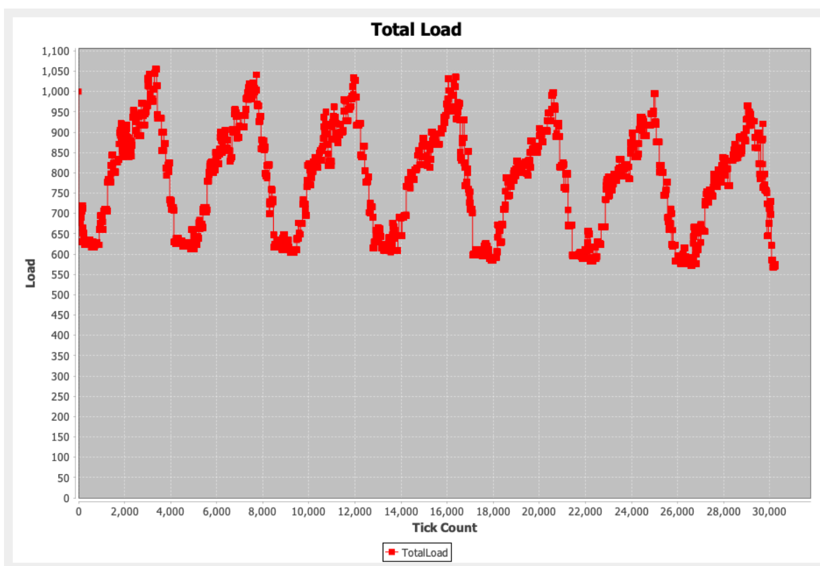


(b) Total load recorded by the regional grid node during the fist simulation of experiment 2.

Fig. 5.5. The two graphs depicts the results from the first simulation from experiment 2, where the price-level is multiplied by 1.0.

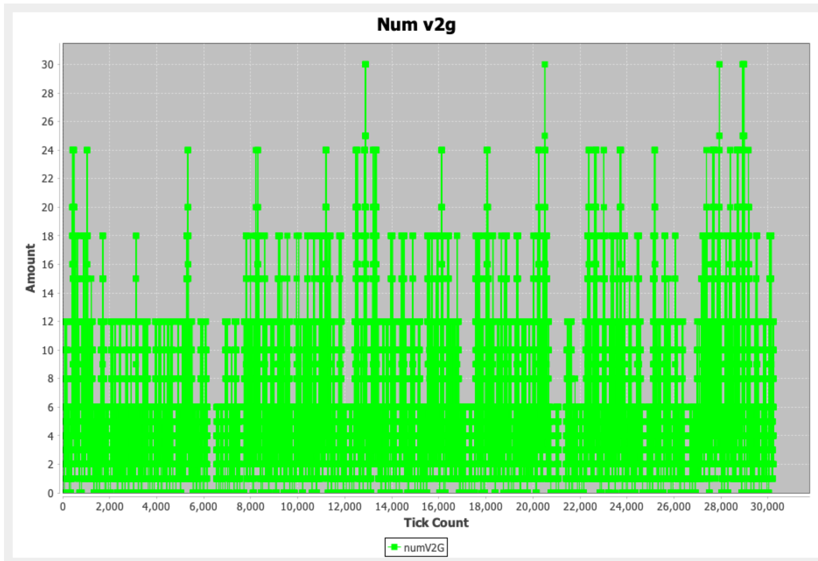


(a) Number of EVs involved in V2G charging throughout the sixth simulation of experiment 2.

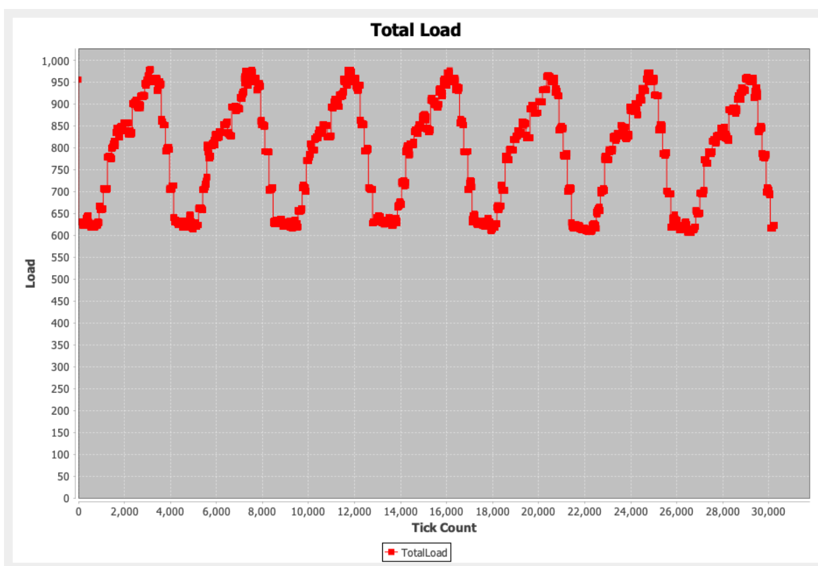


(b) Total load recorded by the regional grid node during the sixth simulation of experiment 2.

