THE 1ST INTERNATIONAL WORKSHOP ON SIMULATION FOR ENERGY, SUSTAINABLE DEVELOPMENT & ENVIRONMENT

SEPTEMBER 25-27 2013
ATHENS, GREECE

EDITED BY
TERRY BOSSOMAIER
AGOSTINO BRUZZONE
GERSON CUNHA
JANOS SEBESTYEN JANOSY
FRANCESCO LONGO

PRINTED IN RENDE (CS), ITALY, SEPTEMBER 2013

ISBN 978-88-97999-28-7 (paperback)
ISBN 978-88-97999-27-0 (PDF)

ISBN 978-88-97999-28-7 (PAPERBACK)
ISBN 978-88-97999-27-0 (PDF)

THE 1ST INTERNATIONAL WORKSHOP ON SIMULATION FOR ENERGY, SUSTAINABLE DEVELOPMENT & ENVIRONMENT, SESDE 2013

SEPTEMBER 25-27 2013 - ATHENS, GREECE

Organized by

DIME – University of Genoa

Liophant Simulation

Simulation Team

IMCS – International Mediterranean & Latin American Council of Simulation

DIMEG, University of Calabria

MSC-LES, Modeling & Simulation Center, Laboratory of Enterprise Solutions

Modeling and Simulation Center of Excellence (MSCOE)

Latvian Simulation Center – Riga Technical University

Logisim

LSIS – Laboratoire des Sciences de l'Information et des Systemes

MIMOS – Movimento Italiano Modellazione e Simulazione

MITIM Perugia Center – University of Perugia

Brasilian Simulation Center, LAMCE-COPPE-UFRJ

MITIM - McLeod Institute of Technology and Interoperable Modeling and Simulation – Genoa Center

M&SNet - McLeod Modeling and Simulation Network

Latvian Simulation Society

Ecole Superieure d'Ingenierie en Sciences Appliquees

Facultad de Ciencias Exactas. Ingegneria y Agrimensura

University of La Laguna

CIFASIS: CONICET-UNR-UPCAM

INSTICC - Institute for Systems and Technologies of Information, Control and Communication

National Russian Simulation Society

CEA - IFAC

AFCEA, HELLENIC CHAPTER

Technically Co-Sponsored

IEEE – Central and South Italy Section Chapter

I3M 2013 Industrial Sponsors

CAL-TEK SRL

LIOTECH LTD

MAST SRL

SIM-4-FUTURE

I3M 2013 Media Partners

Inderscience Publishers – International Journal of Simulation and Process Modeling

Inderscience Publishers – International Journal of Critical Infrastructures

Inderscience Publishers – International Journal of Engineering Systems Modelling and Simulation

Inderscience Publishers – International Journal of Service and Computing Oriented Manufacturing

IGI GLOBAL – International Journal of Privacy and Health Information Management

Halldale Media Group: Military Simulation and Training Magazine

Halldale Media Group: The Journal for Healthcare Education, Simulation and Training

Euromerci

EDITORS

TERRY BOSSOMAIER
CHARLES STURT UNIVERSITY, AUSTRALIA
tbossomaier@csu.edu.au

AGOSTINO BRUZZONE
MITIM-DIME, UNIVERSITY OF GENOA, ITALY
agostino@itim.unige.it

GERSON CUNHA
UNIVERSIDADE FEDERAL DO RIO DE JANEIRO, BRASIL
gerson@lamce.coppe.ufrj.br

JANOS SEBESTYEN JANOSY
MTA KFKI ATOMIC ENERGY RESEARCH INSTITUTE, HUNGARY
jjs@sunserv.kfki.hu

FRANCESCO LONGO
DIMEG, UNIVERSITY OF CALABRIA, ITALY
f.longo@unical.it

INTERNATIONAL MULTIDISCIPLINARY MODELING & SIMULATION MULTICONFERENCE, I3M 2013

GENERAL CO-CHAIRS

AGOSTINO BRUZZONE, *MITIM-DIME, UNIVERSITY OF GENOA, ITALY*
YURI MERKURYEV, *RIGA TECHNICAL UNIVERSITY, LATVIA*

PROGRAM CHAIR

FRANCESCO LONGO, *DIMEG, UNIVERSITY OF CALABRIA, ITALY*

THE 1ST INTERNATIONAL WORKSHOP ON SIMULATION FOR ENERGY, SUSTAINABLE DEVELOPMENT & ENVIRONMENT, SESDE 2013

GENERAL CO-CHAIRS

JANOS SEBESTYEN JANOSY, *MTA KFKI ATOMIC ENERGY RESEARCH INSTITUTE, HUNGARY*
FRANCESCO LONGO, *DIMEG, UNIVERSITY OF CALABRIA, ITALY*

PROGRAM CHAIRS

TERRY BOSSOMAIER, *CHARLES STURT UNIVERSITY, AUSTRALIA*
GERSON CUNHA, *UNIVERSIDADE FEDERAL DO RIO DE JANEIRO, BRASIL*

SESDE 2013 INTERNATIONAL PROGRAM COMMITTEE

Michael Affenzeller, *Upper Austria University of Applied Sciences,Austria*
Angelo Algieri, *University of Calabria, Italy*
Mauricio Alves da Cunha Aghina, *Comissão Nacional de Energia Nuclear, Brasil*
Terry Bossomaier, *Charles Sturt University,Australia*
Eleonora Bottani, *University of Parma, Italy*
Agostino Bruzzone, *University of Genoa, Italy*
Daniel Buchbinder, *Alterna, Guatemala*
Rodrigo Castro, *Universidad de Buenos Aires, Argentina*
François E. Cellier, *ETH Zürich, Switzerland*
Gerson Cunha, *LAMCE/COPPE/UFRJ, Brasil*
Lugi De Napoli, *University of Calabria, Italy*
Jose Drummond Alves, *LAMCE/COPPE/UFRJ, Brasil*
Vittorio Ferraro, *University of Calabria, Italy*
Crisitna Hagenauer, *UFRJ, Brasil*
Stephan Hutterer, *Upper Austria University of Applied Sciences, Austria*
Alessio Ishizaka, *University of Portsmouth, UK*
Janos Sebestyen Janosy, *MTA KFKI Atomic Energy Research Institute, Hungary*
Luiz Landau, *LAMCE/COPPE/UFRJ, Brasil*
Luis Le Moyne, *University of Bourgogne, France*
Arnis Lektauers, *Riga Technical University, Latvia*
Luis Augusto Petrus Levy, *Petrobras, Brasil*
Francesco Longo, *University of Calabria, Italy*
Marina Massei, *University of Genoa, Italy*
Antonio Carlos Moll, *Instituto de Engenharia Nuclear, Brasil*
Roberto Montanari, *University of Parma, Italy*
Sven Christian Müller, *TU Dortmund University, Germany*
Anil Namdeo, *Newcastle University, UK*
Letizia Nicoletti, *CAL-TEK, Italy*
Aurelio Nogueira, *UFRJ, Brasil*
Anna Ostrega, *AGH University of Science and Technology, Poland*
Fernando Pellon, *PETROBRAS, Brasil*
Xavier Roboam, *University of Toulouse III, France*
Enio Russo, *PETROBRAS, Brasil*
Maria Celia Santos Lopes, *LAMCE/COPPE/UFRJ, Brasil*
Gerald Steinmaurer, *Austria Solar Innovation Center, Austria*
Matthias Stifter, *Austria Solar Innovation Center, Austria*
Alberto Tremori, *Simulation Team, Italy*
Luigi Vanfretti, *KTH Royal Institute of Technology, Sweden*
Alejandro Velasco, *Universidad Autónoma de Tamaulipas, Mexico*
Edmund Widl, *Austrian Institute of Technology, Austria*

TRACKS AND WORKSHOP CHAIRS

SIMULATION PRO ENERGY, ENVIRONMENT AND DEVELOPMENT - SPEED

CHAIR: ANGELO ALGIERI, UNIVERSITY OF CALABRIA, ITALY

EMERGY MODELING

CHAIRS: FRANÇOIS E. CELLIER, ETH ZÜRICH, SWITZERLAND; RODRIGO CASTRO, UNIVERSIDAD DE BUENOS AIRES, ARGENTINA

TRANSPORTATIONS

CO-CHAIRS: ARNIS LEKTAUERS, RIGA TECHNICAL UNIVERSITY; LUIS LE MOYNE, UNIVERSITY OF BOURGOGNE, FRANCE

SMART GRID PLANNING, OPTIMIZATION AND CONTROL - SPOC

CHAIRS: MICHAEL AFFENZELLER, UPPER UNIVERSITY OF APPLIED SCIENCES, AUSTRIA; STEPHAN HUTTERER, UPPER UNIVERSITY OF APPLIED SCIENCES, AUSTRIA

SUSTAINABLE LAND USE AND TRANSPORT ADOPTING M&S, CONSUMERSISM AND SUSTAINABILITY

CHAIR: DANIEL BUCHBINDER, ALTERNA, GUATEMALA

CHAIRS' MESSAGE

The workshop "Simulation for Energy, Sustainable Development & Environment" (SESDE) is organized in the framework of the "International Multidisciplinary Modeling & Simulation Multiconference" (I3M) first time this year. It reflects to the concern that slowing down the global warming and at least to mitigate the consequences of our irresponsible consumption are the biggest challenge for the mankind in the XXI century.

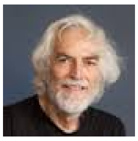
Our efforts should be directed to both ways: first, to find out how to achieve a more responsible living reducing the generation of damaging gases, waste production and unnecessary energy losses. The papers submitted to our Workshop reflect this concern; indeed among others some of the papers focus on switching the modes of transport in Vienna, investigating new multi-house heating systems, experimenting with hybrid electric-driven vehicles.

Second, we all have to learn how to satisfy our needs in an environment-friendly way. The methods of generating renewable energy in a sustainable way have been studied in detail already, but integrating this new form of energy into our existing energy systems is still a problem (i.e. as we can see it at the northern windmills in Germany). Definitely we need smart networks and smart customers to accommodate these power sources. The SESDE papers also investigate these issues with a common point in all the research activities: Modeling & Simulation. We try to investigate our problems doing effective and precious simulation.

Welcome to our workshop, welcome to Athens! For a better world and for a better place to stay, we should all discuss, learn and benefit from the efforts of our colleagues and make SESDE a very fruitful and successful event.

Janos Sebestyen Janosy
MTA KFKI Atomic Energy Research Institute, Hungary

Francesco Longo
DIMEG, University of Calabria, Italy



Terry Bossomaier
Charles Sturt University, Australia

Gerson Cunha
Universidade Federal do Rio de Janeiro, Brasil

ACKNOWLEDGEMENTS

The SESDE 2013 International Program Committee (IPC) has selected the papers for the Conference among many submissions; therefore, based on this effort, a very successful event is expected. The SESDE 2013 IPC would like to thank all the authors as well as the reviewers for their invaluable work.
A special thank goes to all the organizations, institutions and societies that have supported and technically sponsored the event.

LOCAL ORGANIZATION COMMITTEE

AGOSTINO G. BRUZZONE, *MISS-DIPTEM, UNIVERSITY OF GENOA, ITALY*
MATTEO AGRESTA, *SIMULATION TEAM, ITALY*
CHRISTIAN BARTOLUCCI, *SIMULATION TEAM, ITALY*
ALESSANDRO CHIURCO, *DIMEG, UNIVERSITY OF CALABRIA, ITALY*
MARGHERITA DALLORTO, *SIMULATION TEAM, ITALY*
LUCIANO DATO, *SIMULATION TEAM, ITALY*
ANGELO FERRANDO, *SIMULATION TEAM, ITALY*
FRANCESCO LONGO, *DIMEG, UNIVERSITY OF CALABRIA, ITALY*
MARINA MASSEI, *LIOPHANT SIMULATION, ITALY*
LETIZIA NICOLETTI, *CAL-TEK SRL*
FRANCISCO SPADAFORA, *CAL-TEK SRL*
ALBERTO TREMORI, *SIMULATION TEAM, ITALY*

This International Workshop is part of the I3M Multiconference: the Congress leading **Simulation around the World and Along the Years**

Index

CONTROL ALGORITHMS FOR PHOTOVOLTAIC INVERTERS WITH BATTERY-STORAGE FOR INCREASED SELF CONSUMPTION

Rechberger, P. J.[(a)], Steinmaurer, G.[(a)], Reder, R.[(b)]

(a) ASiC – Austria Solar Innovation Center, Roseggerstraße 12, A-4600 Wels
(b) Fronius Int. GmbH, Günter-Fronius Straße 1, A-4600 Thalheim b. Wels

(a)rechberger.philipp@asic.at
(a)reder.robert@fronius.com

ABSTRACT

The aim of this paper is the development and analysis of control algorithms for internal energy management systems in interactive grid solar inverters with a battery storage system. Therefore, such a system consisting of multiple power electronic devices and a lead acid battery is described. Three different energy management algorithms are developed and simulated with different load and production data to gain results which allow to compare the features of the control algorithms. One of the main results are achievable self-consumption-rates which play an enormous role in the cost-effective operation of private photovoltaic (PV) power systems. The simulations were carried out in MathWorks MATLAB for a time span of one year in one-second resolution. This allows a detailed analysis of the different algorithms. Special attention is paid on the time resolution of the power measurements where a significant dependency on the achievable self-consumption-rate has been found.

Keywords: photovoltaics, battery storage, energy management, self-consumption

1. INTRODUCTION

At the moment PV-systems are divided into two groups. On the one hand there are island systems for powering remote users which have no or a very poor connection to a distribution grid. The second type of PV power plants are grid connected systems which faced an enormous increase in the last years. About 175 MWp of grid connected PV systems have been installed in Austria in 2012 which is nearly the double amount of the installed capacity in 2011 (Biermayr et al., 2013). The main part of this capacity is connected to the low voltage transmission grid where in times with high insolation a power flow in reverse direction (from the low to the medium voltage grid) can take place. As a consequence the voltage can reach incorrect levels.

Additionally, due to the decreased prices for photovoltaic (PV) systems subsidies mainly in Germany and Austria are cut strictly. Especially for private users it gets attractive to use as much solar energy as possible themselves. Beside the adaption of the time behaviour of the electricity use it is also possible to store the PV-energy for the use at times with higher electricity demand in the household. Therefore inverter systems with battery back up came on the market especially for grid connected usage.

This allows the costumer to store excess energy and increase the self-consumption-rate and it supports the grid by the reduction of the maximum feeding power if appropriate control algorithms are used.

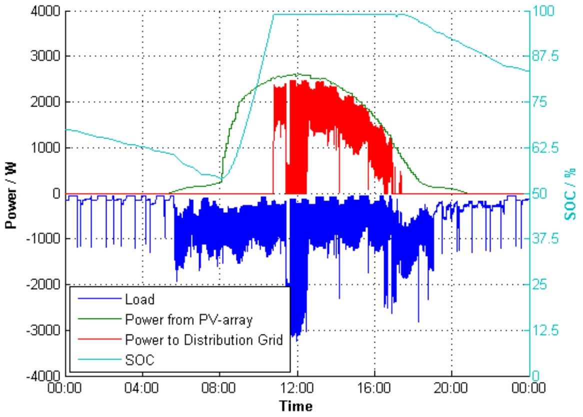


Figure 1: Power flow on a cloudless day.

In figure 1 power curves of an exemplary cloudless day are shown. On the second Y-axis the state of charge (SOC) of an integrated battery is assigned. The figure shows that the storage is not fully discharged from the day before and the maximum state of charge is reached around 11 o'clock a.m.. Afterwards the power on the connection to the transmission grid is equal to the power production of the PV-system minus the load.

2. SYSTEM DESIGN

In this work a photovoltaic inverter is used that combines the features of island- and grid connected converters. As shown in figure 2 a battery, in our case due to economic reasons a lead acid battery with 48 V system voltage is connected via a DC/DC converter to the intermediate direct current link. This circuit is fed by a DC/DC converter acting as a maximum power point tracker and connected to the household grid via an inverter which can be uni- or bidirectional. The latter enables the charging of the battery from the grid which is necessary to prevent the storage from deep-discharge or opens the possibility to grid-dependent load leveling as it is described later.

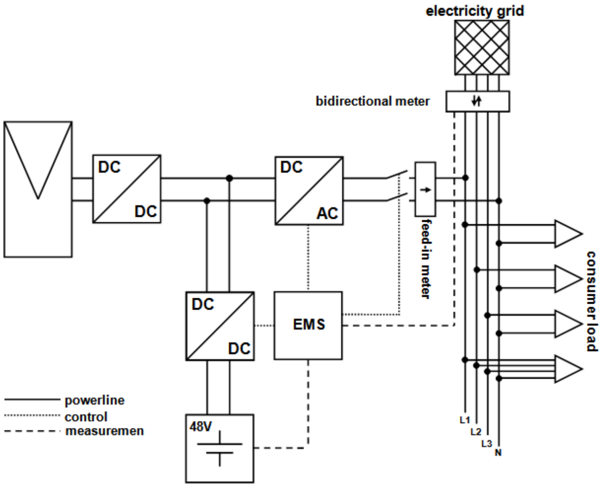


Figure 2: Design of discussed inverter system.

In this work DC-coupling of the storage is used. Alternatively AC-coupling is also possible with the advantages of flexibility in dimensioning the single devices. On the other hand an additional power-conversion step is necessary which increases the system losses. Grater detail is presented in Rechberger (2012).

2.1. Control

During operation of such systems a number of measured values have to be evaluated and the particular control algorithm has to be executed. Therefore a control system is necessary which is illustrated as 'Energy Management System (EMS)' in Figure 2. This central system is responsible for the correct and efficient operation of the inverter. Due to the small storage capacity of the intermediate circuit the control has to be very precise.

Ding et al. (2010) presented an alternative control scheme where the voltage value of the intermediate circuit acts as the only control variable. Every power conversion part of the system has its own control algorithm focusing on the voltage. The storage DC/DC converter acts as a superior system keeping the intermediate voltage constant. This is realized by withdrawing energy from the circuit if the value is to high and using energy of the battery to increase the voltage if it is too low.

2.2. Emergency Function

Such hybrid inverter systems can also be used as a kind of emergency system. In general inverters of grid connected PV power plants have to be switched off in case of grid failure. This means that if a grid outtake happens, a PV system is not allowed to feed in the grid because of security reasons. Because normal grid connected inverters are not able to work as an island inverter, the operator cannot use the PV system to power his loads.

If a hybrid inverter with energy storage functionality is used and the legal requirements like a self-acting disconnection point are fulfilled an island system can be built up. An important point herby is the capacity of the storage which limits the time of self supply. It could be an option to reserve a part of the capacity of the battery in order to support critical loads during grid outtakes. However, it must be kept in mind that this part of storage capacity cannot be used in self-consumption mode.

3. CONTROL ALGORITHMS

In this paper three different energy management strategies are developed. In the following section the control algorithms are described and evaluated for simulation. Further information can be found in Rechberger (2012).

3.1. Own Consumption Strategy

The goal of this scenario is the increase of the own consumption rate which shows the difference between produced energy and energy fed to the grid at the rate of the converted PV energy.

According to Castillo-Cagigal et al. (2011) this results in balancing the power flows in the system. The battery is charged if the photovoltaic power increases the load power as long as it is not fully charged. If the storage system is not able to accept further energy this excess energy is fed into the grid. On the other side the battery is used to power the load up to the maximum power of the inverter/battery system when the load increases the PV power as it is for example during the night or at cloudy days.

In addition to the state of charge (SOC) of the storage system the exact measurements of the power flows are necessary. The determination of the SOC depends mainly on the type of battery used in the system. While modern lithium based batteries usually require a battery-management-system which measures the charge level internally, separate systems for lead acid batteries are needed. The calculation of the SOC is mostly carried out by balancing the energy charged and discharged by the battery or measuring the voltage and calculating the current capacity by the use of characteristic curves. In order to measure the power flow current transformers or energy meters with appropriate output signals can be used.

To increase the expected lifetime of the battery different optimization strategies are integrated. These contain the limiting of the operating SOC range with frequent equalisation charges. Additionally a hysteresis around the full and empty state of charge was implemented to prevent the storage from numerous micro-cycles.

The battery model itself was based on a simple energy-balance model without chemical background.

Because of the constant use of the battery as an active storage system self-discharge was neglected.

3.2. Variable Tariffs Scenario

Electricity system operators in Austria (Traxler 2011) try to appeal the shifting of electricity consumption of the customers by the use of time variable tariffs as a method to delay expensive investments in system improvement.

The use of a storage system could therefore be a solution for the customer not to shift his consumption actively but via the battery. If the progress of electricity tariffs is known in advance the battery could be charged during cheap times directly from the grid while being discharged in expensive times trying to reduce the electricity demand from the grid to a minimum. Weather forecast could be an additional advantage in this process and will be a part of future works.

3.2.1. Development

A dynamic simulation was used to determine the optimal functionality of this strategy. Through artificial load and production curves the simulation chose the way to reach the lowest costs after one day of operation. After a number of runs over different days the optimal sequences were applied to the final variable tariffs scenario.

For one example day the initial and final state of charge was defined. To reduce the requirements of the calculation fixed SOCs were established in between at a time resolution of one minute. Between the single steps the energy required or provided by the battery was transferred by a cost function into absolute energy costs. The simulation resulted in a enormous number of possible ways to reach the goal of a fixed SOC. Different, artificial load and production curves as well as tariff-scenarios were used in multiple simulations. Finally the overall cheapest ways for each scenario were visualised and manually analysed.

It has been found out, that the optimal ways follow the supposed actions, which are:

- In case of a constant electricity tariff the most cost effective model is the own consumption strategy.
- If the feed-in tariff exceeds the consumption tariff including the battery storage costs the alternating charge and discharge respectively the buying and selling of energy is recommended.
- If the tariff increases the battery should be charged to be able to power the consumer loads. Due to the fact that no external weather forecasts were used in this work, the energy production of the previous day is used to predict the optimal state of charge before high energy prices and as well to reduce the amount of bought energy.
- Potential equalising charges should be arranged in low-priced or sunny stages.

Summing up this strategy, the battery is mainly used for load levelling in the household with an advantage of a photovoltaic system.

3.3. Optimised Battery Usage

As already mentioned in reference to the own consumption strategy, the battery lifetime has an enormous impact to the overall costs of such hybrid systems. Therefore an additional strategy was simulated with special adjustments to increase battery lifetime.

For example the depth of discharge (DOD) was reduced to a minimum in dependence of the time of year to minimise states with a low state of charge during times with reduced irradiance like winter. Additionally, the maximum charge current was developed as a function of the SOC which means that charge power is reduced at high and low SOCs to prevent the battery from overheating. To further reduce the number of micro cycles the working state of the battery is changed in intervals of only 30 minutes. Therefore the mean load and production power of the last interval is essential for further operation.

4. SIMULATION

The different energy management algorithms were converted in MathWorks MATLAB scripts which were used to simulate one year of operation. Different load, production and tariff curves were used. To represent a realistic operation measured data of a real PV-system and of multiple households were utilised.

4.1. PV-Data

The data of the PV system was recorded in 2010 in Upper Austria with a sample rate of 300 s. The system is orientated to south-east with an inclination of 25 °. The original power of 4 kWp has been scaled to two datasets with a capacity rating of 3 and 5 kWp respectively.

4.2. Load-Data

The big advantage of this work is, that realistic and high resolution consumer load curves are used. This data originates from the “ADRES-CONCEPT” project, where a dataset for electricity measurements in Austrian households was generated. The measurements were carried out for two weeks of one year (Adres 2011).

To use the data in this work three household-datasets were taken and extrapolated to one year of data. Thus, different household profiles could be represented:

- A double-person household with an annual electricity demand of around 3 MWh.
- A four-person household with an annual electricity demand of around 4.6 MWh.
- A six-person household with an annual electricity demand of around 6.6 MWh.

4.3. Additional boundary conditions

A lead acid battery with a nominal voltage of 48 V and a capacity of around 10 kWh was used as storage unit. Due to the fact that this work brings the topic of energy management into focus the battery has been realised in the simulation as a black box model with charging efficiencies taken from Sauer, Leuthold, Magnor and Lunz, 2011.