Fig. 5.6. The two graphs depicts the results from the sixth simulation from experiment 2, where the price-level is multiplied by 1.5.



(a) Number of EVs involved in V2G charging throughout the tenth simulation of experiment 2.



(b) Total load recorded by the regional grid node during the tenth simulation of experiment 2.

Fig. 5.7. The two graphs depicts the results from the tenth simulation from experiment 2, where the price-level is multiplied by 2.0.

5.3 Experiment 3

The third experiment aims to compare how the initial charge and battery capacity of the EVs are related to the Prosumers' decision to engage in V2G charging. The EVs today vary greatly in battery capacity, ranging anywhere from 10 kWh to over 100 kWh [43]. The power of the EVs batteries, both in terms of remaining charge and overall capacity, will impact their capabilities with regards to charging back to the grid. Simulations like this can aid in providing some information related to RQ3 [1.2.2] and RQ4 [1.2.2], by giving insight into how the variation in EV charge and capacity can influence the agents' decision and how that in turn affects the rest of the systems behaviour.

The experiment was done by comparing the initial charge of the EVs as they connect to the charger with their willingness to sell power back to the aggregator. The EVs were divided into different categories, to represent the variations in different battery technologies that exists, as shown in table 5.4. This allows for the testing of how different EV battery capacity-levels behaves in the system, while also providing support for potential future increase in capacity. These variables are also fed to the determination-function to be used by the agents when deciding whether or not to charge back. The hope is that some emergent patterns will emerge, that shows how the different charge levels and battery technologies of the EVs will respond to the demand requests from the Aggregators. Upon initialization, the EVs in the model are given one of four different battery technologies. These battery technologies determines their ability to hold charge, and should in turn affect the agents' decision making when interacting with the V2G chargers. Table 5.5 details the distribution of EVs used in the different simulations. Each of the simulations had a agent population of 500 with an EV ratio of 0.2 to every 0.8 other vehicles.

Type	**Capacity (kWh)**
Low	10-25
Medium-low	25-50
Medium-high	50-75
High	75-100

Table 5.4. The different battery types used in the third experiment

Sim.	Low (%)	Medium-low (%)	Medium-high (%)	High (%)	Population
1	40	0	30	30	500
2	25	25	25	25	500
3	0	0	100	0	500
1	2012	3	4	5	500

Table 5.5. Overview of the parameters used during the third experiment. Each simulation has a different distribution of different types of EVs.

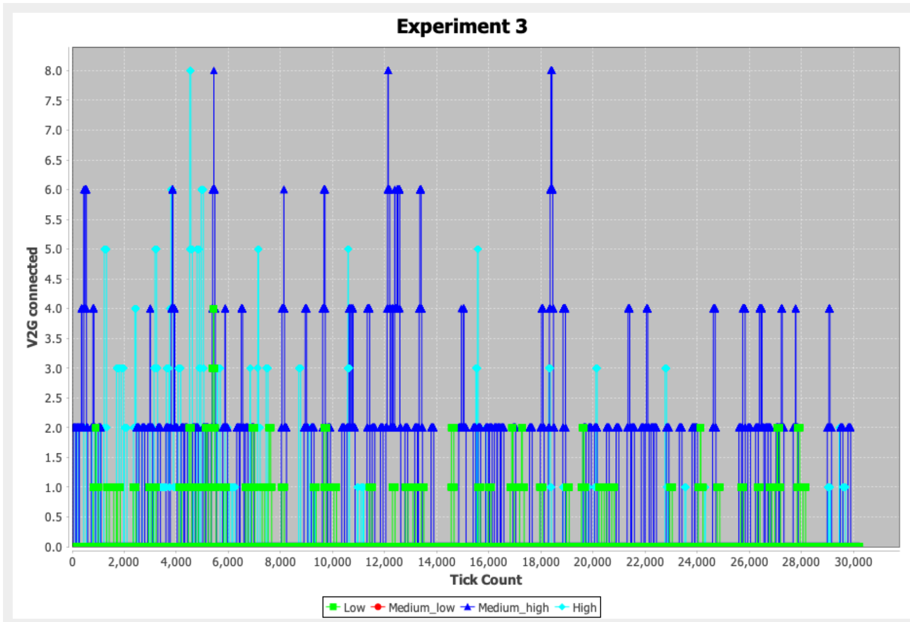
5.3.1 Results

Table 5.6 shows the results from the three simulation runs. The number of each category of EV connected to V2G chargers are given in the top sub-figure of figure 5.8, 5.9 and 5.10. The grids load distribution is given in the bottom sub-figures. The first run was initialised with 40% of EVs belonging to the first capacity-group, while category 3 & 4 made up 30% each. The second run distributed all four capacity-groups evenly between the EVs in the model, with 25% each. And the third run had *all* the EVs belonging to the third group.

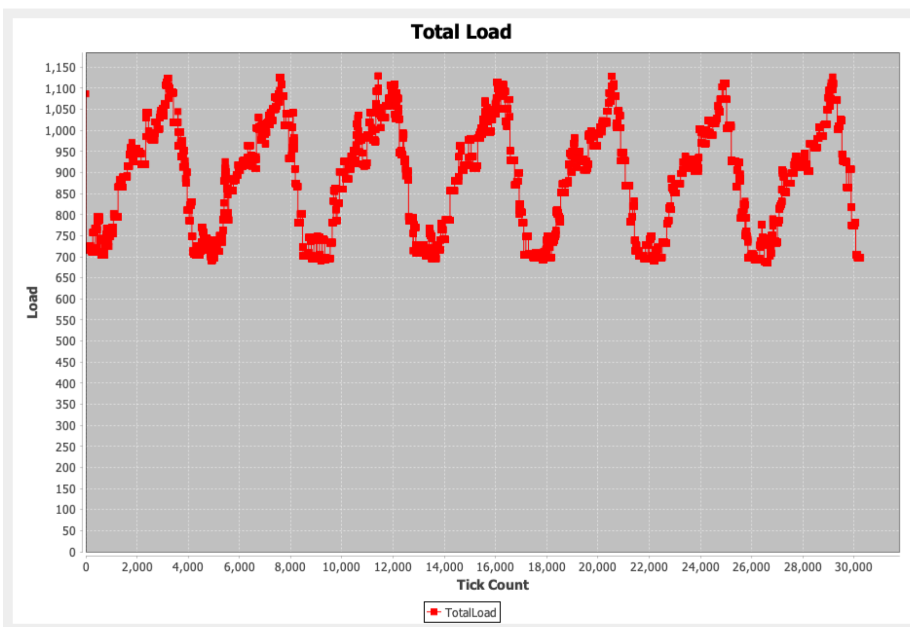
Simulation 1 and 2 gives an indication that the agents tend to engage in V2G charging at a higher rate when their EVs had a high level of stored power, relatively speaking, compared to agents with EVs with low level of stored power. Simulation 3 demonstrated that the system behaves as normal when dividing EVs into different categories.

Sim.	Low - peak connected	Medium-low - peak connected	Medium-high - peak connected	High - peak connected	Peak load (kWh)
1	4	0	8	11	1189
2	2	5	7	12	1254
3	0	0	27	0	1235

Table 5.6. The results from the three simulations ran during the third experiment. The table shows the peak and bottom number of EVs involved in V2G charging during the simulation, as well as the peak and bottom loads recorded by the regional grid node from each simulation.

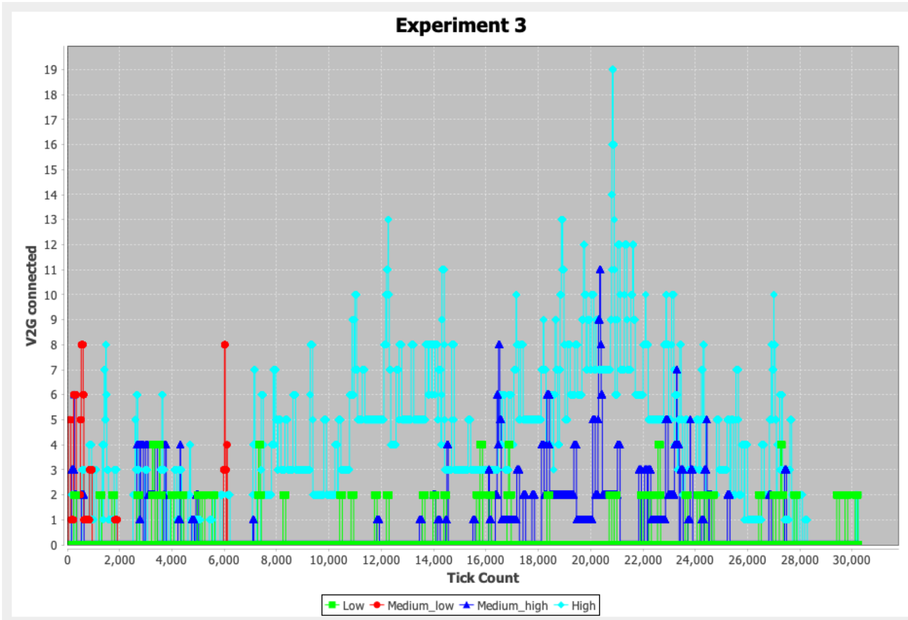


(a) Total number of the different types of EVs involved in V2G charging during the first simulation of experiment 3.