For cost calculation an energy price of 0.2 € per kWh for buying and 0.08 € per kWh for feeding energy into the grid were used. In case of time dependant tariffs a price of 0.3 € per kWh was used from 6 a.m. till 6 p.m., while 0.1 € per kWh was used in the remaining time.

As already mentioned the time resolution of self-consumption and variable-tariffs scenario lie in the order of one second, while the battery optimisation algorithm was simulated in intervals of 30 minutes.

5. RESULTS AND DISCUSSION

In the following section the main results of the simulations are presented.

Figure 3 shows achieved self consumption rates of six different options combining the two PV and three consumer load curves. It can be seen that the self consumption increases around 30.3 % if the own consumption strategy is used. The highest rate is achieved if a small PV-system is combined with a high load. The optimised battery usage algorithm performs relatively poor in contrast to the other energy managements. This is a result of the multiple restrictions taken in order to expand battery lifetime.

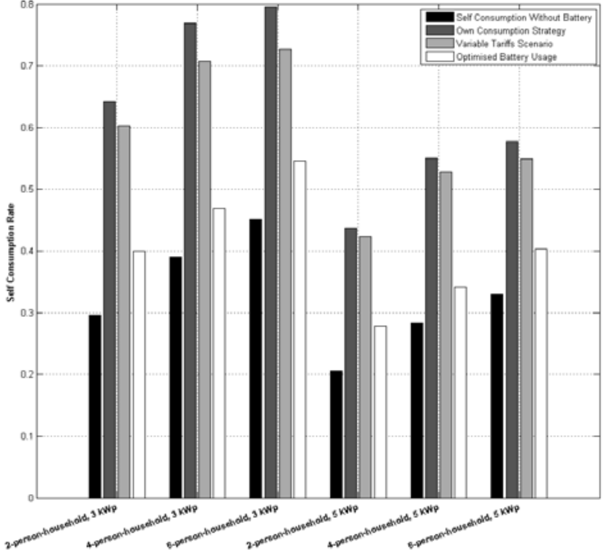


Figure 3: Self Consumption Rates of Different Energy Management Strategies.

In figure 4 the energy throughputs of the battery with different energy management strategies are shown. As expected the battery optimised strategy reduces the throughput significantly. In comparison to the variable tariffs scenario a bisection is nearly possible. Nevertheless the own consumption strategy shows the highest increase in self consumption rate in combination with a medium energy throughput. This means that it is the most effective strategy referring to the energy throughput. It reaches an annual throughput between 1150 and 1350 kWh which is around a hundred times the capacity of the battery which can be seen as 100 full cycles. Taking the lifetime of a standard lead acid battery into account, vague lifetime predictions could be made. But to do so, further battery- and model-specific factors have to be taken into account.

Table 1 shows a financial view of the problem. The energy costs of one year of operation were calculated and compared to the cost which occur for the households if no PV-system is installed. Mean values of all six combinations are displayed. It can be seen that the main savings already appear if a PV-system is installed. Additional savings by installing a storage system as stated in this work remain very limited. Taking current storage prices into account it results that using home-energy-storage systems is not economic at the moment (Sauer et al 2011). If using time-dependent tariffs the savings are on average higher especially with the variable tariffs scenario.

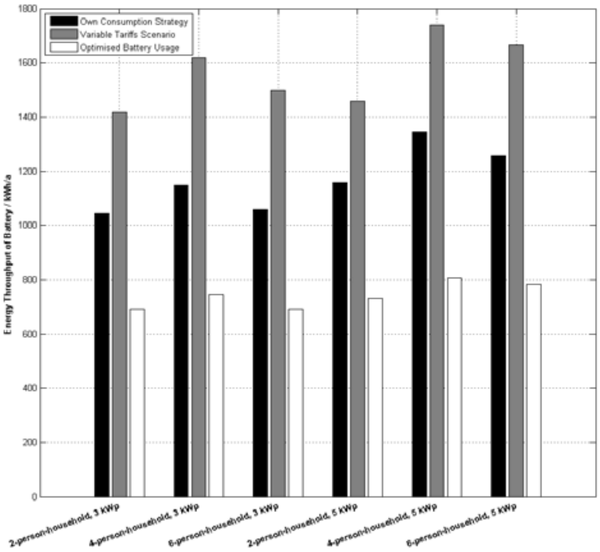


Figure 4: Energy Throughput of the Battery of Different Energy Management Strategies.

Table 1: Cost Savings.

	Savings Compared to a Household Without a PV-System	
	Constant Tariff	Time-Dependent Tariff
PV-System Without Battery	€ 511.48	€ 634.96
Own Consumption Strategy	€ 612.75	€ 689.04
Variable Tariffs Scenario	-	€ 779.47
Optimised Battery Usage	€ 525.35	€ 611.21

In figure 5 the self consumption rate is shown in dependence of the time resolution of the measurements of consumer load. It can be clearly seen that the self consumption rate decreases if measurements happen rarely. While the trend in the two-person-household is nearly stable until a resolution of 15 seconds the other combinations show already significant drops. The graphs visualise also that the load profile itself causes different gradients. It can be stated that the time resolution of the measurement systems and the working frequency of the energy management are very critical factors in calculating the self consumption rate. Comparing the results with data from literature shows the correct functionality and coincidence of the simulations (Braun et al 2010).

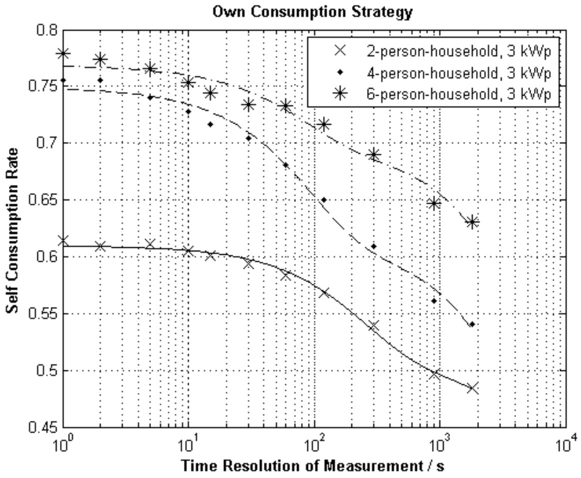


Figure 5: Self Consumption Rate in Dependence of Time Resolution.

Comparing the three energy management strategies it comes up that the own consumption scenario is the most efficient and therefore the most cost effective scenario. Nevertheless it has to be considered that by taking the results of the simulations into account such storage systems are not economically efficient at the moment.

Further steps and simulations regarding the grid functionality have to be executed to find optimal ways of grid assistance. The mentioned algorithms target the economic use of such systems especially for costumers and are not completely suitable for a stable grid operation especially when focusing on increased decentralized feed in of renewable energy sources.

6. CONCLUSION

In this paper different energy management strategies for grid interactive inverters with a battery storage are presented. For several configurations of PV systems and household loads self-consumption rates and a number of other characteristic numbers are calculated.

The energy management algorithms mentioned in this paper include:

- Increased own-consumption of electricity produced by the PV generators through storing excess energy and usage in times with lower solar irradiance.
- The use of the storage system for load adjustment in conjunction with time variable electricity tariffs.
- Optimised operation method for increasing the lifetime of the battery system.

For the simulations datasets of a real PV-power plant and three different households are used. Because of the high resolution of the data the simulations are carried out with a sample rate of 1s for one year of operation. Hence exact and practical representative results for the self-consumption rate could be reached.

The simulations showed that with such a system an increase of the self-consumption rate of more than 30 % compared to a normal photovoltaic system without storage is possible. As expected the own consumption strategy reaches the highest self-consumption rates at the most effective use of the battery storage. Using a special strategy when applying time variable tariffs cost savings of an average household of nearly 780 € per year are possible.

In this work special attention was paid to the influence of the resolution of power measurement to the resulting own-consumption rates which has been compared to known values in existing literature.

Due to the fast development in the sector of implementation of photovoltaics in electricity grids further simulations with other energy management strategies are the objective of further work.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the company *Fronius Int. GmbH, Thalheim bei Wels*, which supported this work.

The load curves used in this project originated from the ADRES-CONCEPT database, therefore it should be stated from Adres (2011):

“The Data was generated in the research project “ADRES-CONCEPT” (EZ-IF: Development of concepts for ADRES – Autonomous Decentralized Regenerative Energy Systems, project no. 815 674). This project was funded by the Austrian Climate and Energy Fund and performed under the program “ENERGIE DER ZUKUNFT”.”

REFERENCES

ADRES, 2011. Research Project „ADRES-CONCEPT“. Terms of Use for the ADRES-Dataset. Available from:http://www.ea.tuwien.ac.at/projekte/adres_concept/ [03.04.2013].

Biermayr, P., Eberl, M., Ehrig, R., Fechner, H., Kristöfl, C., Leonhartsberger, K., Martelli, S., Strasser, C., Weiss, W., Wörgetter, M., 2013. *Innovative Energitechnologien in Österreich Marktentwicklung 2012. Berichte aus Energie und Umweltforschung 17/2013.* Available from: http://www.nachhaltigwirtschaften.at/nw_pdf/1317_marktstatistik_2012.pdf [28.06.2013].

Braun, M., Büdenbender, K., Landau, M., Sauer, D.-U., Magnor, D. und Schmiegel, A. U., 2010. Charakterisierung von netzgekoppelten PV-

Batterie- Systemen – Verfahren zur vereinfachten Bestimmung der Performance. *25. Symposium Photovoltaische Solarenergie*. 3-5 March 2010, Bad Staffelstein.

Castillo-Cagigal, M., Gutiérrez, A., Monasterio-Huelin, F., Caamaño-Martìn, E., Masa, D. and Jiménez-Leube, J., 2011. A semi-distributed electric demand-side management system with PV generation for selfconsumption enhancement. Energy Conversion and Management 52: 2659-2666.

Ding, F., Li, P., Huang, B., Gao, F., Ding, D., Wang, C., 2010. Modeling and Simulation of Grid-connected Hybrid Photovoltaic/Battery Distributed Generation System. *China International Conference on Electricity Distribution 2010*, pp. 1-10, 13-16. Sept. 2010, Nanjing.

Rechberger, P. J., 2012. Entwicklung von Energiemanagementszenarien für netzgeführte Wechselrichter mit Speicher. Masterarbeit, Fachhochschule OÖ, Campus Wels. Wels, Österreich.

Sauer, D. U., Leuthold, M., Magnor, D. und Lunz, B., 2011. Dezentrale Energiespeicherung zur Steigerung des Eigenverbrauchs bei netzgekoppelten PV-Anlagen. Aachen: RWTH Aachen University.

Traxler, E. and Derler, K., 2011. Smart Grids = „Marktorientierte Optimierungsplattform für Elektrizitätssysteme”. Forum Econogy 2011. 9 November 2011, Linz.

AUTHORS BIOGRAPHY

Philipp J. Rechberger received a BSc degree in 2010 and a MSc degree in 2012 in Eco-Energy Engineering from the Upper Austria University of Applied Sciences. He is now with the Austria Solar Innovation Center as a project manager in the field of photovoltaic engineering.

Gerald Steinmaurer completed a diploma study at the Technical University Graz and received a PhD from the University Linz in electrical engineering. Mr. Steinmaurer is the author of several publications in the field of hybrid systems and control engineering.

Robert Reder received a Mag. rer. soc. oec. degree in 2001 in Business Informatics from the Johannes Kepler Universität in Linz. He was working as software concept engineer and software project manager at Comneon Electronic Technology GmbH & Co. OHG – (Infineon Technologies Company) from 2003 to 2008. From 2009 to July 2010 he worked as software project manager at Fujitsu Microelectronics Austria in Linz. Since August 2010 Robert Reder works at Fronius International responsible for pre-development in the solar electronics department.

THEORETICAL AND EXPERIMENTAL INVESTIGATION FOR "STORAGE LESS" CONTROL OF A WATER PUMPING SYSTEM FED BY INTERMITTENT RENEWABLE SOURCES

Amine Ben Rhouma [(a)], **Jamel Belhadj** [(a,b)], **Xavier Roboam** [(c)]

[(a)] Université de Tunis El Manar, ENIT, L.S.E., B.P. 37, 1002, Tunis, Tunisie
[(b)] Université de Tunis, DGE-ESSTT
[(c)] Université de Toulouse, LAPLACE UMR CNRS–INP–UPS, ENSEEIHT 2, Rue Charles Camichel, 31071 Toulouse, France

(a) Amine.Benrhouma@enit.rnu.tn, [(b)] Jamel.Belhadj@esstt.rnu.tn, [(c)] Xavier.Roboam@laplace.univ-tlse.fr

ABSTRACT

This paper focuses on an original control experimentally implemented for water pumping system fed by hybrid (PV-Wind) generator without battery storage. The water pumping system uses centrifugal pumps driven by variable speed three phase Induction Motors (IM) controlled by a new Power Field Oriented Control (PFOC). As we have eliminated the battery storage, the system operating point is imposed by the intermittent renewable source, given the hydraulic load characteristic; the basic idea is to use both degrees of freedom offered by the inverter in order to control the DC bus voltage and the rotor flux of the induction machine. Experimental investigations show the satisfying performance of the system even with variable power source.

Keywords: Intermittent source, water pumping, Power Field Oriented Control, hydraulic storage, experimental setup.

1. INTRODUCTION

Water and electricity are vital for human beings especially for their socio-economic development. However, given the increasing demographic situation, demand significantly increases, varying from one region to another depending on the migration of people. These two shortcomings are more evident in remote areas, often deprived of electricity and water. Thus, water pumping systems fed by intermittent hybrid (wind and/or photovoltaic) generators are relevant especially for remote areas where wind and sun resources are widely existent (Brian 2012; David 2011; Elgendy 2010; Dali 2007; Vongmanee 2005). One major and basic idea of our proposal is to prefer hydraulic storage to replace or at least to minimize electrochemical batteries in order to decrease system owning costs especially by increasing life cycle. In order to operate renewable sources at their maximum power, these latter have to be coupled to a voltage controlled DC link (Dali 2007). One issue is then related to the bus control: in classical approaches with grid connection or including storage device, the DC bus voltage is set from the grid or from the storage sub system. In standalone mode, without storage device, the issue is: "how to control the DC bus, knowing that renewable sources are power (MPPT) controlled"?

The aim of this paper is to present a new Power field Oriented Control for a pumping system fed by intermittent renewable source without battery storage. A steady state analysis will present the energy behavior and the available degrees of freedom to be exploited for the pumping system. A control strategy is conducted to manage the pumping system fed by intermittent power sources. An experimental setup is carried out to validate and test performance of the developed control.

2. THE "STORAGE LESS" PUMPING SYSTEM STRUCTURE

2.1. The hybrid pumping system

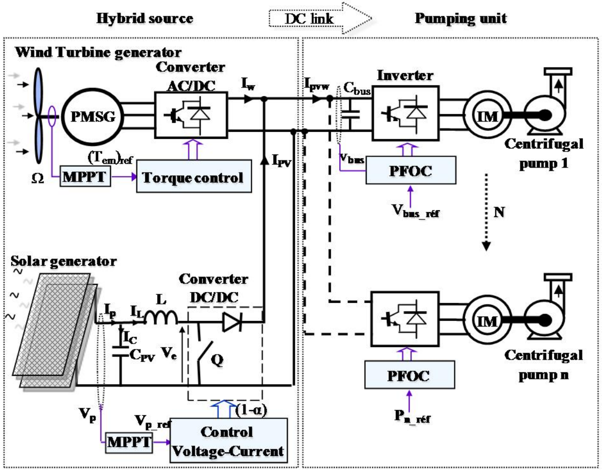


Figure 1: The proposed pumping system

The pumping system mainly consists of the hybrid source and the pumping unit. The pumping unit can be based on a single motor-pump or (N) multi motor-pumps. In this paper we present the first configuration. The hybrid source can be powered by wind and photovoltaic generators coupled to the DC bus through static converters. The wind generator is a direct drive technology based on a multi-poles permanent magnet synchronous generator associated with a PWM rectifier, the photovoltaic panel is connected to the DC link via a boost chopper. To increase the energy availability, MPPT techniques are used to maximize the power transfer (these sources are power controlled if the maximum power of the pumping system is reached): all degrees of freedom offered by power converters connected to renewable sources are then used for MPPT control. This principle is presented in preceding works as in Ben Rhouma (2008). In this paper, we have only considered "given power source" given climatic conditions. The pumping unit is composed of 1 HP motor pumps driven by a voltage source inverter. The pump is associated to hydraulic pipes (see Figure 1).

2.2. Steady state system analysis

A preliminary static study of the operation for the overall system (the hybrid sources and the pumping unit) is needed to analyze the energy behavior and to determine all Degrees Of Freedom (DOF). This study is useful for the development of power management strategies.

First, let remind that electric power delivered by hybrid sources (in MPPT mode) will be transmitted via the DC bus to the pump unit through the inverter. The operation of the pumping system over wind and sun differs from a conventional system that works with batteries. Indeed, for systems that include batteries, the power required by the load is the sum of the power generated by hybrid sources (PV-Wind energy) and power stored in the batteries. In this case, the power consumption being imposed by the load, the power management generally optimizes energy efficiency, at least when the battery is properly charged (SOC inside correct range): this mode is quite similar to the one obtained with a traditional grid connected source with "infinite" power.

On the opposite, for systems which depend on wind and sun intermittent conditions and without electrochemical storage, electric power transmitted to the load will be imposed ("given") by the hybrid source. Furthermore, given an "hydraulic" load characteristic, the operating point (*H,Q* plan: *H* being the manometric height and *Q* the volumic flow) is locked at a single operating point imposed at the crossing of given source powers and hydraulic characteristic.

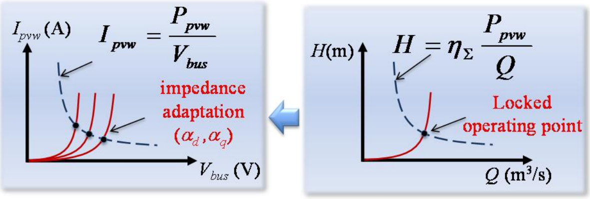


Figure 2: Locked operating point for given input power sources and given load

Figure 3 shows that the operating point is locked to the intersection of the hyperbola of the hybrid power P_{PVW} and the load characteristic (right curve) while the inverter duty cycles may be used to vary the bus voltage in the electric plan, adapting the system impedance (left curve).

So, changing the operation in the hydraulic plan leads to change the input power or to change the hydraulic load. Then, the original idea is to exploit the two degrees of freedom offered by the voltage source inverter (as example varying duty cycles: α_d, α_q) supplying the induction motor: the first DOF α_d is used to set the magnetizing flux in the machine and the second one α_q is "free to be exploited" in order to control the DC bus voltage.

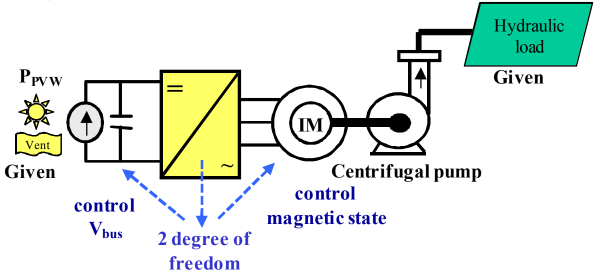


Figure 3: Cooperative energy management inter domain: control of the DC bus voltage by the inverter

3. CONTROL STRATEGY DESIGN

3.1. The Power Field Oriented Control

The induction motor dynamic model can be represented according to the usual (*d,q*) Park's reference frame. To decouple flux and torque a Field Oriented Control (F.O.C) is classically used. The torque is then controlled through the "*q*" axis current. In our case, the torque current reference ($I_{sq\ ref}$) is set following an external loop for the DC bus voltage control. The rotor flux is regulated along the "*d*" axis. Finally, two control loops are proposed for flux and DC voltage.

3.1.1. DC voltage control

As the hybrid system is a power source, it is required to include a link capacitor (C_{bus}) between the source and the inverter. The DC bus voltage (V_{bus}) has to be maintained constant whatever the power transfer in the DC bus.

The current balance in the DC bus is given by the following equation.

$$I_{bus} = I_e + I_c. \tag{1}$$

The basic idea to control the DC bus voltage is to keep the power balance at the input/output of the inverter:

$$V_{bus}.I_e = E_d.I_{sd} + E_q.I_{sq}. \tag{2}$$

(E_d, E_q) are the "*d*" and "*q*" axis motor voltages, which can be estimated from rotation speed knowing machine resistance and flux.

(I_{sd}, I_{sq}) are the "*d*" and "*q*" axis stator current.

The characteristic equation of the DC bus capacitor and the induction machine is represented by the following diagram.

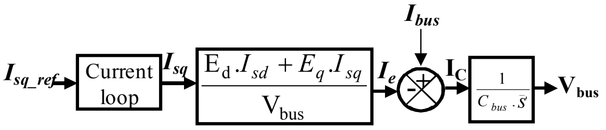


Figure 4: block diagram of the DC bus vs torque current transfer function

From previous equations and by considering that the motor current loop dynamic is faster than the bus voltage dynamic, the cascaded control structure of figure 5 is proposed.

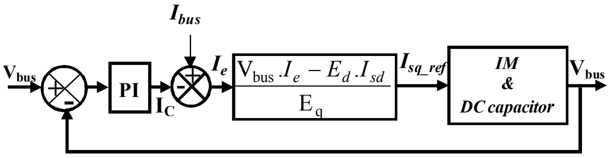


Figure 5: DC voltage control loop

3.2. The experimental setup

The proposed system shown in figures 6 and 7 is composed of a programmable power source (DLM 4kW from Sorensen), a voltage source inverter (Semikron 20kVA), a three phase centrifugal motor-pump (DAB 750W), a Dspic microcontroller and a card generating the DC current reference.

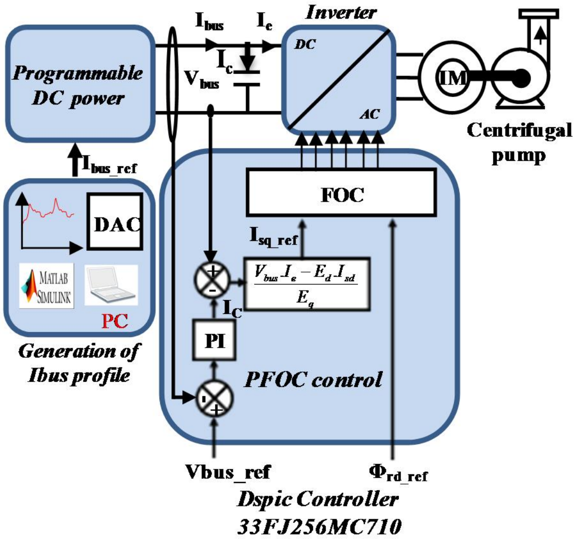


Figure 6: The experimental water pumping system without battery storage

The target for the digital implementation of the PFOC is an "explorer 16" board from microchip.

Three Hall Effect current sensors (LEM LTS-25nP) are used to measure two stator currents of the induction motor and DC bus current produced by the programmable power supply.

One Hall Effect voltage sensors (LEM LV-25P) is used to measure the DC bus voltage.

An acquisition card NI-DAQ 6008 from national instruments is used to measure and save four data: DC bus current, DC bus voltage, hydraulic pressure and water flow.