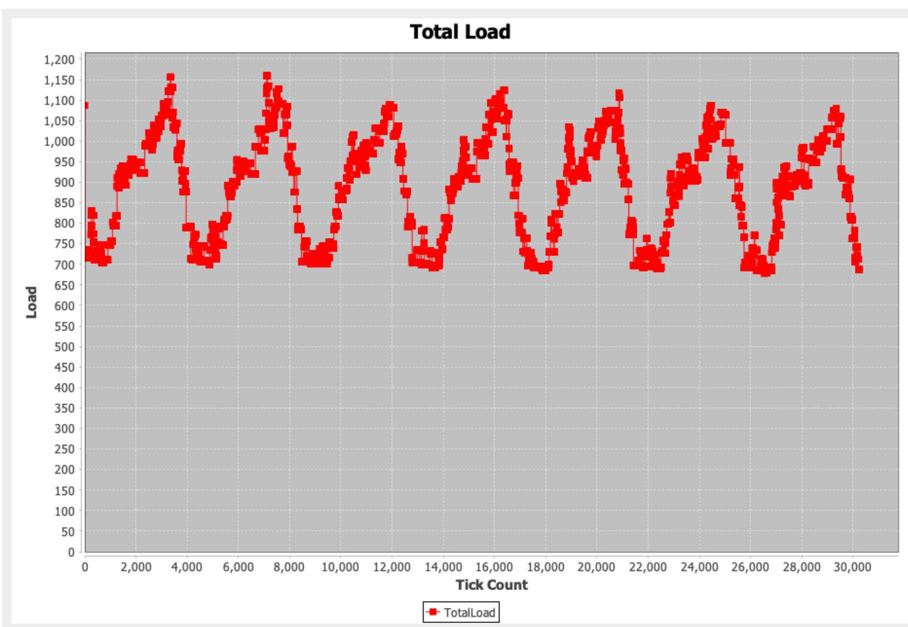


(b) Total load recorded by the grid node during the first simulation of experiment 3.

Fig. 5.8. The two graphs depicts the results from the first simulation from experiment 3.

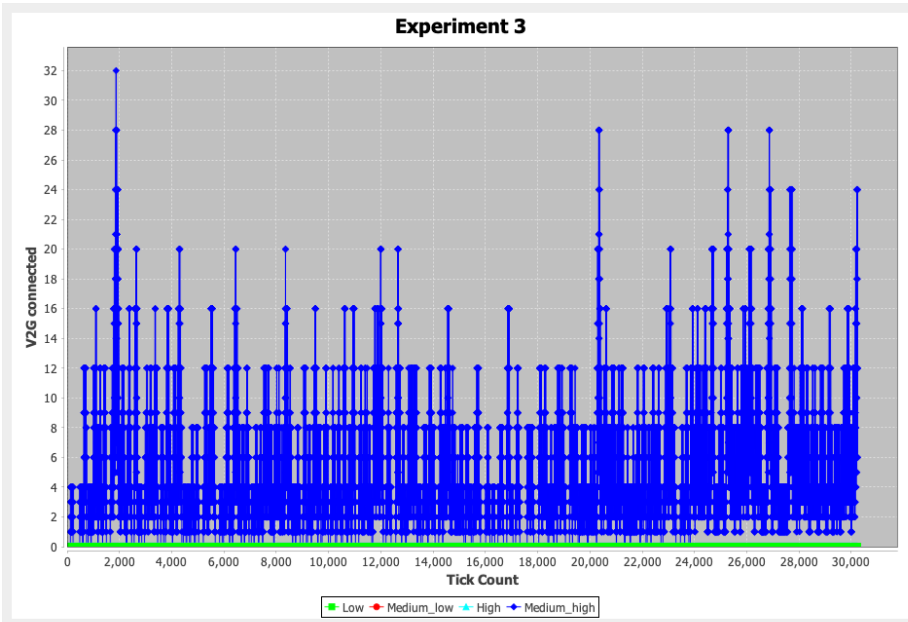


(a) Total number of the different types of EVs involved in V2G charging during the second simulation of experiment 3.

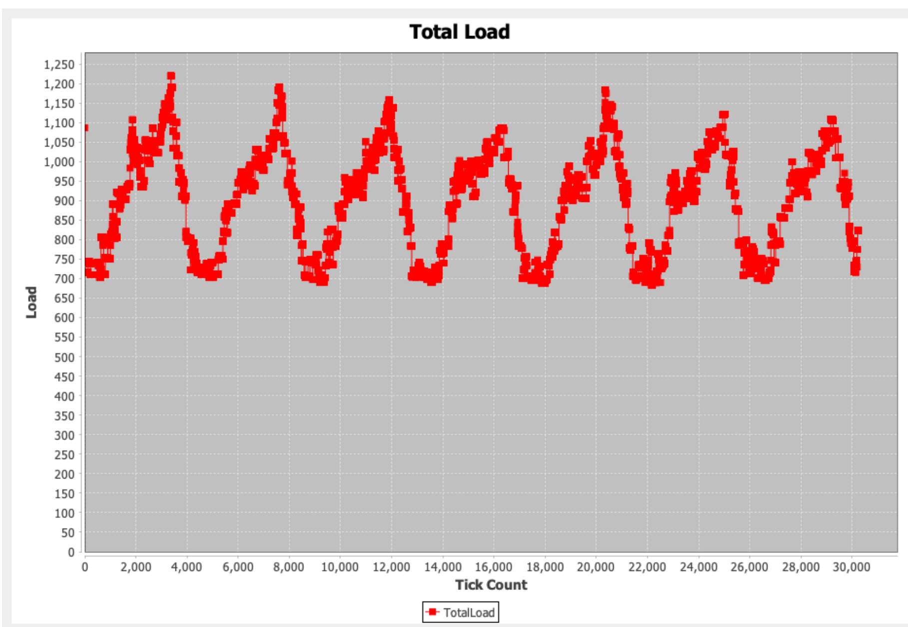


(b) Total load recorded by the grid node during the second simulation of experiment 3.

Fig. 5.9. The two graphs depicts the results from the second simulation from experiment 3.



(a) Total number of the different types of EVs involved in V2G charging during the third simulation of experiment 3.



(b) Total load recorded by the grid node during the third simulation of experiment 3.

Fig. 5.10. The two graphs depicts the results from the third simulation from experiment 3.

6 Discussion

The experiments conducted in this thesis attempted to capture what could be seen as real-life scenarios. Albeit at a fairly simplified level, with few variables and unknowns. As well as with a high level of abstraction of the modelled parts. The goal was not to create the most precise model of what a city was and how its power flows in relation to the people and traffic, but rather to provide one that explored the possibility of modelling these aspects together as a complex adaptive system. So the results of the simulations is more interesting to look at with regards to that, rather than looking at how accurately it was able to simulate and depict the different parts of the urban transport & energy sector.

Experiment 1 [5.1] aimed to see how the the agents would behave based on the geographical placement of the V2G chargers, and how this had a mutual effect on the overall load recorded on the power grid. The average travel time of the agents was also recorded, to see if the placement of the chargers would have an effect on this. The three simulations that were ran did manage to show that the grid's recorded peak load was somewhat lower in areas where V2G charging was available. However, the different placement strategies for the V2G chargers did not seem to have any impact on the average travel time of the agents in the model. The experiment demonstrated how complex systems modelling could be used as a tool to see the flow and demand of energy in relation to how the traffic moves, while also showing a slight pattern of lower recorded power grid peaks by using V2G charging in a specific area. Which can provide some answers to the research questions 1 & 4 given in section 1.2.2.

Experiment 2 [5.2] showed that the agents do behave somewhat differently based on the manipulation of market variables. The pattern that emerged as a result of the agents' behaviour showed how a higher price level had an observable impact on the decisions of whether or not to charge back. This demonstrates how the price of electricity can have an effect on the agents' behaviour, with regards to V2G charging and the decision to sell or buy power back to the grid. The experiment in itself shows how a model like casEV can be utilized to run simulations on smart grid scenarios with easily modifiable parameters. It also served as a means to validate the behaviour of the agents in the system, by observing their actions based on incrementing market values.

Experiment 3 [5.3] had more focus on the actual charging levels of the EVs, and how that in turn can have effects on the flow of energy within the city. The results were fairly similar to what was expected, that the EVs with higher charge levels and battery technologies have a higher chance of engaging in V2G charging. But the uncertainty lies with the modelling and understanding of the agents' decisions regarding charging levels and willingness to charge back, which is inherently hard to predict. Both because of the actual technology difference in the EVs on the road and the fact that people are different and make different decisions. Despite that, a model like casEV could still serve as a tool to design simple simulations to mimic how different Prosumers could potentially act in different settings and scenarios.

The impact the of V2G charging and other smart grid related technologies will have on the transportation energy sector and society as a whole is apparent to see regarding some aspects, and difficult for others. For example, it is quite likely that V2G charging could be beneficial for power distributors, but the successful implementation is dependent on a number of factors. Like political will, technological innovation, urban infrastructure, among many others. This is why the utility value of the technology is hard to predict, and also why complex modelling is suited to make a simplified abstraction and holistic view of the cross connection between urban transportation and energy consumption.