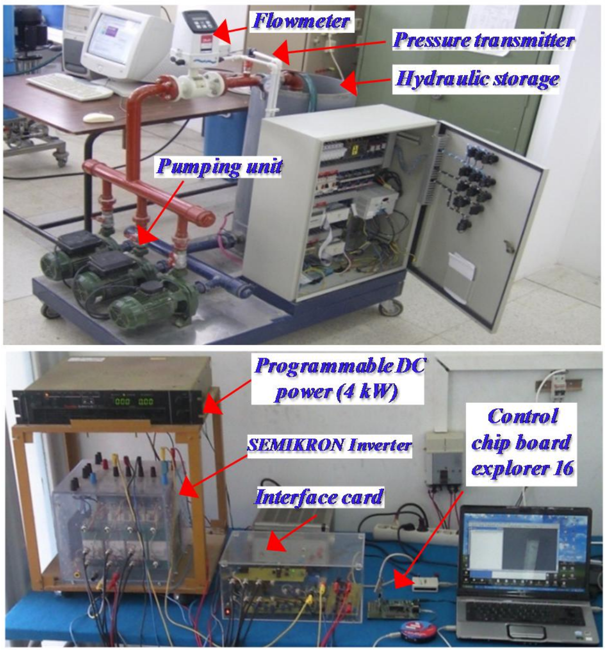


Figure 7: The experimental test bench for water pumping system

The proposed control strategy was implemented using a digital control system based on DSPic 33FJ256MC710 microcontroller. This microcontroller has a high-performance 16-bit central processing unit (40 MIPS) and peripherals that are particularly suitable for motor control applications.

Four analog quantities acquisition has been implemented by using the internal analog–digital (A/D) converter: two stator currents of the induction machine, DC bus current (I_{bus}) and DC bus voltage (V_{bus}).

The interruption of the A/D converter is executed every 62.5µs being triggered every PWM period (the switching frequency of the PWM is set at 16 kHz). The conversion result is transferred and stored in DMA buffer (direct memory access).

The synchronization of the different control blocks is made through the interrupt mechanism. It generates the instants and the order execution of the various modules. This order must take into account the speed of the internal and external loops of the FOC.

The current (I_{sd}, I_{sq}) loop bandwidth is chosen at 5 kHz. The DC voltage loop bandwidth is chosen as 500 Hz.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

To test the performance of the designed control, we have programmed a variable power profile from a cycle test under variable wind generation. The test is validated by simulation. We have chosen a model of wind with rapid fluctuations; its speed is modeled as a function of time as determined by the sum of several harmonics (equation 3):

$$V_{wind} = A_0 + \sum_{i=1}^{n}\left(a_i.\sin(b_i.\omega_v.t)\right) \qquad (3)$$

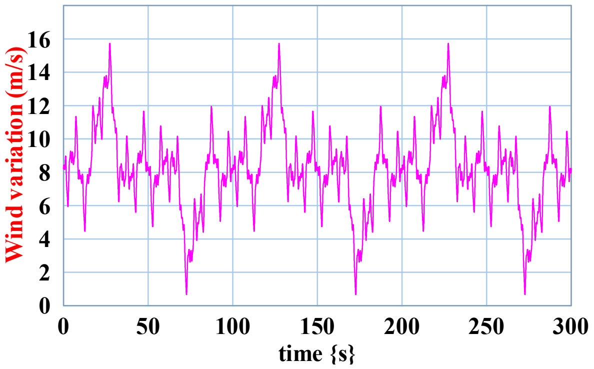


Figure 8: Model of wind variation

The wind model (figure 8) is tested, by software simulation, on a 1kW wind turbine generator with the architecture presented in figure 1. From the simulation, we have taken the variable DC current I_{bus} in digital data format to put it as an input to the control card. By this way, we can generate the adequate analog reference I_{bus} to the programmable power supply.

The current profile will be active only if the power supply operates as current source.

From this device, we can emulate the operation of a wind turbine submitted to variable wind coupled to the DC bus. The emulation process from experimental device is presented in figure 9.

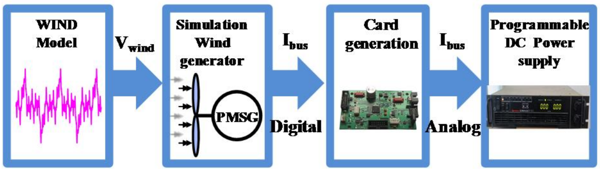


Figure 9: Experimental emulation of the wind power source

Initially, before starting the PFOC control, the programmable power supply works as a voltage source. The source voltage and current limits are also initialized.

The voltage provided by the programmable source is set to an initial value of 320V.

At the initial instant t=0s, we start the Field oriented Control: in this case, only the rotor flux and the current torque "I_{sq}" are controlled.

At the instant t_1= 52s, the DC voltage external loop regulation is started and set to a reference of 300V (PFOC mode). The power supply is then switched to constant current mode. The voltage and the current converge to their references. So, the motor-pump is power controlled. The generated current profile is constant and equal to 1.5A.

From the card of profile generation, we start in t_2=135s the profile with variable powers which emulates the wind turbine operation.

The electrical and hydraulic variables are stored for 600 seconds to fully assess the test cycle.

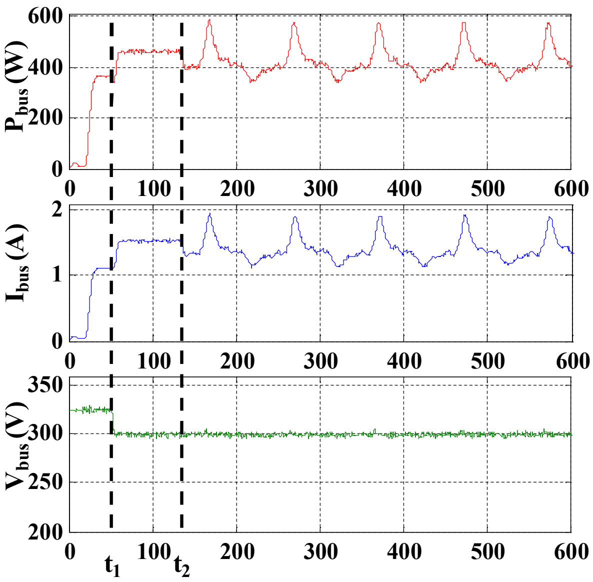


Figure 10: Input power, current and voltage in the DC bus

Figure 10 shows the good performance of the DC bus voltage control V_{bus} for variable DC power. Note that from t1 to 600 seconds the DC power P_{bus} varies according to the reference generated by the card generation. From t2, the programmable power supply operates as wind turbine emulator. The power produced is then variable. This variation is smoother than the wind variation (Figure 8) due to the large inertia of the turbine.

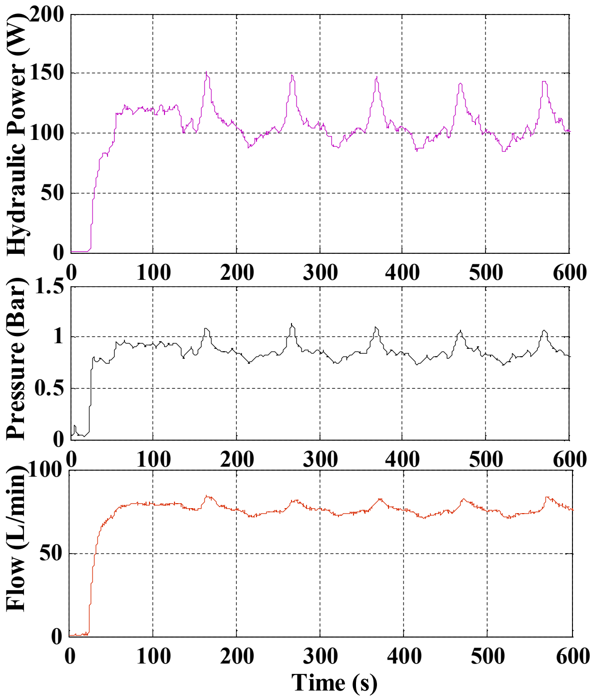


Figure 11: Hydraulic power, pressure and water flow according to DC power variations

Figure 11 shows that, given the hydraulic load, pressure and flow variables follow the variations of the DC bus power P_{bus}.

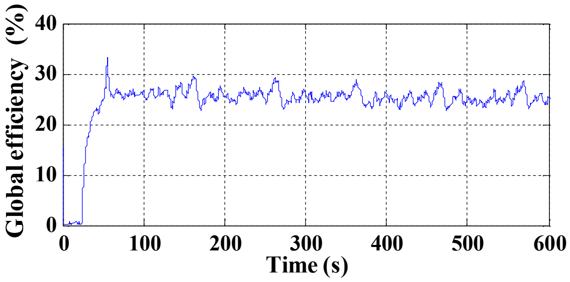


Figure 12: Global efficiency variation

The global system efficiency, shown in figure 12, is the ratio of the hydraulic power and DC bus electrical power. This efficiency is nearly constant for varying power DC bus P_{bus} but it should be noted that this performance can be increasingly fluctuating and even degraded following the hydraulic load.

Indeed, we have shown in previous works Ben Rhouma (2010) that the global efficiency strongly depends on the hydraulic load characteristics and the level of the DC power. As a solution, we have shown the relevance to exploit system modularity by using several pumps which would operate sequentially with better efficiencies. Consequently, for the pumping system as presented in figure 1, using N motor-pumps (N inverter) will increase the number of DOF, 1 DOF would be dedicated to the DC bus voltage regulation of the first motor-pump, while the (N-1) remaining DOF may be exploited to optimize the power management of the overall system.

5. CONCLUSION

An original Power Field Oriented Control PFOC is proposed, based on the two degrees of freedom offered by the voltage source inverter supplying the motorpump. The PFOC is mainly based on FOC principles: motor currents are controlled in Park's reference frame (d,q) oriented along the rotor flux as for the classical rotor field oriented control; an external loop is added for the regulation of the DC bus voltage along the 'q' axis, with an inner loop for the q axis torque current control. The second degree of freedom is used for the regulation of the rotor flux according to the 'd' axis. The PFOC is implemented on a DSPic microcontroller. We have realized experimental device based on a programmable DC power source to emulate the hybrid (solar PV & wind turbine) generator function. Experimental results demonstrate the validity and the performance of the developed control.

For this case study without or with minimum electrochemical storage, the hydraulic operating point is locked so that a bad adaptation between the source and the load may cause weak efficiency. To face such issue, the system modularity principle (using several motorpump devices) offers a convenient solution to optimize the power management for this type of system.

ACKNOWLEDGMENTS

This work was supported by the Tunisian Ministry of High Education and scientific Research, and CMCU-12G1103 project for the financial support.

REFERENCES

Dali, M., Belhadj, J., Roboam, X., Blaquiere, J.M., 2007. Control and Energy Management of a Wind photovoltaic Hybrid System. *EPE conference*, Aalborg, Danemark.

Vongmanee, V., 2005. The Photovoltaic water pumping system using optimum slip control to maximum power and efficiency. *Power Tech, IEEE Russia* , vol., no., pp.1-4, June 27-30.

Brian D. Vick, Byron A. Neal, 2012. Analysis of off-grid hybrid wind turbine/solar PV water pumping systems. *Solar Energy,* Volume 86, Issue 5, Pages 1197-1207,May.

David D. Lara, Gabriel G. Merino, Boris J. Pavez, Juan A. Tapia, 2011. Efficiency assessment of a wind pumping system. *Energy Conversion and Management*, Volume 52, Issue 2, Pages 795-803, February.

Elgendy M., Zahawi B., and Atkinson D., 2010. Comparison of Directly Connected and Constant Voltage Controlled Photovoltaic Pumping Systems", *IEEE Transactions on Sustainable Energy*, Vol. 1, No. 3, October.

Ben Rhouma, A., Belhadj, J., and Roboam X., 2010. A pumping system fed by hybrid photovoltaic-wind sources without battery storage Bond graph modeling, control and energy management. *International Conference on Integrated Modeling and Analysis in Applied Control and Automation (IMAACA)* October 13-15, Morocco.

Ben Rhouma, A., Belhadj, J., and Roboam X., 2008. Control and energy management of a pumping system fed by hybrid Photovoltaic-Wind sources with hydraulic storage: - Static and dynamic analysis - "U/f" and "F.O.C" controls methods comparisons. *Journal of electrical system (JES*, volume 4 issue 4*)*, December.

EFFECTIVE USE OF RESOURCES IN CLOSED VALUE NETWORKS

Braun Anja-Tatjana[a], Mandel Joerg[b], Bauernhansl Thomas[c]

[a] [b] [c] Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Nobelstrasse 12, 70569 Stuttgart, Germany

[a]Anja-Tatjana.Braun@ipa.fraunhofer.de, [b]Joerg.Mandel@ipa.fraunhofer.de, [c]Thomas.Bauernhansl@ipa.fraunhofer.de

ABSTRACT

Currently, almost 60 billion tons of commodities are consumed worldwide each year. The effective use of resources is, therefore, an important key factor for sustainable development. Integrating recovered material at the end of the product's utilization phase into an existing production network can make a significant contribution to the effective use of resources. This paper proposes a methodology to manage inventory levels in order to enable the direct reuse of products considering reverse material flows in the calculations.

Keywords: closed value networks, effective use of resources, reverse material flows

1. INTRODUCTION

Raw materials and disposal capacities are resources that are not infinitely available. The limit to the availability of raw materials also imposes a limit to growth because entire industries depend on raw materials as a basis of modern technologies. For example, a single ton of mobile phones contains about 300 grams of gold. In the mining industry, one ton of rock needs to be processed to get one gram of the precious metal (Rothe 2010). However, at the end of the utilization phase most mobile phones are disposed in the general waste or remain with their owners without being used. Accordingly, the raw materials contained in the used products are not available to us for a long time. Similarly, solar cells do not work without indium, and without lithium there is no electromobility. The integration of reverse material flows into production networks, however, is not only driven by ecological and economic reasons. Environmental legislation and marketing strategies are also advocating a modern circular economy (Inderfurth 2004). The efficient management of the reverse flow or (re-)use of used products creates significant savings and hence competitive advantages. The real benefit to companies is that material costs are reduced, less waste is produced and output is improved while fewer resources are used. But also producer responsibility is increased to better comply with regulatory guidelines and, last but not least, a major contribution is made to life cycle assessment. This is why new and innovative ways are needed to efficiently use raw materials.

Reverse material flows often pose particular problems on companies, as the reverse flows need to be integrated or newly created and coordinated with the existing production network. Lack of planning reliability, specific customer needs, competitive dynamics and regulatory intervention into the market economy are additional challenges to which companies must respond adequately and without delay. Thus, methods to cultivate complexity in order to cope with these challenges are needed.

If direct reuse is to become an integral part of economy, it is necessary to calculate customer demand while taking the inventory levels and the expected future return flows into account. Prerequisite is an optimal inventory management. The focus of this paper lies on the specification of inventory levels considering reverse material flows for the direct reuse of mobile and durable capital goods, such as construction or production equipment.

2. STATE OF THE ART

For a long time now, the typical approach of businesses in the manufacturing industry has been to ignore used products (Thierry, Salomon and Van Nuen 1995). In recent years, however, this attitude has completely changed. At present, most recycling for the sustainable use of raw materials is actually downcycling, which merely delays the disposal as waste. Examples for this approach are polystyrene used as porosity-enhancing additive in bricks; polyester used as insulating material made of recycled fibers; or PET plastic bottles for the manufacture of benches. To counteract this tendency, it is essential to hold products in the economic system as long as possible and at the highest possible level of value creation. The cradle-to-cradle design developed by Braungart and McDonough is an important approach that imitates natural models for the design of production systems to achieve environmental and commercial advantages (Braungart and McDonough 2009). This approach describes the conditions under which both technological and biological cycles are economically viable. Guide and van Wassenhove claim that the reverse flow and the reuse of products help to combine economic goals with sustainable management (Guide and van Wassenhove 2009). The integration of reverse material flows, however, increases the complexity of the planning process. Closed value chains across multiple business units require an interdisciplinary perspective and appropriate planning and control methods (Abbey and Guide 2012). A challenge in the modeling process is to consider uncertainties resulting from the implementation of reverse material flows. These uncertainties have to do with deadlines, quantities, or quality, and increase complexity within the system (Spengler, Stölting and Ploog 2004). In science, numerous deterministic models exist for the planning and control of closed value networks, but they do not take full account of the diversity of the uncertainty values. Stochastic models, by contrast, use vectors to integrate and consider the entire range of uncertainty values within the model. At the moment, only few approaches focus on the integrated planning of closed value networks and not only on a specific operational issue (Ilgin and Gupta 2010). This paper describes a stochastic approach that takes into account not only profit maximization at optimum inventory levels but also environmental aspects as well as uncertainties.

3. RESOURCE EFFICIENCY THROUGH DIRECT REUSE

Berger and Finkbeiner define raw material efficiency as the ratio between economic value added and raw material input (Berger and Finkbeiner 2008). With direct reuse, the added value remains constant while the resource input is reduced, thanks to the fact that a product may have multiple temporary uses. This way, closed value networks are evolving that can be integrated into the existing production network and are independent of external service providers.

This approach holds great potential especially with a view to durable and mobile capital goods, for example machinery, construction or electrical equipment. In case of such products, the life cycle of entire products, individual assemblies, or components does not come to an end after the use phase but instead they can be offered for reuse.

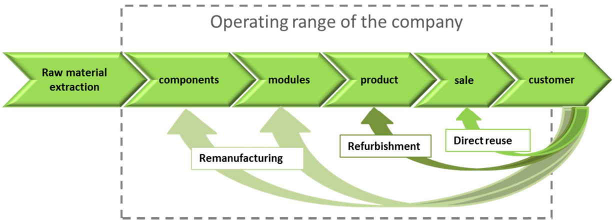


Figure 1: Operating range of companies

At the end of their service life, the products are returned to the manufacturers, who, depending on the condition of the products, decide whether they can be directly reused, if they need refurbishment or if individual components have to be remanufactured. The challenge in planning materials with different flow directions is to identify the optimum inventory level for a company in order to meet demand in an economically optimal way. The role of material flows is essential here, because the reverse material flows of the future will be included in scheduling to meet customer demand.

4. A METHOD FOR THE DETERMINATION OF COST-EFFECTIVE INVENTORY LEVELS CONSIDERING REVERSE MATERIAL FLOWS

It is a complex task to find the right balance in determining cost-effective inventory levels. With direct reuse, complexity rises because of the reverse material flows. To manage the processes while keeping the planning effort low, a defined description of the procedure is required. The objective is to increase the efficiency of the planning process that determines the inventory levels, while taking the reverse material flows into account.

This approach introduces a simple model of a Markov chain indicating the probability of events occurring in the future (Moellering 2007). The factors influencing the inventory levels of direct-reuse products are described in the following. An important parameter in the calculation of the optimal inventory level is customer demand. Being a random variable, it is expressed by the parameter λ as specified by the Poisson distribution. A Poisson process is a stochastic process named after Siméon Denis Poisson. It counts the frequency of certain random events in a given time interval, where N(t) indicates the number of events in the time interval [0,t]. With direct reuse, the temporary periods of use cannot be calculated so that they are specified as $^{1}/_{\mu}$ periods, while π indicates the probability of material availability for direct reuse. The amount paid by the customer for the time a product is used is defined as p. If no products are available for direct reuse, it is assumed that the customer is not willing to wait. It should be noted that it is always the responsible staff member who decides how to manage the reverse material flows. If an order request comes in for which the customer is not willing to wait and no item is on stock and/or the scheduled reverse material flows are delayed, then a decision must be made whether to release a production order or to reject the order request. However, material not sold to a customer will entail warehousing costs of c per period. These costs involve, for instance, tied-up capital or depreciations.

The physical inventory at the time of t is described by the parameter M_t. The inventory currently available is described by $M_t^+ = \max\,[0,M_t]$, while the unfulfilled customer demand is defined by $M_t^- = -\min\,[0,M_t]$.

The key question to be answered is: „How much material for direct reuse should be stockpiled to be able to fill customer demand in the best possible and most economically advantageous way".

The probability of material availability $\pi_0, \pi_1, \ldots, \pi_M$ can be deduced using the following system of linear equations (Arnold and Furmans 2005).

$$\lambda\pi_1 = M\mu\pi_0 \tag{1}$$

$$\pi_i(\lambda + (M - i)\mu) = (M - i + 1)\pi_{i-1} + \lambda\pi_{i+1} \tag{2}$$

$$i = 1, \ldots, M - 1$$

$$\lambda\pi_M = \mu\pi_{M-1} \tag{3}$$

The probability of material availability π_i can change if material is taken out of stock or added to stock from reverse material flows. These two states are equal to $i - 1$ and $i + 1$, dependent on i. Considering

$$\pi_i = \frac{M!}{(M-i)!}\left(\frac{\mu}{\lambda}\right)^i \pi_0 \tag{4}$$

together with

$$\sum_{i=0}^{M} \pi_i = 1 \tag{5}$$

allows deducing the following probability of the target function:

$$\pi_0 \left[\sum_{i=0}^{M} \frac{M!}{(M-i)!(\frac{\mu}{\lambda})^i}\right]^{-1} \tag{6}$$

Taking this as a basis, the following formula is used to determine the most economically advantageous inventory level $RS(M)$ for direct reuse.

$$RS(M) = -cM + \lambda p(1 - \pi_0(M)) \tag{7}$$

The profit gained from direct reuse depends on customer demand and thus on sales and the probability of material availability $(1 - \pi_0)$ at the time of customer demand after deduction of the warehousing costs. Accordingly, the optimum inventory level M should be increased as long as the resulting profit is rising. The next section will present a case study to illustrate the applicability of the approach.

4.1. Case study

This case study assumes that 10 customer order requests are received every month $(\lambda = 10)$. The average temporary period of use by the customer is 3 months $(\mu = 0{,}25)$. The probability of material availability can be deduced from customer demand (i.e. the number of customer order requests) and the average temporary period of use. In this case, the calculation is $\pi_0 = 0{,}36016444$. Monthly costs for depreciation, inventory holding, etc., amount to €100 $(c = 100)$. The monthly revenue from direct reuse amounts to €120 $(p = 120)$.

$$\mathrm{RS(M)} = (120 - 100) * 30 - 120(1{,}97791872)$$
$$\mathrm{RS(M)} = 600 - 237{,}3502464$$
$$\mathrm{RS(M)} = 362{,}6497536$$

The maximum profit to be achieved for the given assumptions is €362.65. From this, it can be concluded that the optimum inventory level for fulfilling customer demand in the best possible way, while achieving maximum profit, is achieved at $M = 30$. Figure 1 shows a curve indicating the optimum of profit and inventory levels.

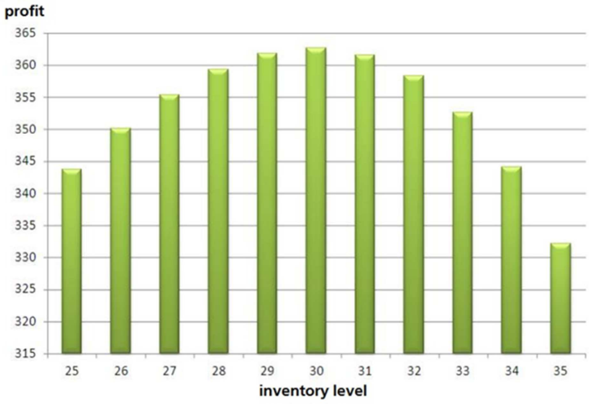


Figure 2: Ratio of inventory to profit in closed value networks

This approach is also applicable for equipment from the energy sector, which is available for temporary use. For example, mobile biomass heating systems or energy storage media in form of batteries can be provided to customers in a flexible and temporary way. Using the described approach, the revers material flows can be calculated and effectively used in closed value networks without reducing the value level. Consequently, a sustainable development in providing renewable energy and a valuable contribution to the environmental performance is being made.

5. CONCLUSION

The presented approach can be used to determine an optimum inventory level taking direct reuse into account. To this end, a stochastic approach considers the occurrence probability for reverse material flows. As direct reuse is not limited to a specific industry, the procedure can be applied to any inventories of durable and mobile capital goods. In addition, the procedure helps to master the complexity in planning and controlling closed value networks. Reduced material consumption, an increase in sales at constant resource deployment, and a reduction of the amount of waste generated are only a few of the possible benefits to companies resulting from direct reuse. Customers profit from the flexibility offered by direct reuse, which allows them to use material temporarily and to pay only for the period of utilization. To ensure a sustainable circular economy and a more effective use of raw materials, it is necessary to address the issue very early at the product development stage. Products must be designed so that they do not become waste and that, after the use phase, the contained raw materials can be continuously and, if possible, fully reused at the same quality. The long-term objective is to make sure that 100 percent of the material inputs end up in the product and are not turned into waste or emissions.