Through the use of existing tools and the author's proposed framework [13], a model for simulating some aspects of smart power grids in relation to urban transportation, titled casEV, has been proposed and used to run simulations on different scenarios. The design and implementation discussed in section 4 gives some insight into how one can potentially model aspects of smart power grids with V2G charging as a complex system. The modular design of the framework makes the model modifiable and expandable, to a certain degree. This was considered in part due to good-practice, but also due to the simplicity of swapping out the different modules of the framework as one sees fit. The parameters and variables that go in to the model are easily changed through the GUI or code. Some benefits of this sort of modelling was displayed through the simulations and results from section 5, by running simulations on simplified, real-world, scenarios and demonstrating how the results from these shows some emerging patterns in the system's behaviour over time. Like the slight reduction in recorded peak grid load when V2G charging is offered, or how the geographic placement of chargers can have an impact on how the energy and traffic flows within the city.

7 Summary

7.1 Limitations

In every model created, there will be some limitations. A perfect representation of the real world is impossible to achieve. In the case of this thesis, casEV does have its limitations. Firstly, the main parts of the model, like agent-behaviour and smart grid functionality, is quite simplified and of a high abstraction level. This does provide a simple and modifiable model for easy testing of different scenarios, but does at the same time leave out important aspects of the inner workings of the elements. Keeping the agents' behaviour as simple as possible was done, in part, after consolidating with Keith L. Downing of NTNU [3.1], as well as to try to keep the computational cost of the system low. Some assumptions has to be made when designing non-deterministic systems like the model created in this thesis, especially regarding the agents' behaviour and parameters used during the experiments. This can in some ways be viewed as a limitation or weakness, due to the adversity often associated with testing and validating such systems [44].

The high computational costs of often associated with ABMs and complex systems models can be said to be a limitation in itself. The simulations that were ran in section 5 could take anywhere from 1-4 hours to simulate a period of seven days, all depending on the model parameters entered and a number of other factors. This indicates that the model does, in some ways, have a *high barrier to entry*, which in turn has effects on the ease of use, applicability and validation of the model. To validate such a model requires a lot of iterative trial and error testing, which can be strenuous and time consuming when each simulation takes a long time to complete.

7.2 Future work

The author has identified some future work that can be done on the model, which is listed below.

Entry point variation

The model spawns and despawns the agents from one of four entry points. Fosvold's paper on *CitySim* explored how the manipulation of the entry point distribution had an effect on the travel time for the agents in the system. By doing similar tests with casEV, there could arise an opportunity to view the cross-connection between entry point distribution and power grid load balancing. *CitySim* has parameters for a number of transport related aspects, were the entry point distribution is one of them. And thus, there exists an opportunity to do more cross examination between the manipulation of these and the smart grid features introduces in this thesis.

Buses with V2G charging

After the discussion with Idar Petersen [3.1] and through the literature review, the author realized that a lot of the potential of V2G-charging lies in buses and other larger vehicles. Like ferries, ships and trams. These vehicles, when powered by electrical energy, will often have far superior battery capacity when compared to the smaller personal EVs. Seeing as the EVs can only deliver a fraction of the total throughput, the larger vehicles could provide a more substantial contribution to the case of power grid peak-valley stabilisation. The conversation with Idar Petersen also revealed that this is already planned in several cities across the world, and experiments are being done to provide the solutions for boats and buses to serve as emergency batteries in this case. A potential future addition of casEV could be to add the capability for buses to engage in V2G charging.

More diverse agents

The way the model has been set up now, the agents are not very diverse. They're created to represent people and vehicles. The real world is more diverse than that, and it would require a large amount of different agents to represent all the types of consumers and producers you have within a city. The decision to not include other types of agents was mainly due to time-constraints. If we were to create a new class of agents, for example a taxi driver or something similar, the impact their difference will have on the system as a whole needs to be clear in order for the extra work to be worth it. The introduction of different types of agents wouldn't add much to the overall computational costs, seen as they'll be created during initialization. If necessary, classes of agents could easily be added in the future if deemed beneficial for the overall system performance.

More smart grid features

The thesis set out to explore the applicability of complex modelling in relation to smart grid features and their mutual effects on flow of energy and traffic. The feature that was focused on was V2G charging. There has been increasing attention and implementation of smaller-scale solar panels across certain parts of the world. The potential of these doesn't only lie in the fact that they can power the buildings their connected to, but also the fact that they can give/sell that power back to the grid if redundant power is produced. This could work on a similar level to the EVs in the model, with the Prosumers and aggregators handling the buying and selling of power on a more decentralized level. Smart grid features such as this can be added in the future, to view their effects on the system and the agents' behaviour.

7.3 Conclusion

The model proposed in this thesis aimed to show how a complex adaptive system could be utilized for exploring scenarios related to smart grid technology and its connection to the flow of traffic and people in an urban context. The goal was never to provide a model that encapsulates all aspects of power grids, V2G charging or urban transportation. But rather one that takes a holistic approach to combine the technologies discussed in the literature review to provide a easily modifiable, low barrier tool for simulating scenarios related to smart power grids and urban transportation. Through the use of V2G charging, the proposed model casEV demonstrated how the use of a framework based on Prosumers and Aggregators can be applied to handle the trading of power between autonomous entities within a given geographical area. By conducting three separate experiments and through the discussion of their results, the author attempted to give solutions and answers to the problem statement and research questions presented in section 1.2.2. The limitations of the model and some potential future work that can be done to expand its functionality and accuracy was also presented. The source code of the model casEV and a detailed user-guide for running simulations can be found on the author's GitHub page [42].

References

[1] UN. *68% of the world population projected to live in urban areas by 2050, says UN.* www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html. [Online; accessed 03-February-2020]. 2018.

[2] *EIA projects nearly 50% increase in world energy usage by 2050, led by growth in Asia.* https://www.eia.gov/todayinenergy/detail.php?id=41433. [Online; accessed 22-January-2020].

[3] *Peak Energy Demand.* https://www.sciencedirect.com/topics/engineering/peak-energy-demand. [Online; accessed 08-February-2020].

[4] *Energy storage is the new efficiency.* www.renewableenergyworld.com/2019/04/22/energy-storage-is-the-new-efficiency/. [Online; accessed 14-March-2020]. 2019.

[5] UN. *Is the world living up to its climate commitments?* https://news.un.org/en/story/2019/09/1045592. [Online; accessed 09-February-2020]. 2019.

[6] Robert N. Stavins. *Economic Incentives for Environmental Regulation.* https://www.belfercenter.org/publication/economic-incentives-environmental-regulation. [Online; accessed 13-April-2020].

[7] Peter Connor and Oscar Fitch-Roy. "Chapter 14 - The Socio-Economic Challenges of Smart Grids". In: *Pathways to a Smarter Power System.* Academic Press, 2019, pp. 397–413. ISBN: 978-0-08-102592-5. DOI: https://doi.org/10.1016/B978-0-08-102592-5.00014-4.

[8] SETIS. *Smart electricity grids.* https://setis.ec.europa.eu/related-jrc-activities/jrc-setis-reports/smart-electricity-grids. [Online; accessed 03-April-2020].

[9] K.T. Chau. "21 - Pure electric vehicles". In: *Alternative Fuels and Advanced Vehicle Technologies for Improved Environmental Performance.* Ed. by Richard Folkson. Woodhead Publishing, 2014, pp. 655–684. ISBN: 978-0-85709-522-0. DOI: https://doi.org/10.1533/9780857097422.3.655.

[10] Alexander Siegenfeld and Yaneer Bar-Yam. *An Introduction to Complex Systems Science and its Applications.* Dec. 2019.

[11] André Fosvold. "CitySim: A modular Agent-Based simulation system for Modeling Cities as Complex Systems". In: (2019).

[12] *The Repast Suite.* https://repast.github.io/. [Online; accessed 19-February-2020].

[13] Sebastian Gunnestad Evans. "Modelling smart power grids as complex systems within an urban context". In: (2019).

[14] Hiroki Sayama. *Introduction to the Modeling and Analysis of Complex Systems.* Open SUNY Textbook, 2015. ISBN: 1942341083.

[15] *emergence*. https://dictionary.cambridge.org/dictionary/english/emergence. [Online; accessed 19-February-2020].

[16] *About - Santa Fe Institute*. https://www.santafe.edu/about. [Online; accessed 12-Febraury-2020].

[17] *ABOUT NECSI*. https://necsi.edu/about. [Online; accessed 12-February-2020].

[18] Seth Blumsack. *How complexity science can help keep the lights on*. https://www.csmonitor.com/Science/Complexity/2017/0302/How-complexity-science-can-help-keep-the-lights-on. [Online; accessed 08-February-2020].

[19] EUC. *Complex System Science for Smart Grids*. https://ses.jrc.ec.europa.eu/complex-system-science-smart-grids. [Online; accessed 11-February-2020]. 2017.

[20] Rehman Zafar et al. "Prosumer based energy management and sharing in smart grid". In: *Renewable and Sustainable Energy Reviews* 82 (2018), pp. 1675–1684. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2017.07.018. URL: http://www.sciencedirect.com/science/article/pii/S1364032117310894.

[21] SINTEF. *Smart Grids*. https://www.sintef.no/prosjekter/smart-grids/. [Online; accessed 28-January-2020].