AUTHORS BIOGRAPHY

M. Sc. Anja-Tatjana Braun, born 1985, studied computer science economy at Reutlingen University. Since February 2011, she has been a research assistant at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart.

Dr.-Ing. Jörg Mandel finished his engineering studies at the University of Stuttgart in November 1999 and has has been working at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Stuttgart since then. As a group leader, he worked for several years for planning and implementation of just-in-time and just-in-sequence concepts, standardization and optimization of logistics processes along the entire value chain. After completing his doctorate in the field of supply chain management and production optimization, he has managed the "Department of Sustainable Production and Quality" since 2012.

Since September 2011, **Univ.-Prof. Dr.-Ing. Thomas Bauernhansl** has been director of the Institute of Industrial Manufacturing and Management (IFF) at the University of Stuttgart and director of the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart, Germany. Additionally, he has been temporary director of the Institute of Energy Efficiency in Production (EEP) at the University of Stuttgart, since October 2012.

Prof. Bauernhansl has eight years of working experience in the German automotive and mechanical engineering industry. As researcher at the RWTH Aachen as well as in industry he was involved in numerous R&D-projects and the application of new manufacturing technologies and concepts. Before September 2011 he was Head of Global Process Technology with Freudenberg Sealing Technologies (among others, an automotive supplier) at worldwide 50 facilities.

REFERENCES

Abbey, J.D., Guide, V.D.R., 2012. Closed-Loop Supply Chains. In: P. Bansal, A.J. Hoffman, eds. *The Oxford Handbook of Business & the Natural Environment*. New York: Oxford University Press, 290-309

Arnold, D., Furmans, K., 2005. *Materialfluss in Logistiksystemen*. 4th ed. Berlin, Heidelberg: Springer Verlag.

Berger, M., Finkbeiner, M., 2008. Methoden zur Messung der Ressourceneffizienz. In: K.J. Kozmiensky, D. Goldmann, eds. *Recycling und Rohstoffe*. Neuruppin: TK-Verlag, 107-130.

Braungart, M., McDonough, W. 2009. *Cradle to Cradle – Remaking the Way We Make Things*. London: Vintage Books.

Guide, V.D.R., van Wassenhove, L., 2009. The Evolution of Closed-Loop Supply Chains. *Operations Research* 57 (1), 10-18.

Ilgin, M.A., Gupta, S.M., 2010. Environmentally conscious manufacturing and product recovery (ECMPRO): A review of the state of the art. *Journal of Environmental Management* 91 (3), 563-591.

Inderfurth, K., 2004. Product Recovery Behavior in a Closed-Loop Supply Chain. In: H. Dyckhoff, R. Lackes, J. Reese, eds. *Supply Chain Management and Reverse Logistics.* Heidelberg: Springer Verlag, 91-114.

Moellering, K., 2007. *Inventory Rationing – A New Modelling Approach Using Markov Chain Theory*. Thesis (PhD). Wilhelms-Universität Münster.

Rothe, P., 2010. *Schätze der Erde – Die faszinierende Welt der Rohstoffe*. Darmstadt: Primus Verlag.

Spengler, T., Stölting, W., Ploog, M., 2004. Recovery Planning in Closed Loop Supply Chains. In: H. Dyckhoff, R. Lackes, J. Reese, eds. *Supply Chain Management and Reverse Logistics.* Heidelberg: Springer Verlag, 61-89.

Thierry, M., Salomon, M., Van Nuen, J., 1995. Strategic Issues in Product Recovery. *California Management Review* 37 (2), 114-135.

ELECTRO-THERMAL SIMULATION OF LITHIUM ION BATTERIES FOR ELECTRIC AND HYBRID VEHICLES

Zul Hilmi CHE DAUD[(a)], Daniela CHRENKO[(b)], Fabien DOS SANTOS[(c)], El-Hassane AGLZIM[(d)] , Luis LE MOYNE[(e)]

[(a)]IEEE Student Member. Mechanical Engineering Faculty,
University of Technology Malaysia, 81310 Skudai, Johore, Malaysia.
[(b)]IEEE Member.
[(a), (b), (c), (d), (e)]DRIVE Laboratory, Institut Supérieur de l'Automobile et des Transports (ISAT),
University of Burgundy, 49 rue Mlle Bourgeois, 58027 Nevers, France.

[(a)]hilmi@fkm.utm.my, [(b)]daniela.chrenko@u-bourgogne.fr, [(c)]fabien.dos-santos@u-bourgogne.fr,
[(d)]el-hassane.aglzim@u-bourgogne.fr, [(e)]luis.le-moyne@u-bourgogne.fr

ABSTRACT

A lithium ion battery is analyzed with regard to its thermal behaviour using modelling. Therefore resistive energy losses are translated into generated heat inside the battery, which is evacuated by forced convection, thus forming an electro-thermal model. Based on that model, simulations are done using OpenFOAM. The simulation underlines the observation that batteries have higher temperature close to the connectors and that temperature increase depends highly on discharge rate.

Keywords: electric and hybrid vehicle, lithium ion battery, thermal electric modelling

1. INTRODUCTION

In electric and hybrid vehicles, batteries are among the most important key components which must continually accept and provide electrical energy by transforming chemical energy into electrical energy and vice versa (Ehsani et al. 2005, Larminie and Lowry 2003). Batteries are desired to have high specific power, high specific energy, long calendar and cycle life, low initial and replacement cost, high reliability and high robustness.

Most commonly used batteries are lead-acid, nickel-cadmium, nickel-metal hydride and lithium-ion battery (Guzzella and Sciarretta 2007). Since the beginning of automotive engineering the lead acid battery is the most used type of battery. It is still used in almost every car for the 12V electric power supply. Due to its limited specific energy it has been replaced by Nickel-Metal Hydride batteries for hybrid application for example in the Toyota Prius (Toyota motor sales 2013).

Finally Lithium based batteries propose higher specific energy, but they have to be supervised and controlled carefully, in order to assure their operation (Shafiei et al. 2011, Väyrynen and Salminen 2012). Figure 1 shows the volumetric energy density against gravimetric energy density for common batteries (Amjad et al. 2010, Väyrynen and Salminen 2012), and figure 2 shows the Ragone plot of specific power density versus specific energy density of various electrochemical energy storage and conversion devices (Pollet et al. 2012).

Lithium-ion batteries are therefore likely a good choice for electric and hybrid vehicles due their superior properties such as high power rating, high energy density, and high cycle life (Ehsani et al. 2005, Chacko and Chung 2012, Larminie and Lowry 2003, Sen and Kar 2009, Urbain et al. 2007) and they are considered as the most promising technology in the next decades (Gerssen-Gondelach and Faaij 2012).

The temperature is one of the parameters of a lithium ion battery that has to be controlled carefully, as the optimum working region is normally limited between 20°C and 65°C (Abdul-Quadir et al. 2011, Al-Hallaj and Selman 2002, Baronti et al. 2010). Furthermore, the working temperature of the lithium ion battery has a big influence on its internal resistance, hence efficiency, cell degradation, and hence life time.

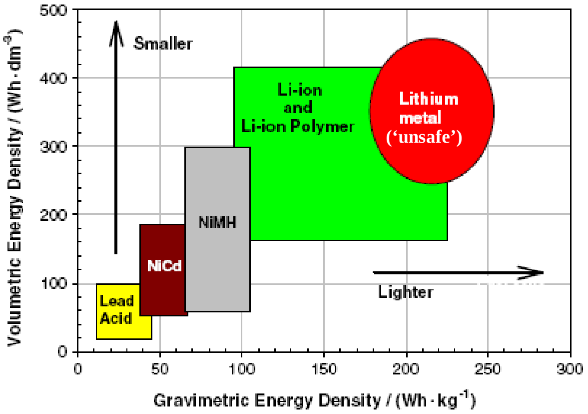


Figure 1: Plot of Volumetric Energy Density against Gravimetric Energy Density for Common Batteries (Amjad et al. 2010, Vayrynen and Salminen 2012)

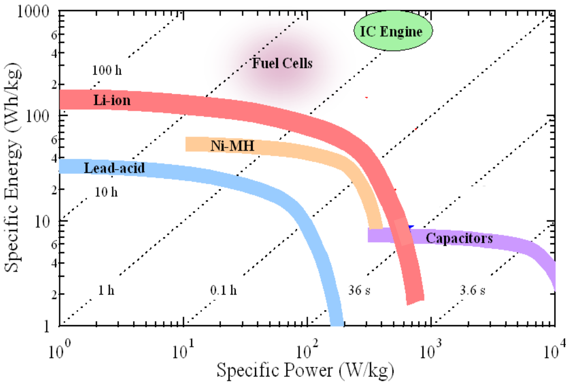


Figure 2: Ragone Plot of Specific Power Density vs. Specific Energy Density of Various Electrochemical Energy Storage and Conversion Devices (Pollet et al. 2012)

This is why an electro-thermal model is presented. First the physical behaviour of a lithium ion battery is described, followed by and introductions to its electro-thermal modelling as well as the modelling software OpenFOAM, which provides the possibility to integrate electric behaviour, like heat generation due to electric resistance into a CFD model. Results for different working conditions are presented in section 3. The article closes with conclusions and perspectives.

2. THERMO ELECTRIC DESCRIPTION

2.1. Thermo Electrical Description of Battery

There are basically four main methods in battery modelling (Bhide and Shim 2011, Tan et al. 2011): mathematical models, electrochemical models, polynomial-based models and electrical models.

Mathematical models are the easiest but the least accurate model (Tsang et al. 2010). It cannot provide any I-V information and most of them only work for specific applications (Bhide and Shim 2011). Electrochemical models, based on chemical reactions occurring inside the battery cells (Shafie et al. 2011), are complex and time consuming but able to produced more accurate result. Polynomial-based models use a simplistic expression containing state of charge (SOC) to represent a battery. These models have limited capacity in presenting the I-V information (Bhide and Shim 2011).

Electrical models are based on a combination of voltage sources and other electrical components such as resistors, and capacitors that describe the electrochemical processes and dynamics of a battery (Shafie et al. 2011, Tsang et al. 2010). Electrical models are more realistic, intuitive, and easy to handle as compared to other models. Furthermore, it can be applied to any battery model irrespective of its chemistry, configuration and rate of discharge; by using suitable combination of parameters (Tan et al. 2011).

Most of the existing electrical models can be grouped into three main basic categories, which is Thevanin-based models, impedance-base models, and runtime-based models (Chen and Rincon-Mora 2006). Thevanin-based models use series resistor and RC parallel network(s) to predict the battery response to transient load events. Impedance-based models use electrochemical impedance spectroscopy method to obtain an equivalent impedance model in the frequency domain, and then use a complicated equivalent network to fit the impedance spectra. On the other hand, runtime-based models use a complex circuit network to represent the battery runtime and voltage response for a constant discharge current (Chen and Rincon-Mora 2006). Figure 3 shows a simple electrical equivalent circuit model for a single lithium-ion battery cell as proposed by Thirugnanam et al. (Thirugnanam et al. 2012). This model consists of series resistor R_s, and an RC parallel network composed of R_1 and C_1.

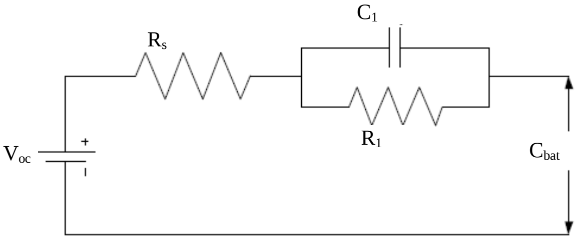


Figure 3: Single Cell Electrical Equivalent Circuit Model (Thirugnanam et al. 2012)

Temperature is an important factor that affects the battery pack performance and life time (Shafie et al. 2011). It is proved experimentally that for the increase of each 10°C in the operating temperature compared to the nominal temperature of the designed battery pack, the life cycle of the batteries will reduce approximately to half of the nominal life cycle (Shafie et al. 2011). Furthermore, temperature of each battery cell is different throughout the battery pack depending on the battery pack design.

The difference in temperature between the individual cells in a battery pack might be the result of the difference of forced convection at the various points of the battery pack surface, which is caused by the different conditions of air speed and initial air temperature. Another reason is non-uniform impedance distribution among cells, and difference in heat transfer efficiency among cells (Al-Hallaj and Selman 2002). Non-uniform impedance may result from defects in quality control and also difference in local heat transfer rate. While, the differences in heat transfer efficiency depends on where the cell is positioned in the battery pack.

The temperature difference may then lead to further difference in impedance which amplifies the capacity imbalance among the cells that further causes the cells to be over-charged or over-discharged during cycling (Abdul-Quadir et al. 2011, Al-Hallaj and Selman 2002). This is the major contribution to premature failure in the battery packs in form of thermal runaway or accelerating capacity fading (Abdul-Quadir et al. 2011, Al-Hallaj and Selman 2002). The BMS (battery management system) is intended to provide a supervision of the individual cells in order to improve the battery pack performance and decrease risks. The supervision provided by the BMS includes not only the cell voltage, charging and discharging current, but can also include an interface to the cooling system (Martel et al. 2011, Sen and Kar 2009, Shafie et al. 2011).

2.2. Thermal Modelling

Thermal modelling of the battery packs is very important, helping in designing battery management systems for better performance such as to prevent battery degradation and extend battery lifetime (Martel et al. 2011) and also preventing safety risks such as thermal runaway (Shafie et al. 2011). An accurate thermal model of battery packs (Shafie et al. 2011) and the individual cell is very important in order to illustrate the real condition of the battery temperature and prevent any potential abuse (Sen and Kar 2009, Vayrynen and Salminen 2012).

The local heat generation in the battery cell due to the electrochemical reactions and mass transfer of ions in the electrolyte can be characterized by local internal resistance and the current densities (Chacko and Chung 2012). The battery cell temperature is calculated based on internal energy balance that can be described by:

$$m \cdot C_p \cdot \frac{dT(t)}{dt} = R \cdot i^2(t) - (Q_{conv} + Q_{rad}) \quad (1)$$

Where m stands for the cell mass (kg), C_p is the specific heat capacity (J/kg.K), T the cell temperature (K), i the charge/discharge current (A), and R the cell internal resistance (Ω). Q_{conv} represent the convection heat energy, and Q_{rad} the radiation heat energy.

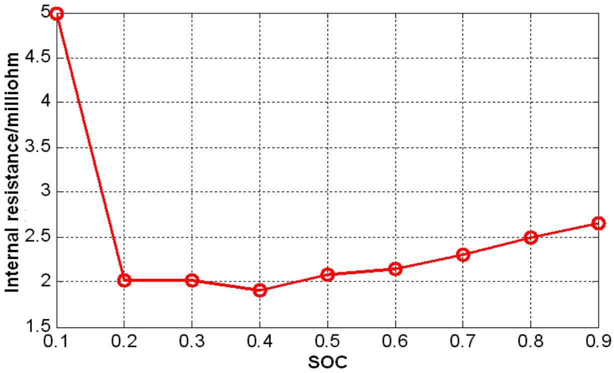


Figure 4: Relationship of Internal Resistance and SOC (Lin et al. 2009)

Generally, the battery internal resistance, R is described as a function of battery state of charge (SOC) (Chen and Rincon-Mora 2006, Kroeze and Krein 2008, Lin et al. 2009). The value of resistance is approximately constant over 20% to 90% SOC as shown in figure 4. The battery internal resistance also varies with temperature. Figure 5 illustrates the effect of temperature on the variation of the battery internal resistance as presented by Sen and Kar (Sen and Kar 2009). It shows that the battery resistance slightly changes with the change of the battery temperature (Sen and Kar 2009).

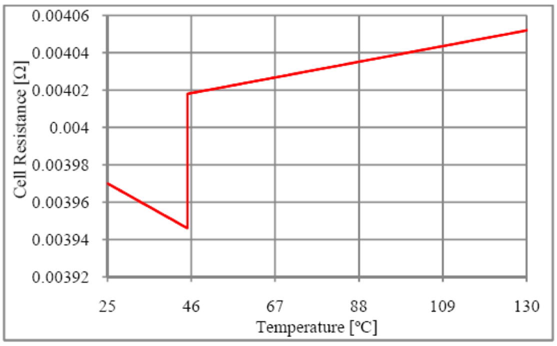


Figure 5: Cell Resistance Variations with Temperature (Sen and Kar 2009)

In this project the value of internal resistance will be first considered as constant for an easier model manipulation. This is justified by the fact that the battery normally will not be fully discharge (not less than 20% SOC) to avoid any potential damage to the battery, where the resistance is approximately constant over 20% to 90% SOC as shown in figure 4. Also, from figure 5 we can conclude that the variation of resistance in the temperature range of 25 °C to 130 °C is less than 1.8 % from its initial value at the temperature of 25 °C. Here, 2 mΩ is used as the battery internal resistance.

The convection heat transfer, Q_{conv} of the battery cell surface can be expressed as in equation 2 (Mousavi et al. 2012, Tan et al. 2011).

$$Q_{conv} = hA(T_s - T_c) \quad (2)$$

Where h represent the convective heat transfer coefficient (W m^{-2} K^{-1}), A the cell surface area (m^2), T_s the cell surface temperature (K) and T_c the cooling air temperature (K). The convective heat transfer coefficient depends on the cooling fluid and the types of fluid flow (Tan et al. 2011). In this work, air is used as the cooling fluid. Here the convection type can be considered as force convection as moving air is introduced to the system. The radiation heat transfer is ignored in this stage of work because it is less significant as compared to force convective heat transfer.

During charge/discharge process, all the current flows to the positive and negative terminal from the entire electrode plate (Kim et al. 2009). Thus, the current densities and consequently the temperature of positive and negative terminal are higher than the other parts of the battery cell (Kim et al. 2009). Furthermore, the temperature at the positive terminal is higher than the negative terminal due to lower electrical conductivity of the positive electrode, despite the fact that the current flow in both terminal are similarly high (Chacko and Chung 2012).

2.3. OpenFOAM

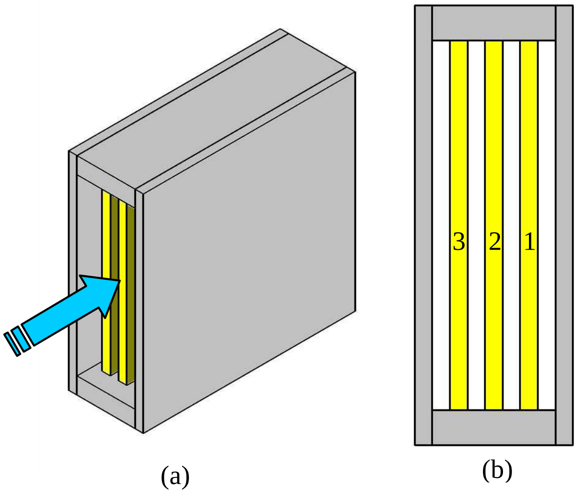
OpenFOAM is a free, open source CFD software package produced by OpenCFD Ltd for numerical simulation written in the C++ programming language (OpenCFD Ltd., 2011). OpenFOAM is gaining popularity in both academic research and industrial users (Jasak et al. 2007). This is because of several factors:

- Free, open source software, meaning that complete source code is available to all users at no cost.
- Flexibility and extensive capability, where users are free to customize and extend its existing functionality.
- Capability to solve complex problems from complex fluid flows, solid dynamic to electromagnetic that can level up with commercial CFD.
- Expressive and versatile syntax, allowing easy implementation of complex physical model.

2.4. Modelling Conditions

In this project, a three cells lithium ion battery pack is modelled using OpenFOAM. The cells are arranged in parallel to each other in a battery box, as shown in figure 6. The blue flesh shows the airflow direction. The battery cells are connected in series electrical connection. The space between each cell is 10 mm to allow the air to circulate and act as forced cooling system that takes the heat from cell surface to the environment.

The battery cells used in this project are Kokam SLPB 100216216H cells and have a typical capacity of 40 Ah and nominal voltage of 3.7 V. Each cell has a weight of 1.1 kg with dimensions of 10 mm thickness, 215 mm width, and 210 mm length as shown in figure 7. Cell properties such as density, thermal conductivity and specific heat capacity are assumed to be uniform throughout the battery and to remain constant within a known range of temperature.



(a) (b)

Figure 6: 3 battery cells arranged in a box with (a) represent the isometric view and (b) the front view

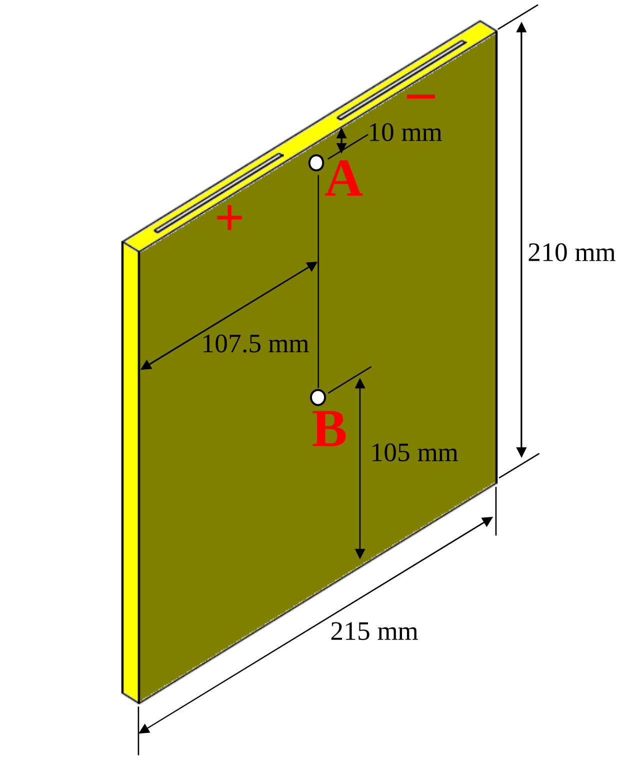


Figure 7: Battery Cell Parameters

3. RESULTS AND DISCUSSION

Figure 8 shows the surface temperature of the 1st battery cell at the end of discharge with 5C discharge rate. Here, a constant air velocity at inlet of 3 m/s and air at ambient temperature is used as a cooling system. We considered that the ambient air temperature is at 25 °C.

It can be seen that the temperature near the battery positive and negative terminal is higher than at the other location on the cell surface. This is due to different current densities at cell terminal and electrode plate as explained in section 2.2. The temperature near the positive terminal is also higher than at the negative terminal. Figure 9 shows the airflow inside the battery box and between the battery cells. The value of air velocity between the battery cells is higher than the initial inlet velocity due to the reduced in volume.

Figure 10 shows the temperature cell surface of the 1st battery cell at two different points A and B (as marked in figure 7) for different discharge rate of 1C, 3C, and 5C. The battery cell have a typical capacity of 40 Ah, so it means that at 1C rate the discharge current is 40A, 120A for 3C and 200A for 5C. Here, the inlet air velocity is fixed at 3 m/s at ambient temperature. The same type of temperature evolution is also observed by Kim et al. (Kim et al. 2009). This shows that the battery temperature is much infected by the amount of discharge rate. Higher discharge rate generates more heat and thus increases the temperature.

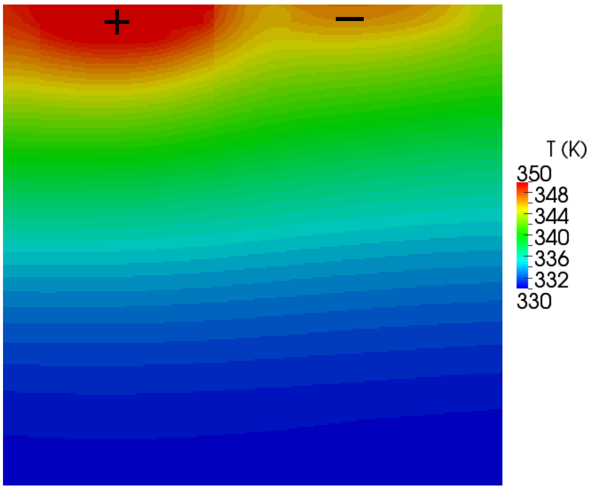


Figure 8: Surface Temperature of Battery Cell

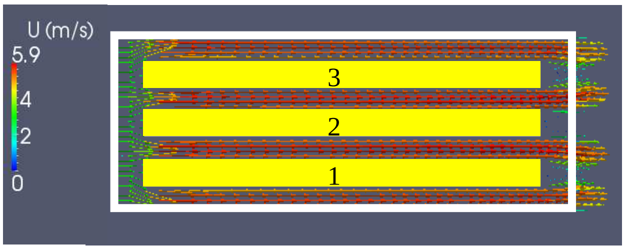


Figure 9: Air Flow between Battery Cells in the Battery Pack

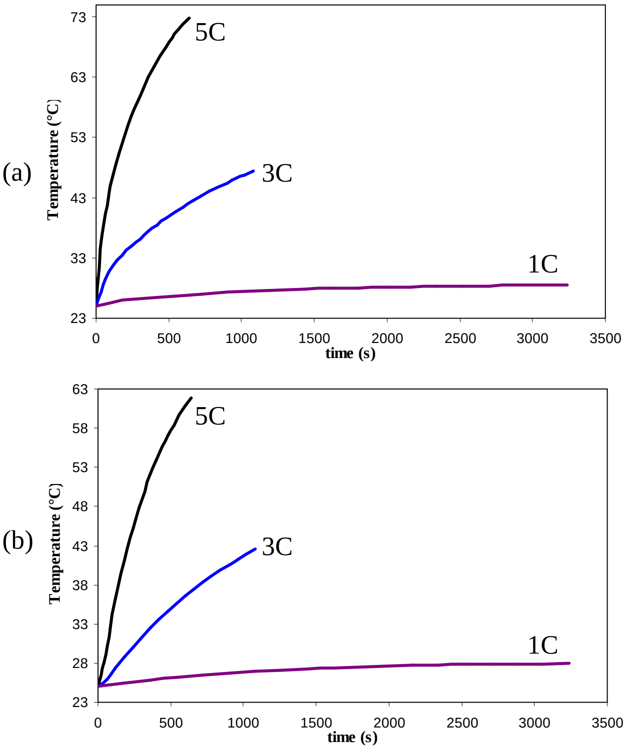


Figure 10: Cell Surface Temperature (a) at Point A and (b) at point B for Different Discharge Rate

To see the effect of cooling system on the battery temperature, we have run a set of simulation with 3 different cooling air initial temperatures which is the ambient temperature, 15°C and 5°C. At the same time the air inlet velocity is maintain at 3 m/s, and the discharge rate is fixed at 5C. Figure 11 shows the surface temperature evolution of 1^{st} cell at point A for different cooling air temperature. It shows a strong increase of temperature at the beginning of discharge process for all three cases. Higher cell surface temperature increase is observed at higher cooling air temperature. By using cooling air at ambient temperature, the cell surface temperature increase to more than 70°C at the end of discharge process, which is over the save working limit of battery. This shows that at higher discharge rate (5C), the cooling air of 3 m/s at ambient temperature is insufficient to keep the battery in save working region. An additional cooling is needed for this purpose.

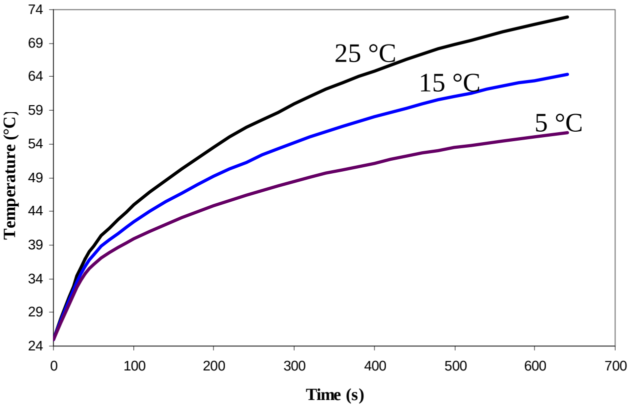


Figure 11: Cell Surface Temperature at Point A with Different Cooling Air Temperature

4. CONCLUSION AND PERSPECTIVES

A thermo-electric modelling of a lithium ion battery for automotive applications is presented. An electric equivalent description including temperature dependence is implemented in OpenFOAM, an open source CFD software, providing the possibility to link thermal losses inside the battery cells to forced convection of an air stream. The simulation results confirm observations from experimental results were the temperature is higher close to the connectors. Also there is a strong link between the discharge rate and the temperature decrease.

In the following the theoretical studies will be continued with regard to different aspects like air velocity and validated using experimental results, before drawing conclusions toward the improvement of the cooling of lithium ion batteries for automotive applications.

ACKNOWLEDGMENTS

Authors wish to thank Burgundy region council (CRB), Malaysian Government and UTM (University of Technology Malaysia) for continuous support.

REFERENCES

Abdul-Quadir, Y., Heikkila, P., Lehmuspelto, T., Karppinen, J., Laurila, T., and Paulasto-Krockel, M., 2011. Thermal investigation of a battery module for work machines. *Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems Conference (EuroSimE)*, pp. 1-6. April 18-20, Palais Kaufmannischer Verein (Linz, Austria).

Al-Hallaj, S. and Selman, J. R., 2002. Thermal modeling of secondary lithium batteries for electric vehicle/hybrid electric vehicle applications. *Journal of Power Sources*, 110: 341–348.

Amjad, S., Neelakrishnan, S. and Rudramoorthy, R., 2010. Review of design considerations and technological challenges for successful development and deployment of plug-in hybrid electric vehicles. *Renewable and Sustainable Energy Reviews*, 14: 1104–1110.

Baronti, F., Fantechi, G., Leonardi, E., Roncella, R., and Saletti, R., 2010. Effective modeling of temperature effects on lithium polymer cells. *International Conference on Electronics, Circuits, and Systems (ICECS)*, pp. 990-993. December 12-15, Athens, Greece.

Bhide, S. and Shim, T., 2011. Novel predictive electric li-ion battery model incorporating thermal and rate factor effects. *IEEE Transactions on Vehicular Technology*, 60: 819 – 829.

Chacko, S. and Chung, Y.M., 2012. Thermal modelling of li-ion polymer battery for electric vehicle drive cycles. *Journal of Power Sources*, 213: 296–303.

Chen, M. and Rincon-Mora, G.A., 2006. Accurate electrical battery model capable of predicting runtime and i-v performance. *IEEE Transactions on Energy Conversion*, 21(2): 504–511.

Ehsani, M., Gao, Y., Gay, S.E. and Emadi, A., 2005. *Modern Electric,Hybrid Electric, and Fuel Cell Vehicles*. USA: CRC Press.

Gerssen-Gondelach, S.J. and Faaij, A.P.C., 2012. Performance of batteries for electric vehicles on short and longer term. *Journal of Power Sources*, 212: 111–129.

Guzzella, L. and Sciarretta, A., 2007. *Vehicle Propulsion systems (Introduction to Modelling and Optimization)*. 2nd ed. New York: Springer.

Jasak, H., Jemcov, A., and Tukovic, Z., 2007. Openfoam: A c++ library for complex physics simulations. *International Workshop on Coupled Methods in Numerical Dynamics*, pp. 1-20. September 19-21, Dubrovnik, Croatia.

Kim, U.S., Shin, C.B. and Kim, C., 2009. Modeling for the scale-up of a lithium-ion polymer battery. *Journal of Power Sources*, 189(1): 841–846.

Kroeze, R.C. and Krein, P.T., 2008. Electrical battery model for use in dynamic electric vehicle simulations. *Power Electronics Specialists Conference(PESC)*, pp. 1336-1342. June 15-19, Rhodes, Greece.

Larminie, J. and Lowry, J. 2003. *Electric Vehicle Technology Explained*. 1st ed. West Sussex, England: John Wiley & Sons Ltd.

Lin, C., Chen, K., Sun, F., Tang, P. and Zhao, H., 2009. Research on thermo-physical properties identification and thermal analysis of ev li-ion battery. *IEEE Conference on Vehicle Power and Propulsion (VPPC)*, pp. 1643-1648. September 7-11, Dearborn.

Martel, F., Dube, Y., Boulon, L. and Agbossou, K., 2011. Hybrid electric vehicle power management strategy including battery lifecycle and degradation model. *Vehicle Power and Propulsion Conference (VPPC)*, pp. 1-8. September 6-9, Chicago, USA.

Mousavi, M., Hoque, S., Rahnamayan, S., Dincer, I. and Naterer, G.F., 2011. Optimal design of an air-cooling system for a Li-ion battery pack in electric vehicles with a genetic algorithm. *IEEE Congress on Evolutionary Computation (CEC)*, pp. 1848-1855. June 5-8, New Orleans, USA.

OpenCFD Ltd., 2011. *The OpenFOAM Foundation*. OpenCFD Ltd. Available from: http://www.openfoam.org [accessed 25 March 2013]

Pollet, B.G., Staffell, I. and Shang, J.L., 2012. Current status of hybrid, battery and fuel cell electric vehicles: From electrochemistry to market prospects. *Journal of Electrochimica Acta*, 84: 235–249.

Sen, C. and Kar, N.C., 2009. Battery pack modeling for the analysis of battery management system of a hybrid electric vehicle. *Vehicle Power and Propulsion Conferences (VPPC)*, pp. 207-212. September 7-11, Dearborn, MI.

Shafiei, A., Momeni, A. and Williamson, S.S., 2011. Battery modeling approaches and management techniques for plug-in hybrid electric vehicles. *Vehicle Power and Propulsion Conference (VPPC)*, pp. 1-5. September 6-9, Chicago, USA.

Tan, Y. K., Mao, J. C. and Tseng K. J., 2011. Modelling of battery temperature effect on electrical characteristics of li-ion battery in hybrid electric vehicle. *International Conference on Power Electronics and Drive Systems (PEDS)*, pp. 637-642. December 5-8, Singapore.

Thirugnanam, K., Saini, H. and Kumar, P., 2012. Mathematical modeling of li-ion battery for charge/discharge rate and capacity fading characteristics using genetic algorithm approach. *IEEE Transportation Electrical Conference and Expo (ITEC 2012)*, pp 1-6. June 18-20, Michigan, USA.

Toyota motor sales, 2013. *Toyota Prius Features & Specs*. Toyota web pages. Available from: http://www.toyota.com [accessed 11 April 2013]

Tsang, K. M., Sun, L. and Chan W. L., 2010. Identification and modelling of lithium ion battery. *Journal of Energy Conversion and Management*, 51: 2857–2862.

Urbain, M., Raël, S. and Davat, B., 2007. Energetical modelling of lithium-ion batteries. *IEEE Conference on Industry Applications*, pp 714-721. September 23-27, New Orleans (Louisiana, USA).

Väyrynen, A. and Salminen, J., 2012. Lithium ion battery production. *The Journal of Chemical Thermodynamics*, 46: 80–85.

AUTHORS BIOGRAPHY

CHE DAUD zul hilmi received the B.Sc degree in Mechanical (automotive) Engineering from University of Technology Malaysia (UTM), Johore, Malaysia, in 2007 and the M.Sc. degree in Mechanical Engineering from University of Burgundy, Nevers, France, in 2011. He is currently working toward his Ph.D. degree in Mechanical Engineering from University of Burgundy, Nevers, France. His research area is in the development of hybrid vehicle model with focus on the thermo-electrical characteristic of the battery cells and the battery pack.

Daniela CHRENKO (M'09) received the Dipl-Ing. FH degree in applied physics of the university of applied sciences in Wedel, Germany in 2002, the MSc of process engineering at the university of applied sciences in Hamburg Germany in 2006 and the PhD for the study of onboard hydrogen production for low temperature fuel cell systems at the university of Franche Comté in Belfort, France in 2008. Her research is linked to technologies for automotive applications, namely fuel cell systems. She worked on Stirling engines in combination with high temperature fuel cell systems, activities are carried out at the université of Franche Comté. The aime of her research is to increase energy efficiency in transportation applications. She is now working as associate professor at the University of Burgundy.

Fabien DOS SANTOS holds an engineering degree from Institut Supérieur de l'Automobile et des Transports, France in 2004. In 2012, he received his PhD for his numerical study on engine injectors, with a focus on cavitation and needle movement inside the nozzle, at the DRIVE laboratory of the University of Burgundy, France. The aim of his research is to understand the flow formation inside an injector nozzle (for automotive applications) and its influence on the liquid atomisation. He is now working as teaching assistant at the University of Burgundy.

Dr. El-Hassane AGLZIM received in 2004 the “DESS” degree (specialized graduate degree) in embedded electronics systems from the University of Metz, France. In 2005, he received the M.Sc. degree science engineering, from the University of Nancy, France. In October 2009 Aglzim obtained the Ph.D. degree in the Instrumentation and Microelectronics (IM) Science at the University of Nancy. His Ph.D. thesis was entitled ‘Characterization by electrochemical impedance spectroscopy method of the complex impedance of a fuel cell - evaluation of the influence of humidity’. From 2009 to 2010, he completed a PostDoc in the System and Transportation Laboratory (SeT) in Belfort, France and he joined the Energetic team of the ISAT in September 2010 as an associate professor. His current research interests the diagnosis of fuel cells by using the Impedance Spectroscopy method and the control strategies on HEV vehicles.

Prof. Luis LE MOYNE received the Engineer diploma in 1992, and PhD in 1997 from Arts&Métiers-Paritech. His research experience of 15 years is related to different aspects of automotive engines and powertrains energy efficiency.

OPTIMIZATION OF RACING SERIES HYBRID ELECTRIC VEHICLE USING DYNAMIC PROGRAMMING

Z. Asus [(a)], **E.H. Aglzim** [(b)], **D. Chrenko** [(c)], **Z. Che Daud** [(d)], **L. Le Moyne** [(e)]

[(a), (d)] IEEE Student Member. Mechanical Engineering Faculty,
University of Technology Malaysia, 81310 Skudai, Johore, Malaysia.
[(c)] IEEE Member.
[(a), (b), (c), (d), (e)] DRIVE Laboratory, Institut Supérieur de l'Automobile et des Transports (ISAT),
University of Burgundy, 49 rue Mlle Bourgeois, 58027 Nevers, France.

[(a)] zainab@fkm.utm.my, [(b)]el-hassane.aglzim@u-bourgogne.fr

ABSTRACT

This paper discusses modelling of a racing series hybrid electric vehicle called Noao. This plug-in hybrid system is equipped with an engine/generator set as its range extender. The battery acts as the prime mover to propel the vehicle. Available applications of control strategies for hybrid vehicle system in the literature are reviewed to identify a suitable solution for its optimization. The behaviour of the system and all of its components are modelled in simulation and validated through experiments performed on the real racing circuit. A dynamic programming approach is applied offline to optimize the existing rule based control parameters defined for this racing car application. The same approach is implemented to adjust the engine operating point in order to achieve a longer endurance and to have a better performance.

Keywords: racing car, series hybrid electric vehicle, engine/battery, dynamic programming optimization

1. INTRODUCTION

Hybrid electric vehicle (HEV) system appears as one of the most viable technologies with significant potential to reduce fuel consumption and pollutant emissions within realistic economical, infrastructural, and customer acceptance constraints. It possesses new degrees of freedom to deliver power, thanks to presence of its reversible energy storage system (ESS) that offer capability of idle off, regenerative braking, power assist, and engine downsizing (Lin et al. 2001, Serrao et al. 2011). It also has higher fuel efficiency and can achieve better performance than a conventional vehicle (Gao et al. 2009, Wirasingha et al. 2011).

The design of HEV system architecture is complex, and the power management is complicated due to a high degree of control flexibility, non-linear and multi-domain components organization. So, an appropriate energy management is necessary to coordinate its multiple energy sources and converters to obtain maximum energy efficiency and optimize its potential (Lin et al. 2001, Salmasi 2007, Park et al. 2007).

The vehicle studied in this paper is a result of a collective work by the experts and specialists of racing car application around Magny-Cours circuit industrial site (PPNMC 2012, Magny Cours Circuit 2012). They use their expertise and experiences to build the car and define its control parameters. They adopt a heuristic approach of rule based method to control the amount of power given by the battery and the power generated by the engine/generator (EG) set which is easily implemented in real vehicle by using a set of deterministic rules or fuzzy rules.

There are two methods of control strategies; the rule based method and the optimization method. The rule based (RB) power management strategy is based on engineering intuition and simple analysis on component efficiency tables or charts (Lin et al. 2003, Ambühl et al. 2009, Guzzella et al. 2009). It is robust, has less computational load, and is effective in real-time supervisory control of power flow in a hybrid drive-train (Koot et al. 2005, Langari et al. 2005, Salmasi 2007, Gong et al. 2008, Bayindir et al. 2011). It can achieve near optimal solution, but it may fail to fully exploit potentials of HEV architecture (Koot et al. 2005, Gong et al. 2008, Serrao et al. 2011, Wirasingha et al. 2011). It also cannot be easily implemented to another vehicle or driving cycle due to lack of formal optimization and generalization (Serrao et al. 2011).

The optimization based control methods can be local, global, real-time, and parameter or threshold optimization. It can provide generality and reduce heavy tuning of control parameters (Sciarretta et al. 2004). Optimization based controllers main task is to minimize a cost function which is derived based on the vehicle and component parameters, and also the performance expectations of the vehicle (Wirasingha et al. 2011).

Global optimization approach can find a global optimum solution over a fixed driving cycle and known future driving conditions to determine power distribution of each system, make it unsuitable for a real time vehicle control (Sciarretta et al. 2004, Salmasi

2007, Sundstrom et al. 2009, Nino-Baron et al. 2011). It requires heavy computation and usually used for offline simulation applications as a design tool to analyze, assess, and adjust other control strategies for online implementation (Salmasi 2007, Gao et al. 2009, Wirasingha et al. 2011, Bayindir et al. 2011). The example of this method is Dynamic Programming (DP), Genetic Algorithm (GA), and Direct Algorithm.

Real time optimization minimizes a cost function at each instant that depends only upon the system variables at the current time which have been developed using the system past information. It has limits on knowledge of future driving conditions and the electrical path self-sustainability causing the solution to be not global optimal (Sciarretta et al. 2004, Salmasi 2007, Wirasingha et al. 2011). The common method are the optimal control theory (Delprat et al. 2004, Ngo et al. 2010) and the equivalent consumption minimization strategy (ECMS) (Ambühl et al. 2009, Gao et al. 2009, Geng et al. 2011). The ECMS is mostly utilized because it only relies on the equivalence factor (EF) to solve the optimization problem (Geng et al. 2011).

In this work, DP optimization method is chosen for this Noao car. This method has never been utilized to optimize a racing type vehicle. The complete driving schedule is obtained from the experiment carried out at Magny-Cours racing circuit in France. A global optimization can be done because a precise specification of all components is available.

DP is preferred over other approaches because it has established a reputation as the benchmark of other strategies with its global optimum solution (Lin et al. 2001, Gong et al. 2008, Sezer et al. 2011). And it is chosen over multi-objective GA trade-off solution since minimization of pollutant emissions is not one of the focuses of this optimization.

The target of the control is to deplete the state of charge (SOC) of the battery from its high initial SOC at the start of the race and reach a low limit of final SOC after a number of turns at the end of the race. The objective of this study is to optimize the power split of both power sources in order to minimize the system power losses and improve energy efficiency through regenerative braking and power assist. The results are then utilized to adjust the control parameters to achieve the objective and improve the car endurance and enhance its performance.

The next part of this paper introduces the vehicle and its components. It is followed by an explanation of the DP algorithm of dynamic programming used for the case studies, which results will be analyzed in the results and discussion part, and finally the conclusion in the last part.

2. VEHICLE MODEL

The Noao car used in this work is a series hybrid electric racing car system developed by the Association des Entreprises Pôle de la Performance Nevers Magny-Cours (PPNMC 2012, Magny Cours Circuit 2012) shown in Figure 1.

Figure 2 presents the architecture of the system which consists of transmission (T), electric motor (EM), power conditioner (PC), Lithium-ion battery (B), internal combustion engine (ICE), and electric generator (G). Note that the arrows show the energy flows between components in the power-train. Parameters of this vehicle are given in Table 1, other characteristics of this vehicle can be found in the website of the association (PPNMC 2012).

Figure 1: Noao Vehicle

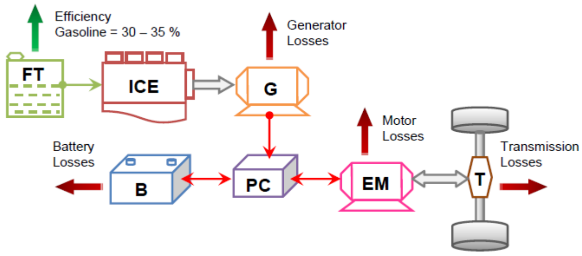


Figure 2: Series HEV Configuration

Table 1: Vehicle Parameters

Mass m_v [kg]	Front surface S [m^2]	Drag coefficient C_x [-]	Rolling resistance μ [-]	Wheel diameter [m]
1200	2.0	0.35	0.012	0.62

2.1. Vehicle Dynamics

The power needed at wheels from the two main energy sources, the battery and the engine are calculated using Equation 1, referring to (Guzella et al. 2007).

The terms on the right side of the vehicle dynamics equation represent the sum of aerodynamic force, friction force, inertia force, and climbing force times the average velocity, V_a of the car. Due to relatively high value of V_a, the road slope factor cannot be ignored for this racing car system. The detail of the circuit and the profile of the road elevation in function of distance can be found in (Magny Cours Circuit 2012). For simulation purpose, the model is represented in a time discrete model in Matlab.

$$P_w = \eta_{trans}\eta_{EM}P_{EM} = \eta_{trans}\eta_{EM}(P_{bat} + P_{EG}) \quad (1)$$
$$= \left(\frac{1}{2}\rho S C_x V^2 + m_v g\mu + m_{eq}a + m_v g(\sin\alpha)\right)V_a$$

Equivalent mass m_{eq} is the sum of vehicle mass m_v and the equivalent mass of the rotating parts m_r. It is used to calculate the inertia force to accelerate the rotating parts inside the vehicle (Guzella et al. 2007). Different from a conventional vehicle, this mass is determined from the EM down to the wheels as detailed in Equation 2. From calculation, it is found out to be 185kg for a mechanical efficiency of 0.95, transmission ratio of 2.9, and polar moment of inertia of 3.2kgm^2, 0.05kgm^2, and 1.8kgm^2 for the wheels, propeller shaft, and electric motor respectively.

$$m_r = \left(\frac{1}{r_w}\right)^2 \cdot \left(I_w + I_p \eta_f {i_f}^2 + I_{EM} \eta_f \left(i_f i_g\right)^2\right) \qquad (2)$$

The model development of the components used in this study is based on models developed in (Butler et al. 1999, Rizzoni et al. 1999, Lin et al. 2001, Ehsani et al. 2004, Guzella et al. 2007, Liu et al. 2008). The driving cycle of the circuit and the requested power profile at wheels are shown in Figure 3 which represent four turns of the racing circuit. Verification of the model is made in the same figure and errors are identified to be ±1.5%. Consistent behaviour can be observed even if there are still errors in the power request profile of the model.