[22] European Comission. *Smart Grids*. www.ec.europa.eu/energy/en/topics/markets-and-consumers/smart-grids-and-meters/overview. [Online; accessed 07-April-2020].

[23] *Distribution Automation Smart grid analysis*. https://www.geenergyconsulting.com/practice-area/power-systems/distribution-automation-and-smart-grid-analysis. [Online; accessed 03-April-2020].

[24] Jarand Hole Hallgeir Horne Magnus Buvik. "Smarte ladesystemer og Vehicle-to-Grid". In: *NVE FAKTA* (2019). URL: http://publikasjoner.nve.no/faktaark/2019/faktaark2019_09.pdf.

[25] *The battery decade: How energy storage could revolutionize industries in the next 10 years)*. https://www.cnbc.com/2019/12/30/battery-developments-in-the-last-decade-created-a-seismic-shift-that-will-play-out-in-the-next-10-years.html. [Online; accessed 14-April-2020].

[26] VIRTA. *Vehicle-to-Grid: Everything you need to know*. https://www.virta.global/vehicle-to-grid-v2g. [Online; accessed 14-March-2020]. 2020.

[27] *Amsterdam pilots V2G charging*. https://www.fleeteurope.com/fr/maas-smart-mobility-technology-and-innovation/netherlands/news/amsterdam-pilots-v2g-charging?a=FJA05&t%5B0%5D=NewMotion&t%5B1%5D=Alliander&t%5B2%5D=Enervalis&t%5B3%5D=&curl=1. [Online; accessed 02-May-2020].

[28] *Discrete Event and Agent-based Modeling and Simulation.* www.mit.edu/~moshref/Simulation.html. [Online; accessed 23-January-2020].

[29] R.M. Rylatt et al. "CASCADE: An Agent Based Framework For Modeling The Dynamics Of Smart Electricity Systems". In: *Emergence* 15 (June 2013), pp. 1–13.

[30] R.M. Rylatt et al. "Exploring Smart Grid Possibilities: A Complex Systems Modelling Approach". In: *Smart Grid* 1 (Jan. 2015), pp. 1–15. DOI: 10.1515/sgrid-2015-0001.

[31] Manuel Welsch et al. "Modelling elements of Smart Grids - Enhancing the OSeMOSYS (Open Source Energy Modelling System) code". In: *Energy* 46 (Oct. 2012). DOI: 10.1016/j.energy.2012.08.017.

[32] Guillaume Guérard, Soufian Ben Amor, and Alain Bui. "A Complex System Approach for Smart Grid Analysis and Modeling". In: vol. 243. Jan. 2012, pp. 788–797. DOI: 10.3233/978-1-61499-105-2-788.

[33] Guillaume Guérard, Soufian Ben Amor, and Alain Bui. "Survey on smart grid modelling". In: *International Journal of Systems, Control and Communications* 4 (Jan. 2012), pp. 262–279. DOI: 10.1504/IJSCC.2012.050822.

[34] *SmartPower).* https://www.sintef.no/en/digital/applied-mathematics/optimization/smartpower/. [Online; accessed 18-April-2020].

[35] *Power Grid Optimiser).* https://www.sintef.no/en/software/power-grid-optimizer/. [Online; accessed 18-April-2020].

[36] SINTEF. *KogniGrid - Digital tvilling for optimal nettdrift er et Pilot-E prosjekt ledet av Kongsberg Digital.* https://www.sintef.no/en/projects/kognigrid-digital-tvilling-for-optimal-nettdrift/. [Online; accessed 14-February-2020]. 2019.

[37] SINTEF. *ENERGYTICS.* https://www.sintef.no/prosjekter/energytics/. [Online; accessed 29-January-2020]. 2017.

[38] *Trafikkdata).* https://www.vegvesen.no/trafikkdata/start/. [Online; accessed 14-March-2020].

[39] Torgeir Ericson and Bente Halvorsen. "Hvordan varierer timeforbruket av strøm i ulike sektorer?" In: (June 2008).

[40] *Introduction to A*).* http://theory.stanford.edu/~amitp/GameProgramming/AStarComparison.html. [Online; accessed 06-March-2020].

[41] Alvin Toffler. *The Third Wave.* Bantam Books, 1980. ISBN: 0517327198.

[42] *CAS-EV).* https://github.com/sebastge/thesisFinal. [Online; accessed 20-June-2020].

[43] *BU-1003: Electric Vehicle (EV).* https://batteryuniversity.com/learn/article/electric_vehicle_ev. [Online; accessed 13-April-2020].

[44] *The Challenges of Testing in a Non-Deterministic World).* `https://insights.sei.cmu.edu/sei_blog/2017/01/the-challenges-of-testing-in-a-non-deterministic-world.html`. [Online; accessed 19-May-2020].

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