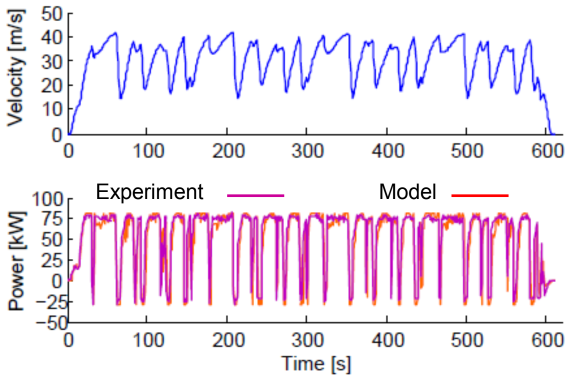


Figure 3: Driving Cycle and Power Request Profile

2.1.1. Battery Model

There are three Lithium-ion batteries of 500V nominal voltage installed in this car. Equation 3 to Equation 7 represent the model of the battery. P_{bat} is the power of the battery, positive during discharge and negative value if it is recharged (Butler et al. 1999). The battery open circuit voltage V_{oc} and its resistance R are in function of SOC. Figure 4 shows the verification of this model in terms of battery current, voltage, and SOC evolution with its results from experiment.

$$P_{bat} = I \cdot V_{\sum bat} \qquad (3)$$

$$SOC = SOC_{Initial} - \frac{\int I \cdot V_{\sum bat}}{C_t} \qquad (4)$$

$$V_{oc} = -1.031\,exp(-35SOC) + 3.685 + 0.2156SOC \\ -0.1178SOC^2 + 0.321SOC^3 \qquad (5)$$

$$V_{bat} = V_{oc}(SOC) - R \cdot I \qquad (6)$$

$$V_{\sum bat} = n_{cell} \cdot V_{bat} \qquad (7)$$

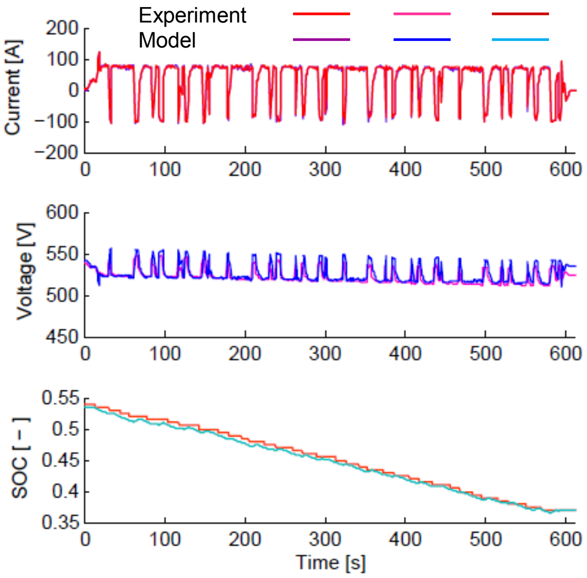


Figure 4: Battery Model Verification

2.1.2. Engine/Generator Model

The ICE is a three cylinders direct-injection gasoline engine of 1.0L, 50kW nominal power and coupled with a generator of 54kW nominal power at 4500rpm. As applied in most of series HEV configuration optimization studies like in (Konev et al. 2006, Park et al. 2007, Nino-Baron et al. 2011, Moura et al. 2011, Serrao et al. 2011, Sezer et al. 2011), the combined efficiency map of these components is demonstrated in Figure **5**. Assuming that the dynamic behaviour of the EG can be neglected for a discrete time optimization of 1s interval.

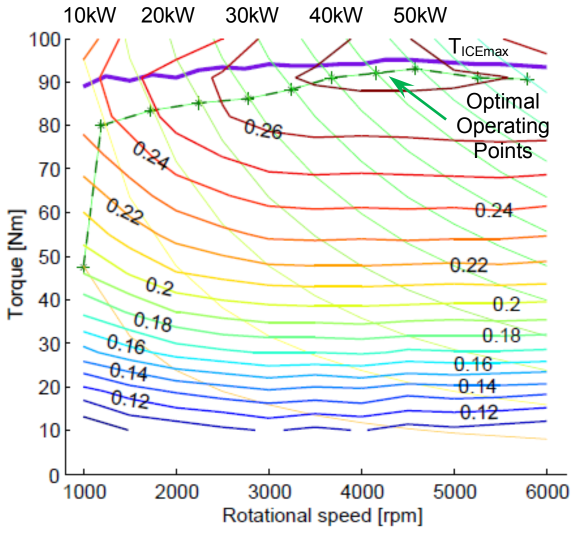


Figure 5: Engine/Generator Efficiency Map

The optimal operating points are the best efficiency point at a specific power value. It is traced along an increment of 5kW power until the maximum power that can be given by the engine. Efficiency map of the engine is obtained by a zero dimensional thermodynamic model explained in (Asus et al. 2012) which is done in simulation and confirmed with the experimental result.

3. DYNAMIC PROGRAMMING ON NOAO

DP can solve the optimal control of non-linear, time-variant, constrained, discrete time approximations of continuous-time dynamic models of HEV. It can achieve absolute optimal fuel consumption for different system configurations, but it needs all of the future conditions for inputs to be known a priori (Sundstrom et al. 2009, Ambühl et al. 2009).

It is not implementable in real vehicle due to their preview nature and heavy computation requirement, therefore is difficult to be applied in real time control. But, it can be used for offline simulations and to compare performance of a real time controller (Lin et al. 2001, Lin et al. 2003, Gong et al. 2008, Sezer et al. 2011). Stochastic DP has been implemented by (Liu et al. 2008, Opila et al. 2011, Moura et al. 2011) to be use in a real vehicle by selecting a finite number of sampled power demand defined using Markov-chain model.

The DP optimization method is largely implemented in parallel HEV to determine optimal torque split of the system (Gong et al. 2007, Gong et al. 2008, Gong et al. 2009, Lin et al. 2001, Lin et al. 2003, Lin et al. 2004, Sundstrom et al. 2008, Sundstrom and Guzella 2009, Ngo et al. 2010). While (Bonnans et al. 2004, Liu et al. 2008, Opila et al. 2011, Moura et al. 2011) use it to optimize the power split in a series-parallel HEV.

3.1. Dynamic Programming Problem Formulation

The DP used for this car is based on the problem formulation discussed in (Brahma et al. 2000, Perez et al. 2006, Koot et al. 2005) for a series HEV architecture. The power request at time t is the sum of both power sources (Equation 8), the power flow from the engine/generator and the power flow of the ESS. The ESS power is positive if the power flowing away from the ESS. The requested power here is defined as the amount of power needed at the electic motor.

$$P_{EG}(t) + P_{ESS}(t) = P_{req}(t) \tag{8}$$

The power sources are subjected to physical constraints expressed in Equation 9 and Equation 10.

$$0 \leq P_{EG}(t) \leq P_{EG_{max}} \quad \forall t \in [0, T] \tag{9}$$

$$P_{ESS_{min}} \leq P_{req} - P_{EG}(t) \leq P_{ESS_{max}} \quad \forall t \in [0, T] \tag{10}$$

The control objective is to minimise the energy consumption of the system in a time interval [0,T]. It finds the power flow profile in the EG path and ESS path that minimises cost function in Equation 11. P_{fuel} is the amount of power of the fuel burnt.

$$\begin{aligned} COST = \int_0^T \frac{P_{fuel}(t)}{P_{EG}(t)} dt \; \ldots \\ + \int_0^T \frac{P_{bat}(t)}{P_{ESS}(t)} dt \quad if \quad P_{ESS}(t) \geq 0 \\ + \int_0^T \frac{P_{ESS}(t)}{P_{bat}(t)} dt \quad if \quad P_{ESS}(t) < 0 \end{aligned} \tag{11}$$

The dynamic programming model is implemented in Matlab function developed by (Sundstrom and Guzella 2009) and is modified to improve the power split factor, u_k applied for this system.

Battery SOC, x_k is the state variable at instance k, forms the time-variant model (Equation 12) that includes the known variables of the driving cycle. N is the number of the time steps T_s, which defines L_N, the length of the problem.

$$x_{k+1} = f_k(x_k, u_k) + x_k, \; k = 0,1, \ldots, N-1 \tag{12}$$

$$x_k \in [0.09, 0.9] \tag{13}$$

$$N = \frac{L_N}{T_s} + 1 \tag{14}$$

Throughout this paper, the initial and final state variables x_0 and x_N will be changed according to optimizations carry out for this car.

3.2. Refinement of the Actual System

The rule based control strategy method implemented in the actual car decides the amount of power that will be delivered by the battery and generated by the EG set to assist the propulsion during traction. And help recharging the battery during regenerative braking as can be observed in Figure 7. For this experiment, the SOC decreases from 0.54 to 0.37 after four turns of the circuit for the duration of 610 seconds. It chooses the operational points in function of the requested power to operate the EG around its optimal operating region.

DP optimization is carried out for the same driving cycle to see improvement that can be made on the system energy efficiency. It is because, it is possible for the EG to help recharging the battery or to be idle during regenerative braking phase. The compared values are presented in Table 2.

3.3. Improvement on Vehicle Endurance

As stated before, the battery charge is expected to decrease to its lower limit by the end of a target number of turns. And the existed defined control parameters can achieve 14 turns of the circuit with SOC depletion from 0.9 to 0.3, assuming that the depletion is constant between this ranges.

The endurance of the car depends on the distance it can cover before the SOC falls to 0.3. Considering the same assumption, the car is imposed to complete 20 turns in this DP optimization to see its feasibility for a longer autonomy range. So, using the same driving cycle the state constraint which is the final SOC value is changed to 0.42.

Table 2: Results Comparison of DP Optimization

	Actual RB Method	DP	DP Endurance
SOC Initial	0.54		0.54
SOC Final	0.37		0.42
Σ P_{req} [MWs]	32.448		32.448
Σ P_{EG} [MWs]	20.894	20.513	22.790
Σ P_{fuel} [MWs]	84.194	76.099	84.166
Average η_{EG}	0.2482	0.2696	0.2708
Σ m_{fuel} [kg]	1.914	1.729	1.913
Σ P_{ESS} [MWs]	11.554	11.935	9.6577
Σ P_{bat} [MWs]	11.599	11.769	9.6439
Average η_{ESS}	0.9961	1.0141	1.0014
Average η_{system}	0.3387	0.3693	0.3459

3.4. Improvement on Vehicle Performance

The same approach is used to enhance the performance of this car by using a more aggressive driving cycle for the same driving circuit. It is expected that it will have higher power consumption, rapid battery discharge, and cause more losses. But, the vehicle can arrive in a shorter time at the finish line which is essential for a racing car.

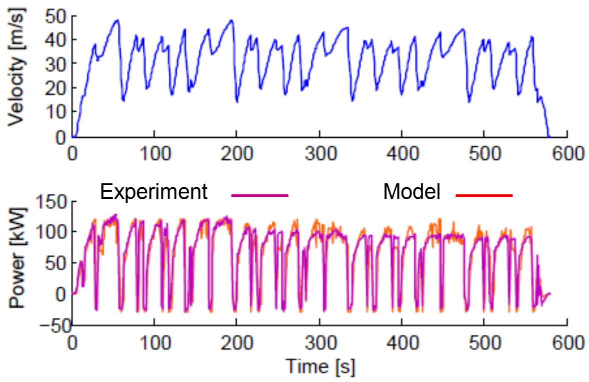


Figure 6: Aggressive Driving Cycle and Its Power Request Profile

Experimental data obtained for this case study has higher limits of maximum power given by the power sources of the system. It results in superior velocity than the previous configuration because it has more available power for acceleration as can be observed in Figure 6.

SOC depletes from 0.38 to 0.09 in 580 seconds to complete four turns of the circuit for this experiment, which means only eight circuit turns for the targeted 0.9 to 0.3 SOC diminution. After that, a higher SOC lower limit is set to see the maximum number of turns that can be achieved for this power configuration. The results of this case study are presented in Table 3.

Table 3: DP Optimization for Better Performance

	Actual RB Method	DP Performance	
		Optimized	Maximum
SOC Initial	0.38		0.38
SOC Final	0.09		0.14
Σ P_{req} [MWs]	38.342		38.342
Σ P_{EG} [MWs]	19.276	17.829	21.498
Σ P_{fuel} [MWs]	72.600	66.483	79.377
Average η_{EG}	0.2655	0.2682	0.2708
Σ m_{fuel} [kg]	1.650	1.511	1.804
Σ P_{ESS} [MWs]	19.136	20.514	16.845
Σ P_{bat} [MWs]	19.063	19.354	16.073
Average η_{ESS}	0.9962	1.0600	1.0480
Average η_{system}	0.4183	0.4467	0.4017

4. RESULTS AND DISCUSSION

In the previous section, three study cases are highlighted in order to optimize the racing car system. As can be seen in Table 2 and Table 3, DP approach enables the system to have lower fuel consumption and better system efficiency compared to its actual utilized control parameters.

Refinement of the actual system gives result as can be observed in Figure 7. For the same SOC trajectory, at the beginning DP optimization selects to use more power from EG, and then reduces its consumption to utilize more energy from the ESS to finish the rest of the cycle. As demonstrated in Table 2, we can see that the optimization results in lower fuel consumption, enhanced fuel power efficiency, and improved system efficiency. Recuperated energy during regenerative braking has improve the ESS average efficiency which is simply taken as the total ESS power divided by the total battery power of the system.

The second study case is to improve the vehicle endurance. The results of both power profiles are presented in Figure 8 and the considered values are stated in Table 2. As can be analyzed, the EG outputs more power to compensate battery energy utilization and choose to generate power during deceleration phase to help recharging the battery.

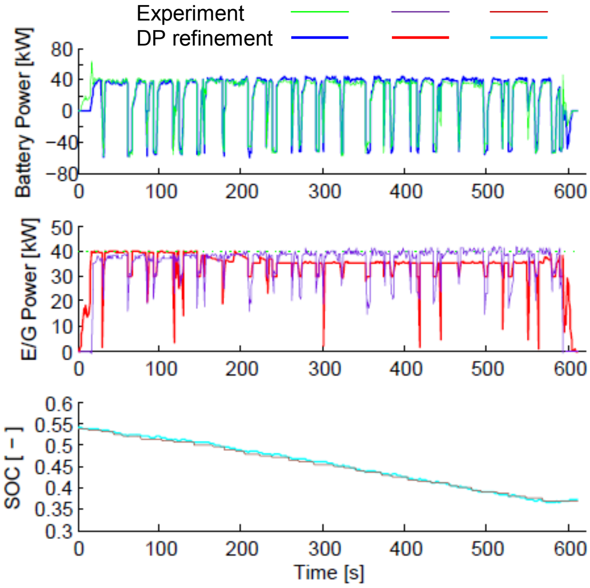


Figure 7: Results Comparison between the Actual RB Method and DP Optimisation

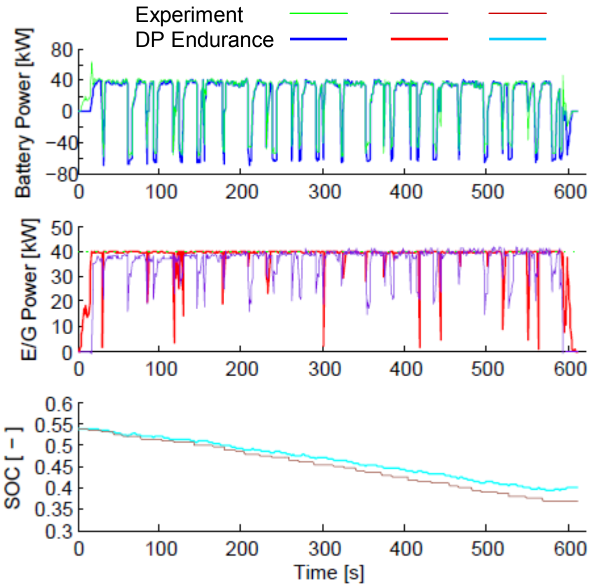


Figure 8: Results of DP Optimization to Increase the Vehicle Endurance

Figure 9 shows the distribution points of the EG power in function of the power request compared between the actual RB control, DP optimization, and DP optimization for longer endurance. In the RB method, the points are concentrated at 40kW EG power when the power request for traction is more than 60kW. But for DP, the threshold is at 40kW power request.

The EG power of RB goes to 0kW when the power request is in the range of -20kW to 20kW, and then scattered between 15kW to 35kW EG power during regenerative braking. However during this phase, DP chooses to help recharging the battery.

In this chart (Figure 9), we cannot see the difference between the DP solution and the DP endurance, but we can study it further in Figure 7 and Figure 8. These results will be used to recalibrate the control parameters of the electric generation path i.e EG power of the racing car for the regular driving cycle of the circuit.

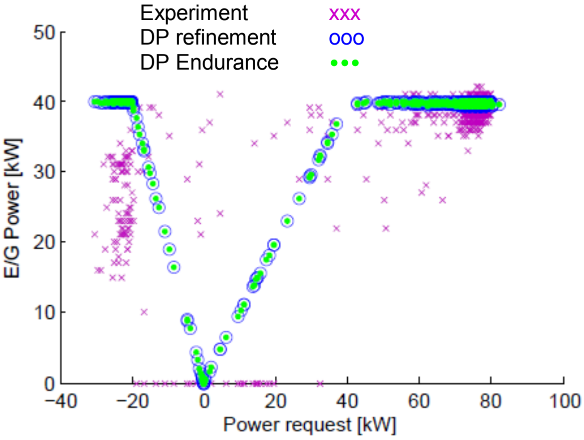


Figure 9: The EG Power in Function of Power Request

As shown in Table 3, as expected in the last case study, the total power request is higher for this aggressive driving cycle than in its regular driving cycle. The car can arrive about 7.5 seconds earlier per turn but it decreases the battery charge rapidly and causes important energy losses in the power train. In the real car, the system prefers to utilize energy from the battery to achieve the better performance.

Through optimization, DP method can improve the system overall efficiency during this condition. The fuel consumption is lower because it chooses to limit the EG power production as in Figure 10 to give a way for the battery to supply a slightly more power for propulsion for the same SOC trajectory like in the experiment.

In order to determine the maximum number of turns that can be completed by using this power configuration, the final SOC is set at 0.26. But, it turns out to be unattainable due to limitations and physical constraints of the system. And it gives 0.14 as the final SOC value demonstrated in Figure 11 which means a shorter autonomy range for the optimal SOC depletion. This corresponds to only 10 turns of the circuit even if the EG tries to give a maximum power to recharge the battery during regenerative braking phase.

For the moment, even though this method is not applicable in the real vehicle, this approach can be the reference to set the parameters of the power sources to boost the performance of the vehicle optimally.

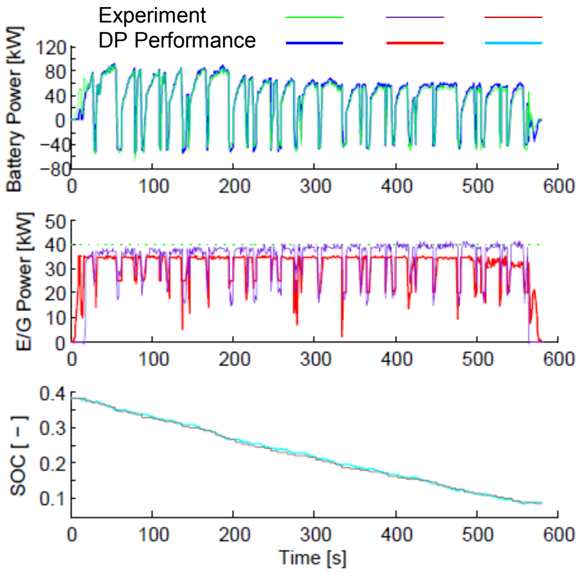


Figure 10: Results of DP Optimization by Using a More Aggressive Driving Cycle

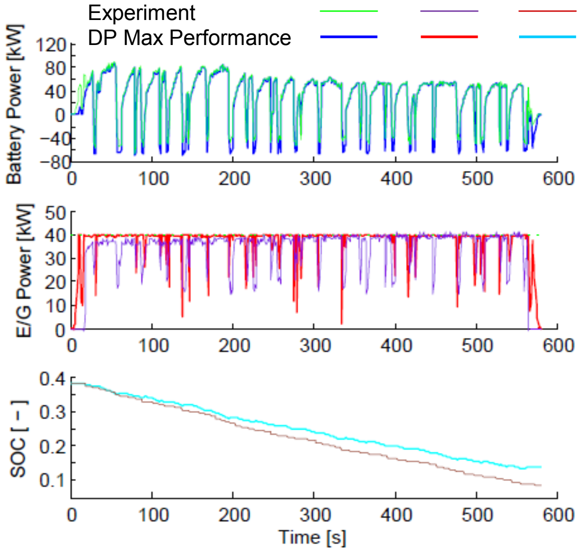


Figure 11: Maximum Endurance by Using a More Aggressive Driving Cycle

The simulations of the case studies are performed on a 32-bit Intel(R) Pentium Dual CPU 1.8GHz with 2GB RAM. The computational time for the calculation varies from 53s to 65s to analyse about 20 millions points, which mean 330000 potential points per seconds to solve these problems.

In the future, it is possible to consider the implementation of this method online by using the results obtained in this paper. Because the driving cycle can be recognized in advance given the limitations determined for the power sources. The repeatable driving schedule during a race allows a segmentation of the optimization that can reduce the computational burden of the calculation. And the SOC trajectory is predictable through an offline optimisation for the whole period of any race. The SOC evolution can be checked every time the car passes the starting point of the racing circuit and update its data for the next turns.

5. CONCLUSION

A DP optimization method is applied on Noao, a series hybrid racing car with a range extender. Some modifications are made on the existing vehicle model for the racing car application which error is controlled in the range of ±1.5%. The results from simulation show possible improvement in the fuel and system efficiency for the same driving cycle and SOC depletion from experimental result of the real car. The same approach of DP is used to study the possibility to increase the autonomy range of the racing car and proven to be feasible. These results then analyzed and will be utilized to adjust the control parameters of the engine/generator generation power. Then, the DP approach is implemented to enhance the performance of this racing car for a more aggressive driving cycle applied for the same racing circuit. But the car has a shorter autonomy range under this condition. As perspectives, this global optimisation approach will be studied further to be used in the racing car online control application.

ACKNOWLEDGMENTS

Authors wish to thank Burgundy region council (CRB), Malaysian Government and UTM (University of Technology Malaysia) for continuous support.

APPENDIX

α	road slope
a	acceleration
C_t	Capacity of battery
C_x	Drag coefficient
DP	Dynamic Programming
ECMS	Equivalent Consumption Minimization Strategy
EF	Equivalent Factor
EG	Engine/Generator
EM	Electric Motor
ESS	Electrical Storage System
FT	Fuel Tank
g	gravity
G	Generator
GA	Genetic Algorithm
HEV	Hybrid Electric Vehicle
I	Battery current
I_w, I_p, I_{EM}	Polar moment of inertia
ICE	Internal Combustion Engine
m_{fuel}	mass of fuel consumption
m_v	vehicle mass
μ	rolling resistance
n_{cell}	number of cells
η_{ESS}	ESS efficiency
η_{EM}	Electric Motor efficiency
η_{EG}	Engine/Generator efficiency
η_{trans}	Transmission efficiency
η_{system}	System efficiency

P_{bat}	Battery Power
P_{EM}	Electric Motor Power
P_{ESS}	Electrical Storage System Power
P_{fuel}	Fuel Power
P_{req}	Requested Power
P_w	Power at wheels
PC	Power Conditioner
ρ	air density
RB	Rule Based
S	Front surface
SOC	State of Charge
T	Transmission
V	Velocity
V_a	Average velocity
V_{bat}	Battery voltage
V_{oc}	Open circuit voltage

REFERENCES

Ambühl, D., & Guzzella, L., 2009. Predictive Reference Signal Generator for Hybrid Electric Vehicles. *IEEE Transactions on Vehicular Technology , 58* (9), 4730–4740.

Asus, Z., Chrenko, D., Aglzim, E. H., Keromnes, A., & Le-Moyne, L., 2012. Simple method of estimating consumption of internal combustion engine for hybrid application. *IEEE Transportation Electrification Conference and Expo (iTEC),* June 18-20, Michigan, USA.

Bayindir, K., Gozukucuk, M., & Teke, A., 2011. A comprehensive overview of hybrid electric vehicle: Powertrain configurations, powertrain control techniques and electronic control units. *Energy Conversion and Management , 52* (2), 1305–1313.

Bonnans, J., Guilbaud, T., Cherif, A., von Wissel, D., Sagastizábal, C., & Zidani, H., 2004. Parametric Optimization of Hybrid Car Engines. *Optimisation and Engineering, Springer , 5* (4), 395–415.

Brahma, A., Guezennec, Y., & Rizzoni, G., 2000. Optimal Energy Management in Series Hybrid Electric Vehicles. *American Control Conference*, pp. 60–64. June, Chicago, USA.

Butler, K. L., Ehsani, M., & Kamath, P., 1999. A Matlab-Based Modeling and Simulation Package for Electric and Hybrid Electric Vehicle Design. *IEEE Transactions on Vehicular Technology , 48* (6), 1770–1778.

Delprat, S., Lauber, J., Guerra, T., & Rimaux, J., 2004. Control of a Parallel Hybrid Powertrain: Optimal Control. *IEEE Transactions on Vehicular Technology , 53* (3), 872–881.

Ehsani, M., Gao, Y., Gay, S., & Emadi, A., 2004. *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design.* Texas, US: CRC Press.

Gao, J., Zhu, G., Strangas, E., & Sun, F., 2009. Equivalent fuel consumption optimal control of a series hybrid electric vehicle. *Journal of Automobile Engineering, 8* (223), 1003–1018.

Geng, B., Mills, J., & Sun, D., 2011. Energy Management Control of Microturbine Powered Plug-In Hybrid Electric Vehicles Using Telemetry Equivalent Consumption Minimization Strategy. *IEEE Transactions on Vehicular Technology , 60* (9), 4238–4248.

Gong, Q., Li, Y., & Peng, Z., 2009. Power Management of Plug-in Hybrid Electric Vehicles Using Neural Network Based Trip Modeling. *American Control Conference*, pp. 4601-4606. June 11-13, Washington, USA.

Gong, Q., Li, Y., & Peng, Z., 2008. Trip Based Optimal Power Management of Plug-in Hybrid Electric Vehicles Using Gas-Kinetic Traffic Flow Model. *IEEE Transactions on Vehicular Technology , 57* (6), 3393–3401.

Gong, Q., Li, Y., & Peng, Z., 2007. Trip Based Power Management of Plug-in Hybrid Electric Vehicle with Two-Scale Dynamic Programming. *IEEE Vehicle Power and Propulsion Conference* , pp. 12–19, September 9-12, Texas, USA.

Guzella, L., & Sciarretta, A., 2007. *Vehicle Propulsion Systems*, 2nd ed.. Zurich, Switzerland: Springer.

Guzzella, L., & Onder, C. H., 2009. *Introduction to Modeling and Control of Internal Combustion Engine Systems*, 2nd ed.. Zurich, Switzerland: Springer.

Konev, A., & Lezhnev, L., 2006. Control Strategy Optimization for a Series Hybrid Vehicle. *SAE Technical Paper Series* (2006-01-0663).

Koot, M., Kessels, J., de Jager, B., Heemels, W., van den Bosch, P., & Steinbuch, M., 2005. Energy Management Strategies for Vehicular Electric Power Systems. *IEEE Transactions on Vehicular Technology , 54* (3), 771–782.

Langari, R., & Won, J., 2005. Intelligent Energy Management Agent for a Parallel Hybrid Vehicle-Part I: System Architecture and Design of the Driving Situation Identification Process. *IEEE Transactions on Vehicular Technology , 54* (3), 925–934.

Lin, C., Filipi, Z., Wang, Y., Louca, L., Peng, H., Assanis, D., et al., 2001. Integrated, Feed-Forward Hybrid Electric Vehicle Simulation in SIMULINK and its Use for Power Management Studies. *SAE Paper* (2001-01-1334).

Lin, C., Peng, H., & Grizzle, J., 2004. A Stochastic Control Strategy for Hybrid Electric Vehicles. *American Control Conference*, pp. 4710–4715. June 30-July 2, Boston, USA.

Lin, C., Peng, H., Grizzle, J., & Kang, J., 2003. Power Management Strategy for a Parallel Hybrid Electric Truck. *IEEE Transactions on Control Systems Technology , 11* (6), 839–850.

Liu, J., & Peng, H., 2008. Modeling and Control of a Power-Split Hybrid Vehicle. *IEEE Transactions on Control Systems Technology , 16* (6), 1242–1251.

Magny-Cours International Circuit. *Pistes et pilotage, Presentation de la Piste Grand Prix*. Available from: http://www.circuitmagnycours.com [accessed 5 February 2013]

Moura, S., Fathy, H., Callaway, D., & Stein, J., 2011. A Stochastic Optimal Control Approach for Power Management in Plug-In Hybrid Electric Vehicles. *IEEE Transactions on Control Systems Technology , 19* (3), 545–555.

Ngo, D., Hofman, T., Steinbuch, M., & Serrarens, A. 2010. An Optimal Control-Based Algorithm for Hybrid Electric Vehicle using Preview Route Information. *American Control Conference*, pp. 5818-5823. June 30-July 2, Baltimore, USA.

Nino-Baron, C., Tariq, A., Zhu, G., & Strangas, E., 2011. Trajectory Optimization for the Engine-Generator Operation of a Series Hybrid Electric Vehicle. *IEEE Transactions on Vehicular Technology , 60* (6), 2438–2447.

Opila, D., Wang, X., McGee, R., Gillespie, R., Cook, J. A., & Grizzle, J., 2011. An Energy Management Controller to Optimally Trade Off Fuel Economy and Drivability for Hybrid Vehicles. *IEEE Transactions on Control Systems Technology* , (99), 1–16.

Park, J., Park, Y., & Park, J., 2007. Real-Time Powertrain Control Strategy for Series-Parallel Hybrid Electric Vehicles. *SAE Technical Paper Series* (2007-01-3472), 1–9.

Perez, L., Bossio, G., Moitre, D., & Garcia, G., 2006. Optimization of power management in an hybrid electric vehicle using dynamic programming. *Mathematics and Computers in Simulation , 73*, 244–254.

Pôle de la performance de Nevers Magny-Cours. *Noao, vehicule electrique avec prolongateur d'autonomie. Pole de la performance de Nevers Magny-Cours*. Available from: http://www.asso-ppnmc.fr [accessed 15 March 2013]

Rizzoni, G., Guzzella, L., & Baumann, B., 1999. Unified Modeling of Hybrid Electric Vehicle Drivetrains. *IEEE/ASME Transactions on Mechatronics , 4* (3), 246–257.

Salmasi, F., 2007. Control Strategies for Hybrid Electric Vehicles: Evolution, Classification, Comparison, and Future Trends. *IEEE Transactions on Vehicular Technology , 56* (5), 2393–2404.

Sciarretta, A., & Guzzella, L., 2007. Control of Hybrid Electric Vehicles: Optimal Energy Management Strategies. *IEEE Control Systems Magazine , 27* (2), 60–70.

Sciarretta, A., Back, M., & Guzzella, L., 2004. Optimal Control of Parallel Hybrid Electric Vehicles. *IEEE Transactions on Control Systems Technology , 12* (3), 352–363.

Serrao, L., Onori, S., & Rizzoni, G., 2011. A Comparative Analysis of Energy Management Strategies for Hybrid Electric Vehicles. *Journal of Dynamic Systems, Measurement, and Control , 133* (3).

Sezer, V., Gokasan, M., & Bogosyan, S., 2011. A Novel ECMS and Combined Cost Map Approach for High-Efficiency Series Hybrid Electric Vehicles. *IEEE Transactions on Vehicular Technology , 60* (8), 3557–3570.

Sundstrom, O., & Guzzella, L., 2009. A Generic Dynamic Programming Matlab Function. *18th IEEE International Conference on Control Applications*, pp. 1625–1630. July 8-10, Saint Petersburg, Russia.

Sundstrom, O., Guzzella, L., & Soltic, P., 2008. Optimal Hybridization in Two Parallel Hybrid Electric Vehicles using Dynamic Programming. *The International Federation of Automatic Control.* July 6-11, Seoul, Korea.

Wirasingha, S., & Emadi, A., 2011. Classification and Review of Control Strategies for Plug-In Hybrid Electric Vehicles. *IEEE Transactions on Vehicular Technology , 60* (1), 111–122.

AUTHORS BIOGRAPHY

Zainab ASUS received in 2007 the B.Sc degree in Mechanical Engineering from University of Technology Malaysia (UTM), Johore, Malaysia, and the M.Sc. degree in Mechanical Engineering from University of Burgundy, Nevers, France, in 2011. She is currently working toward her Ph.D. degree in Mechanical Engineering at the University of Burgundy, Nevers, France. Her research interests are the modelling of hybrid vehicles and the control strategies optimisations of HEVs.

Dr. El-Hassane AGLZIM received in 2004 the “DESS” degree (specialized graduate degree) in embedded electronics systems from the University of Metz, France. In 2005, he received the M.Sc. degree science engineering, from the University of Nancy, France. In October 2009 Aglzim obtained the Ph.D. degree in the Instrumentation and Microelectronics (IM) Science at the University of Nancy. His Ph.D. thesis was entitled ‘Characterization by electrochemical impedance spectroscopy method of the complex impedance of a fuel cell - evaluation of the influence of humidity’. From 2009 to 2010, he completed a PostDoc in the System and Transportation Laboratory (SeT) in Belfort, France and he joined the Energetic team of the ISAT in September 2010 as an associate professor. His current research interests are the diagnosis of fuel cells by using the Impedance Spectroscopy method and the control strategies on HEV vehicles.

Dr. Daniela CHRENKO (M’09) received the Dipl-Ing. FH degree in applied physics of the university of applied sciences in Wedel, Germany in 2002, the MSc of process engineering at the university of applied sciences in Hamburg Germany in 2006 and the PhD for the study of onboard hydrogen production for low temperature fuel cell systems at the university of Franche Comté in Belfort, France in 2008. Her research is linked to technologies for automotive applications, namely fuel cell systems, she worked on Stirling engines in combination with high temperature fuel cell systems an activities are carried out at the Université of

Franche Comté. The aim of her research is to increase energy efficiency in transportation applications. She is now working as associate professor at the University of Burgundy.

Zul Hilmi CHE DAUD received the B.Sc degree in Mechanical (Automotive) Engineering from University of Technology Malaysia (UTM), Johore, Malaysia, in 2007 and the M.Sc. degree in Mechanical Engineering from University of Burgundy, Nevers, France, in 2011. He is currently working toward his Ph.D. degree in Mechanical Engineering at the University of Burgundy, Nevers, France. His research area is the development of hybrid vehicle model with focus on the thermo-electrical characteristic of the battery cells and battery pack. He is currently developing a thermo-electrical battery cells in OpenFOAM software in order to have detailed information on the thermal behaviour of the battery cell surface which is associated to different charging/discharging current and cooling system.

Prof. Luis LE MOYNE received the Engineer diploma in 1992, and PhD in 1997 from Arts & Métiers-Paritech. His research experience of 15 years is related to different aspects of automotive engines and power-trains energy efficiency.

ECO-BOND GRAPHS: AN ENERGY-BASED MODELING FRAMEWORK FOR COMPLEX DYNAMIC SYSTEMS WITH A FOCUS ON SUSTAINABILITY AND EMBODIED ENERGY FLOWS

Rodrigo D. Castro(a,c), **François E. Cellier** (b), **Andreas Fischlin**(c)

(a)CONICET and Computer Science Dept., University of Buenos Aires, Argentina
(b)Computer Science Dept., ETH Zurich, Switzerland
(c)Dept. of Environmental Systems Sciences, ETH Zurich, Switzerland

(a)rodrigo.castro@usys.ethz.ch, (c)rcastro@dc.uba.ar, (b)fcellier@inf.ethz.ch, (c)andreas.fischlin@env.ethz.ch

ABSTRACT

This article presents general methodology for modeling complex dynamic systems, focusing on sustainability properties that emerge from tracking energy flows.

We adopt the embodied energy (*em*ergy) concept that traces all energy transformations required for running a process. Energy can therefore be studied in terms of all energy previously invested up to the primary sources, and sustainability can be analyzed structurally.

These ideas were implemented in the bond graph framework, a modeling paradigm where variables are explicitly checked for adherence to energy conservation principles.

We introduced the new Ecological Bond Graphs (EcoBG) along with the EcoBondLib Modelica library.

EcoBG represent systems in a three-faceted fashion, describing dynamics at their mass, energy, and *em*ergy facets.

EcoBG offers a scalable formalism for the description of *em*ergy *dynamic* equations (resolving some mathematical difficulties present in their original formulation) and new capabilities for detecting unsustainable phases not automatically discovered when using the *em*ergy technique alone.

Keywords: energy, sustainability, emergy, bond graph, Modelica

1. INTRODUCTION

Modern societies rely on complex interactions with natural systems at many spatio-temporal scales. Such interactions often operate at rates exceeding the natural systems' capacity to renew (Rockström et al. 2009), leading to unsustainable structures.

As all human-driven processes depend ultimately on natural resources, their depletion, or overexploitation in case of naturally renewable ones, will necessarily shape the intensity, or even feasibility, of these processes in the future.

In order to study feasible future scenarios for human-driven processes, different approaches are required depending on the sustainability of the human´s utilization of non-renewable and renewable services and goods, notably those from ecosystems.

For this kind of analysis it may be key to take into account the whole pathway of energy transformations that human-driven processes require (e.g. notably the combustion of fossil fuels).

Means are needed to model systems and analyze the sustainability of such energy transformation paths.

A sustainable socio-natural system can be thought of as a "healthy ecosystem" (Campbell 2000). Quantitative views of ecology (Breckling, Joop, and Reuter 2011) help defining, measuring, and interpreting ecosystems' health. In his seminal textbook, E.P. Odum (1954) proposed also to quantify relations among the components of an ecosystem in a systems theoretical manner to enable ecosystem management. His brother H.T. Odum extended this idea (Odum 1983, Odum 1996) to represent related elements of ecological systems in energy equivalents, e.g. as contained in biomass (the energetic content of biomass was used as a unifying measure for universal descriptions across differing ecosystem types).

It was recognized that ecosystems have structures and functions that operate across a broad range of spatial and temporal dimensions (Allen and Starr 1982) and the overall integrity of a system, when adding human dimensions, may differ depending on the hierarchical scale at which the ecosystem is being utilized (e.g., an ecosystem supporting an industrial society may be "healthy"; however, an ecosystem receiving extensive waste from industrial processes may become "unhealthy").

A modeling approach known as Energy Systems Language (ESL) (Odum 1971, Odum 1994) was proposed to represent and analyze such systems across many spatial and temporal scales and hierarchies of organization (e.g. Allen and Hoekstra 1990).

Modeled processes should observe the laws of thermodynamics just like their physical counterparts (Odum 1996). H.T. Odum proposed that the emergence of hierarchical organization results from dissipation of the available energy (Odum 1983) and that feedback loops are created if energy is available in sufficient amounts (Odum 1988). The transfer of energy throughout a hierarchy served Odum as the basis for defining "embodied energy", or ***em*ergy**.

ESL proposes a modeling approach that represents all conceivable resources in terms of a common accounting unit. As a simple illustration, (Baral and Bakshi 2009) consider a hypothetical supply chain for a biofuel, where 1000 J of sunlight are needed to produce 10 J of biomass, which in turn are used to produce 1 J worth of fuel. Note all those energy amounts correspond to each other and are equated by introducing some common unit. Say 1 J of biofuel is equal to 1000 solar equivalent Joules (sej). Such an approach allows for adding various further resources in terms of their solar equivalents, and the assumption of substitutability is satisfied. This approach retains information on resource quality, thereby diminishing criticism about the loss of information due to energy path aggregation (Haberl et al. 2006).

An energy quality indicator referred to as "Transformity" (Tr) converts all resources into solar equivalent joules. It has been proposed that resources with higher transformity values are of higher quality and may be scarcer (Odum 1996).

Emergy analysis is therefore of great importance as it features the unique capability of quantifying the contribution of diverse ecosystem goods and services under a common and meaningful measure, enabling a comprehensive, yet rigorous sustainability analysis.

Nevertheless, the emergy approach relies on detailed knowledge about complex socio-natural systems, which is likely to be inaccurate and incomplete. As a consequence, the method is considered controversial by some authors (Haberl et al. 2006).

Since this approach permits the modeling of flows of energy by highly non-linear functions, very complex behavior can arise. This is already the case with very simple model equations. Thereby it becomes difficult to guarantee that the resulting model is consistent with physics, i.e., that the laws of thermodynamics are not violated. However up to the present, correctness in terms of the adherence of models to physical first principles relies to a large extent on the experience of the modeler, and little assistance is provided by current modeling and simulation technologies supporting the modeler in this endeavor.

Iterative improvements or other refinement of such models by including the latest insights or by increasing resolution, often implemented over the course of several years, add particular risks. It may well be that the model is not only improved by reducing inaccuracies or removing incompleteness, but is also exacerbated by becoming thermodynamically no longer feasible.

Therefore, there arises a need for a modeling methodology that supports all of the features of ESL while guaranteeing thermodynamic feasibility.

1.1. Solutions proposed

Here we propose a new methodology that offers not only means to extend and enhance models incrementally, modularly, and hierarchically, but also provides techniques for tracking flows of matter and/or energy through the system in a systematic and rigorous way.

We present a formal system-theoretic Modeling and Simulation (M&S) framework, named Ecological Bond Graphs (EcoBG), along with a software tool that supports this novel methodology. This methodology is expected to be applicable in a flexible and efficient, yet rigorous and sound manner in M&S of complex natural and socio-economic systems, in particular when studying sustainability.

The framework consists of two pivotal cornerstones: an abstract graphical *specification layer* to work with system elements and structures (served by bond graph technology) at the top, and a specific equation *encoding level* (served by Modelica technology) at the bottom. Such an approach offers separation of the model specifications from implementation details while still aiding hierarchical modeling of target systems at all levels in an integrated manner.

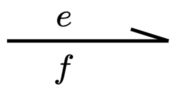
2. BACKGROUND

2.1. Bond graphs

Bond graphs (BG) (Borutzky 2010, Cellier 1991) are a multi-physics modeling paradigm intimately concerned with the conservation of energy flows. The interdisciplinary concept of energy flow creates a semantic level that allows BGs to be independent of the modeling domain. Basic concepts of physics, such as the laws of thermodynamics, can be verified in a bond graph independently of their application domain.

Three different Modelica libraries have been created for dealing with different modeling goals embracing the bond graph approach: BondLib, MultiBondLib, and ThermoBondLib.

BondLib (Cellier and Nebot 1991) makes use of the regular (black) bonds shown below.



Regular bonds carry two variables, the effort, e, and the flow, f. They do not carry units in order to make them usable for all application areas. If a bond gets connected e.g. to an electrical system, the bond inherits units of Volts for the effort variable and units of Amperes for the flow variable and propagates those units across junctions throughout the model topology.

Following this idea, complex models involving interactions among different energy domains (e.g. electrical, mechanical, and hydraulic) can be built under the same paradigm.

MultiBondLib (Zimmer and Cellier 2006) operates on (blue) multi-bonds, consisting of vectors of unit-less scalar bonds. Multi-bonds represent generalizations of regular bonds. This feature is usually needed in applications modeling 2D and 3D mechanical systems, but the concept is completely general. Here, the effort and the flow are vectors of length N that don't carry units by themselves, but inherit those later through connections to elements that belong to a particular energy domain, such as mechanics.

Whereas the dynamics of e.g. electrical or mechanical phenomena can be fully captured by pairs of power variables, thermodynamic phenomena require three independent variables for their description. ThermoBondLib (Cellier and Greifeneder 2008) operates on (red) thermo-bonds. Contrary to the regular and multi-bond, they carry units of their own. Red thermo-bonds carry three effort variables (Temperature, Pressure, and Gibbs potential), three scalar flow variables (Entropy flow, Volume flow, and Mass flow), and also three state variables (Entropy, Volume, and Mass).

2.2. Bond graphs for sustainability analysis

In this work, we are interested in the ability of tracking flows of emergy, particularly in systems described by their mass flows. The emergy concept presents a fundamental departure from previous existing specializations of bond graphs.

Therefore, we introduced the concept of Ecological Bond Graphs (EcoBG) that operate on (green) eco-bonds. These were implemented in a fourth Modelica library, coined EcoBondLib.

As shall be discussed in detail, eco-bonds transport a single pair of power variables (just as in regular black bonds) carrying Specific Enthalpy and Mass Flow, but in addition, they also transport state information (just like in the red thermo-bonds), namely the Mass, and they also carry an information variable representing Specific Emergy. The latter will allow conducting sustainability analysis based on the embodied energy technique.

3. ENERGY CONSISTENCY AND SUSTAINABILITY ANALYSIS IN COMPLEX DYNAMIC MODELS

Our methodology focuses on models exhibiting complex dynamics. Emphasis is on structurally complex models used to study sustainability. In the following, we shall refer to these models as Complex Dynamics Sustainability Models, or CDSM for short. CDSMs are often derived from observations of the evolution of measurable variables. In the context of sustainability, the energy is key, and we therefore focus on CDSMs that describe processes by means of flows of mass and their associated energy.

CDSMs in socio-natural sciences are often impossible to be deduced from first-principle physical laws (bottom-up approach) in spite of the fact that the latter are invariably dominating any real world process. Following top-down approaches, CDSMs are built from, tuned for, and validated against real world observations, thereby gaining validity.

However, the internal structure of a model validated at the level of its observables may sometimes make questionable assumptions from an energetic point of view. Such a CDSM can be misleading in at least two ways. If the goal of the model is to *understand* the mechanisms behind a system under analysis, it may provide wrong explanations for the observed phenomena. If the goal is to *forecast* plausible future evolutions of the system, it may fail to offer credible predictions even for previously well-fitted variables.

Improving the internal energy consistency of CDSMs cannot guarantee that the model is correct, but it can at least help to rule out models that are energetically unfeasible, thus enhancing the overall model reliability.

Moreover, an energy consistent CDSM can provide novel insights about the *sustainability* of the underlying mechanisms driving the real system. By making explicit the main paths of energy transformation attached to every observable variable -including all energy sources- can point out dependencies on energy renewability constraints that might otherwise remain hidden.

4. ENERGY AND EMERGY FOR CDSM: A SYSTEM THEORETIC FORMULATION

We can abstract and generalize the modeling problem in terms of system theoretic principles, boiling it down to producing a mesh of Nodes (sources -or inputs- U, accumulators -or system states- X, and sinks -or outputs- Y) that are interlinked by Edges (physical transformation processes PR). The model is complete once we also define a system boundary to delimit our system Σ from the rest of the universe Ω (Figure 1). Linear dynamics can be expressed by defining the four system matrices A, B, C, D. Nevertheless for CDSMs, linearity is not the most usual case, and therefore we need to resort to a more general process $\dot{X} = PR(U, X, Y)$ to describe the (possibly complex) interactions among any two Nodes, similarly to what Fischlin introduced (Fischlin 1991) as the relational di-graph to define system structure using a 2nd order predicate for such a generalized process.

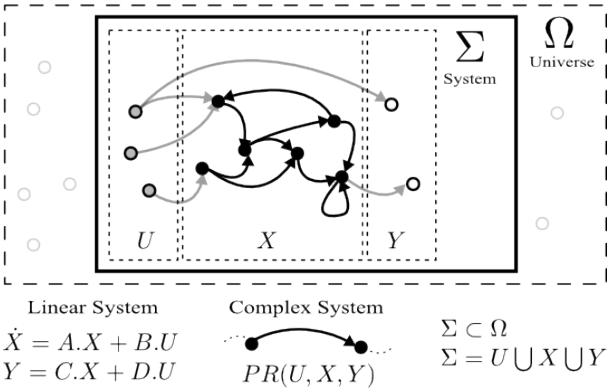


Figure 1: System-theoretic formulation of complex dynamic systems with Sources, Internal States, and Sinks.

We want each Node to express explicitly the relation between its mass and the associated energy. We shall denote the latter with H [Joule] referring to the enthalpy of the mass M[kg].

Such a relation must be consistent with the flows of energy (i.e. Power $\dot{H}$ [Watt=Joule/sec]) routed in and out through its connected Edges.

This problem is of a "local" nature in the sense that all variables required to formulate a consistent set of mass and energy equations are local to the Node and its connected Edges. No information about other Nodes is required.

We also want to track flows of e*m*ergy[1], $\dot{EM}$ [W]. This problem, however, bears characteristics of a "structural" nature. The e*m*ergy flowing into a Node must equal the sum of e*m*ergies flowing out from its donor Nodes *regardless of the processes connecting them*.

As every real process results in dissipation of energy in the form of flows of irreversible entropy $\dot{S}_{irr}$ [W], the amount of energy actually reaching a Node will always be smaller that the energy extracted from its donor Node. Nevertheless the e*m*ergy must track the original energy required to drive the Process, i.e., *the en*ergy *used before considering losses*.

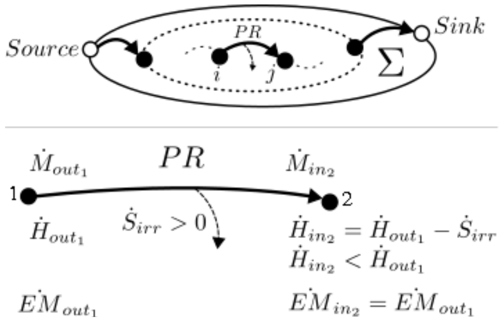


Figure 2: Process relation (PR) as the generalized Edge. Production of irreversible entropy is explicitly considered with $\dot{\boldsymbol{S}}_{\boldsymbol{irr}} > 0$ (2nd principle of thermodynamics).

The bottom graph of Figure 2 represents a general pair of nodes i=1,j=2. The e*m*ergy flowing into Node 2 is the e*m*ergy flowing out from Node 1, which in turn accounts for all the e*m*ergy supplied by its donor nodes[2]. When this concept is propagated across all connected pairs in a system, we realize that a change anywhere in the structure of the mesh can potentially influence the e*m*ergy of a given Node, even when its local energy balance remains intact.

E*m*ergy captures a system property sensitive to its structure by memorizing energy supplies back to the sources at the system's boundary.

At a given node, the Transformity $Tr = \frac{EM}{H}$ denotes the proportion between the e*m*ergy (EM) sustaining all previous paths of transformations (leading to the existence of that node) and the locally usable energy (H). For a given H, a higher Tr implies chains of energetically less efficient transformations, the system having to invest more energy at its sources.

4.1. A Multi-Faceted Approach

In accordance with the system-theoretic framework developed above, we propose a compact view of Nodes and Edges decomposed into three facets: a "Mass Facet," where the local laws derived from observations are encoded, and two energy-oriented facets, namely the "Energy Facet" and the "E*m*ergy Facet" (of local and structural nature, respectively), as depicted in Figure 3.

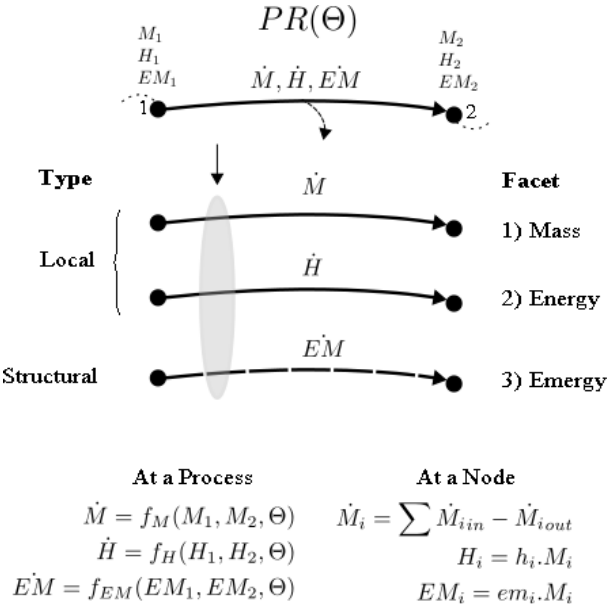


Figure 3:Three-faceted view (Mass, Energy, and Emergy) of the generalized process $\mathbf{PR}(\boldsymbol{\Theta})$. $\boldsymbol{\Theta}$ is a parameter vector.

All Nodes and Edges are then equipped with mass-, energy- and e*m*ergy-awareness. This separation of concerns helps us to obtain a compact core set of equations for expressing CDSMs that is capable of scaling up for defining complex systems in a robust way.

It also fosters easy assimilation of techniques other than e*m*ergy tracking to account for past energy transformations while keeping equations in the mass and energy facets encapsulated and self-consistent.

5. BOND GRAPHS AS THE ENERGY-BASED PRACTICAL MODELING PARADIGM

We shall now map the systemic approach of the previous section into a practical modeling formalism.

---

[1] Flows of emergy are also referred to as Empower in the emergy literature.

[2] H.T.Odum's original formulation for $\dot{EM}$ resorts to a set of differential equations that are switched depending on the dynamics of the energy at a Node: increasing, decreasing or steady state (Odum 1996) These were termed "differential-logic equations" for "Dynamic Emergy Accounting – DEA." Strictly speaking, it consisted of a piecewise continuous type of system with discontinuities triggered by state events. As we shall see later, by sticking to our BG-based methods, we are driven to reject this switching idea, obtaining a more physically sound formulation for $\dot{EM}$. Tilley reached the same conclusions following other rationales (Tilley 2011). The two approaches were developed in parallel and independently of each other (Castro and Tilley 2012, personal communication).

As illustrated in Section 2.1, BGs offer a highly suitable modeling framework for the purposes at hand: BGs natively distinguish between structure and behavior, are based on the explicit tracking of energy flows (expressed by their basic pairs of *effort* and *flow* variables), and enforce energy conservation laws.

As already conveyed in Section 2.2, we shall define a new core set of BG elements suitable for building CDSMs including e*m*ergy tracking capabilities. We shall refer to those as "Ecological Bond Graphs," or EcoBG for short. We shall proceed guided by motivating examples of increasing complexity.

5.1. Motivating Example 1: Source-Storage-Sink

This first example is inspired by a frequently referenced model proposed by H.T. Odum (1996) named EMTANK (E*m*ergy Tank), a classical starting point for e*m*ergy methodology. It represents the most basic case possible from a structural point of view, as one single node "Storage" has connections only to system boundaries, and from a dynamical point of view, because processes from/to sources/sinks are simpler to model than processes linking storages.

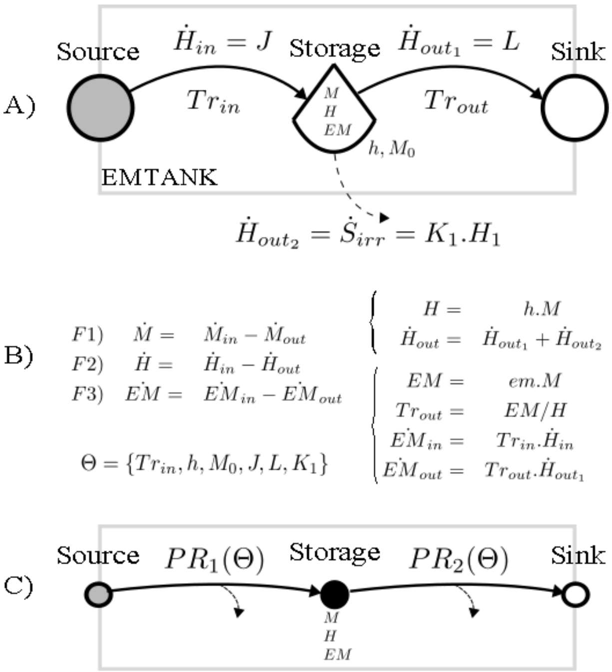


Figure 4: The EMTANK system. A) Original ESL formulation, B) Three-faceted view, and C) System-theoretic formulation.

Some considerations are in order. In Figure 4A, the dynamics of the original model are expressed directly in terms of flows of energy ($\dot H$) rather than flows of mass. In our approach, we can mimic this by setting the specific enthalpy to $h = 1$ J/kg, thus operating on generic masses. The equations of Facet 1 and Facet 2 look the same and deliver identical numerical values, albeit using different measurement units.

For the e*m*ergy equations (Facet 3), we can assume $\dot{EM}_{in} = \dot H_{in}$ by setting $Tr_{in} = 1$. A Source Node is a special case as it may import e*m*ergy flows from other subsystems, and Tr_{in} is the way of encoding it. Also, different Tr values can be used to scale flows of different types of energy in such a way that they are "converted" to flows of a single chosen type.

In Figure 4C, we mapped the example to our graph-like system-theoretic formulation.

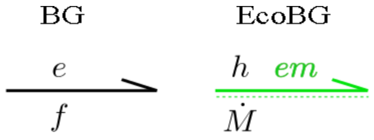
5.2. The EcoBG Bond element

The basic BG element that transports energy between elements is the bond.

The most suitable pair of variables for CDSMs is that formed by the specific enthalpy h (an *effort variable*) and the mass flow $\dot M$ (a *flow variable*). Hence $\dot H$ [J/sec] = h [J/kg] · $\dot M$ [kg/sec] represents power [W=J/sec], i.e., flow of energy.

While h and $\dot M$ provide enough information for depicting equations of Facets 1 and 2, we need additional information for Facet 3, i.e., the e*m*ergy facet. We thus add to our bond the specific e*m*ergy em [J/kg] as an *information variable*, whereby $\dot{EM}$ [J/sec] = em [J/kg] · $\dot M$ [kg/sec] also denotes flow of energy.

The reason for choosing the *information* type rather than the apparently more suitable *effort* type for em will become evident later on. We shall represent EcoBGs with the classical harpoon with an extra dashed line indicating that information variables are being included.

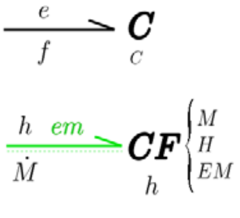


In the Modelica implementation of the EcoBG methodology, i.e., in the EcoBondLib Modelica library, we color-coded the new EcoBG bonds (eco-bonds) using the green color.

5.3. The EcoBG Mass Storage element

We made it already clear that our approach is particularly concerned with processes transporting and transforming mass, as well as storage elements for accumulating mass.

The type of BG element suitable for mass storage is the C-element (or capacitor), as by definition, a C element integrates the flow variable and calculates the effort variable.



$$e(t) = \frac{1}{C}\int f(t).dt$$

$$\begin{aligned} H(t) &= h.\int \dot M(t).dt \\ M(t) &= H(t)/h \\ EM(t) &= \int em(t).\dot M(t).dt \end{aligned}$$

As we can see, the parameter C of the mass storage element must be $C = 1/h$. This is consistent with the idea that storages in a model represent *one particular* *type of mass* that can be uniquely characterized by its specific enthalpy.

The EcoBG C must also integrate *em*ergy. To that end it resorts to em, the specific *em*ergy information attached to the mass flow $\dot{M}$. In this case however, there does not exist a constant specific *em*ergy characterizing the mass, as it is a consequence of chains of processes taking place somewhere else in the topology. Therefore $em = em(t)$ is kept inside the integral.

5.4. The EcoBG Junction element

Junctions in BGs are structural elements enforcing *en*ergy *conservation* among those elements interconnected via the junction through their bonds.

0-Junctions achieve that goal by enforcing *flow conservation* while operating at a common effort. 1-Junctions enforce *effort conservation* among components operating under a common flow.

As systems described by mass flows are the primary objects to be captured by EcoBG models, the 0-Junction is the suitable element to be extended to cope with the concept of *em*ergy.

The EcoBG 0-Junction element distributes a common specific enthalpy among its connected bonds, and enforces mass conservation through $\sum \dot{M} = 0$ (cf. Figure 5). When a storage is connected to a 0-Junction, C becomes the element imposing its specific enthalpy h to the other connected bonds.

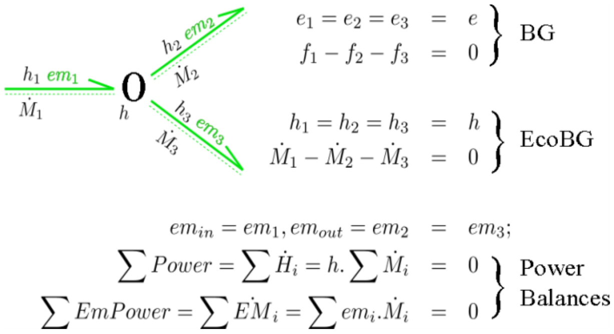
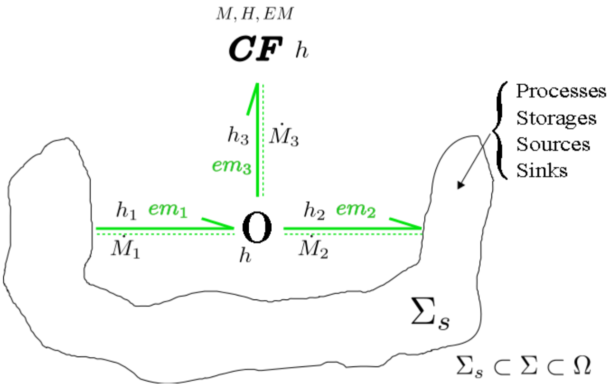


Figure 5: The EcoBG 0-Junction. Balances of Mass, Power, and EmPower.

In Figure 5, the *em*ergy balance looks different from the power balance represented by $\sum h.\dot{M} = 0$, as there is no em common to all flows. According to the *em*ergy principle, incoming flows contribute their own values of *em*ergy per unit mass to build and sustain the storage, while all outgoing flows bear a new and common value of specific *em*ergy imposed by the storage. This explains why we treat em as an information variable rather than as an effort variable.

We can now take a look at a basic unit composed by the EcoBG elements defined so far, which will serve as an important building block for more complex models.



With the proposed variables, we are now able to describe the storage of mass while adhering to the multi-faceted approach proposed in Section 4.1.

5.5. EcoBG Process elements

So far we described the basic tools needed to make Nodes connectable to the rest of the system while observing basic conservation principles. We still lack an element where to encapsulate the relations connecting Nodes. This will be our Process element that populates the Edges webbing our topology. A Process shall encapsulate two fundamental pieces of information:

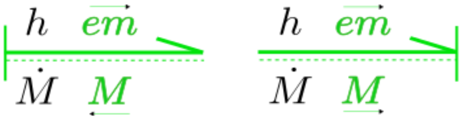
Firstly at the Mass Facet, it describes the laws relating masses. The most general dynamic formulation for defining relations among masses looks as follows:

$$\begin{cases} \dot{M}_1 = f_1\,(M_1, \ldots, M_n) \\ \vdots \\ \dot{M}_n = f_n\,(M_1, \ldots, M_n) \end{cases} \qquad \textbf{(1)}$$

In our motivating example, we have only one type of mass, and assuming $h = 1$ for the sake of simplicity, the Process must express:

$$\begin{cases} \dot{M}_1 = J - K_1.M - L \\ H = h.M, h = 1 \end{cases} \qquad \textbf{(2)}$$

For a Process element to be able to calculate $\dot{M}_1 = -K_1.M$, it needs to know the value of M, which so far is a variable internal to the C element. Therefore, we need to extend our bond element with one additional information variable carrying M, i.e., the *state* of the accumulated mass at the storage. Just like h, this variable can only be imposed by a C element.



Secondly at the Energy Facet, Processes shall be responsible for encoding the loss of energy due to production of irreversible entropy, an inevitable feature of all real processes.

The consequence of the latter for the E*m*ergy Facet is evident: the information of the energy used *before* the discounting of irreversible entropy shall be passed along unaltered for the emergy accounting purposes already discussed.

In Example 1, the two required Processes are special ones -in fact, the simplest possible- due to Source and Sink being special types of Nodes. These Nodes' mass and energy balances are unidirectional as they only impose or accept power flows, respectively. They are placed at the system's border, and they don't accumulate mass or energy.

We shall first define the Source Process and the Sink Process. At a later example, we shall deal with the more general type of Process interconnecting Storage Nodes among themselves.

5.5.1. The EcoBG Source Process

We must derive a structure to represent "Process 1" in Figure 4C.

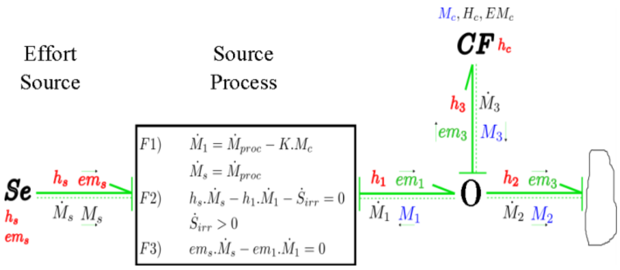


Figure 6: The Source Process

Facet 1 (Mass Facet). The EcoBG Source Process (Psrc) element provides the flow of mass injected into the Storage (after losses).

An EcoBG Effort Source (Se) element must feed Psrc with the energy associated with the demanded mass flow in the form of specific enthalpy (before losses).

Eq.(F_1) expresses the laws for the mass flows considering that the mass brought in from the Source ($\dot{M}_S$) is configured as a *parameter of the process* ($\dot{M}_{proc}$) by the user and taking into account the mass lost due to the generation of entropy ($K.Mc$). The mass flow is imposed by Psrc to Se ($\dot{M}_S = \dot{M}_{proc}$), as we adopted mass flow, rather than energy flow, as the main flow describing the dynamics of the system.

Facet 2 (Energy Facet). The flow of energy entering Psrc must equal the flow of energy carried by the mass entering the Storage plus the flow of energy dissipated as entropy ($\dot{S}_{irr}$).

The specific enthalpy is imposed at the right hand side of Psrc by the Storage element ($h_1 = h_c$).

Under normal circumstances, the user-provided parameters h_S and h_C should match, as the type of substance being supplied by Se and subsequently accumulated in C is of the same type. Yet, these parameter values can be chosen differently. The energy balance would then absorb the disparity with the additional capability of checking whether this generates physical inconsistencies (i.e., $\dot{S}_{irr} > 0$ must always hold). An h_S greater that h_C can be used to represent the energy required to procure the mass from the rest of the system (e.g., to extract a mineral from its ore).

Facet 3 (Emergy Facet). The specific emergy em_S supplied by the Se element can be set as a parameter by the user. Emergy flow reaches Psrc to the amount of $E\dot{M}_S = em_S.\dot{M}_S$. This emergy flow is propagated unaltered to the right hand side of Psrc as $E\dot{M}_1 = em_1.\dot{M}_1 = E\dot{M}_S$, ignoring the irreversible loss of energy via $\dot{S}_{irr}$ (in accordance with the principle of emergy accounting).

5.5.2. The EcoBG Sink Process element

Following a similar approach, we shall derive the structure to represent "Process 2" in Figure 4C. In fact, we can already take advantage of the systematic formulations made so far and make the Sink Process be just a mirror version of the Source Process.

Conceptually, we should be able to simply invert the signs of flow equations in Facets 1, 2, and 3, thus transforming inputs to outputs, and vice-versa. In BGs, such an idea is achieved by inverting the bonds' harpoons that indicate the direction of positive flows (cf. Figure 6).

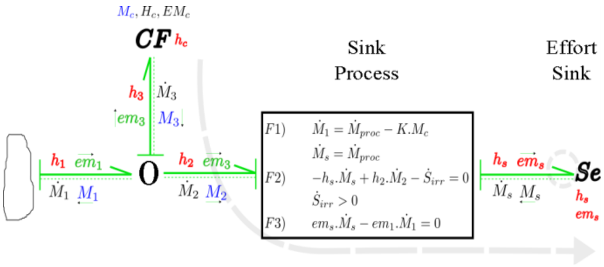


Figure 7: The Sink Process

In Figure 7, we see the schematic representation of this idea. The Sink Process (Psnk) element defines through its phenomenological law, how mass is extracted from C.

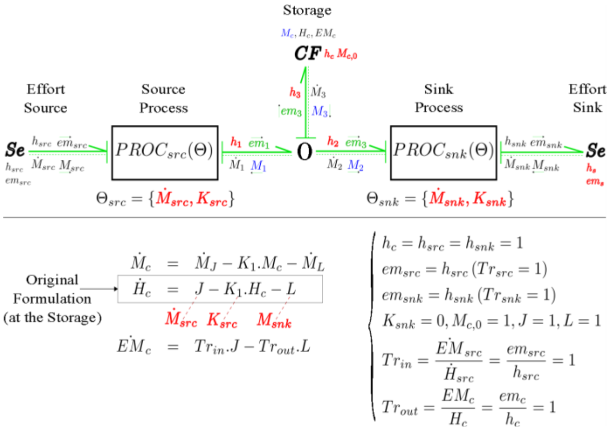
The Se element (a source of effort now operating as a Sink) can state the energy required for taking the mass out of the C element (h_S) together with the emergy associated with that energy (em_S).

However, these parameters will not have any influence on the rest of the model: the energy contained per unit mass in C is defined by h_C, and its emergy per unit mass is calculated as $em_C = \frac{EM_C}{M_C}$ also at the storage element. Yet, specifying h_S and em_S can serve for the comprehensiveness of the model as a whole.

5.6. The EcoBG EMTANK Model

We already defined all of the EcoBG elements required for representing the model of Figure 4.

The next figure shows the coupling of elements achieving that goal.



$$\begin{aligned}
\dot{M}_c &= \dot{M}_J - K_1.M_c - \dot{M}_L \\
\dot{H}_c &= J - K_1.H_c - L \\
\dot{EM}_c &= Tr_{in}.J - Tr_{out}.L
\end{aligned}$$

$$\begin{cases}
h_c = h_{src} = h_{snk} = 1 \\
em_{src} = h_{src}\,(Tr_{src} = 1) \\
em_{snk} = h_{snk}\,(Tr_{snk} = 1) \\
K_{snk} = 0, M_{c,0} = 1, J = 1, L = 1 \\
Tr_{in} = \dfrac{\dot{EM}_{src}}{\dot{H}_{src}} = \dfrac{em_{src}}{h_{src}} = 1 \\
Tr_{out} = \dfrac{EM_c}{H_c} = \dfrac{em_c}{h_c} = 1
\end{cases}$$

Figure 8: The Source-Storage-Sink system (EMTANK).

In the lower part of Figure 8, we can see the equations that are automatically extracted from the graphical model by the Modelica compiler. We set the specific enthalpies and emergies to 1 for the sake of simplicity while analyzing the first results.

At Facet 2, we see that parameter K_{snk} of process Psnk plays no role, as we set $K_{snk} = 0$, implying that the process of mass/energy consumption from the Storage considers no losses. On purpose, we decided to assign all losses due to entropy generation in the original model to process Psrc.

In Odum's ESL language, dissipation losses can be modeled at Storages and/or Processes, with the former option being the one usually adopted. In ESL, dissipation losses represent emergy-less processes on their own. Nevertheless in the EcoBG approach, we consider that losses exist only as consequences of mass transformations (i.e., processes), and therefore the correct place to model them is at the EcoBG PROC elements.

At Facet 3, we recognize that the term $K_{src}.M_C$, present at Facets 1 and 2, takes no effect. This is because in EMTANK, this is the flux meant to describe irreversible losses, therefore carrying no emergy. For this reason, it must not be subtracted for emergy accounting.

5.6.1. Model Implementation

We implemented the EcoBG elements introduced so far as individual models encoded in the Modelica language (Modelica 2013a)

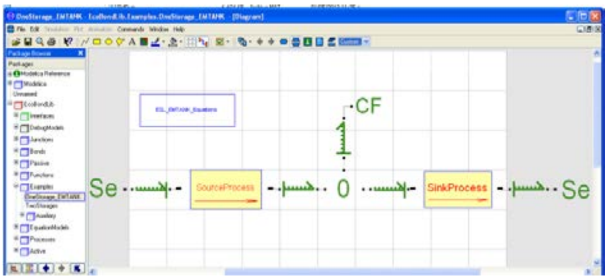


Figure 9: The EcoBG implementation of the Source-Storage-Sink system in Dymola.

In particular, we used the Dymola visual modeling and simulation environment (Dymola 2013). We shall delve more into the implications of this approach in Section 7.

Figure 9 shows EMTANK implemented in the Model view of Dymola.

Besides implementing the EcoBG version of EMTANK, we encoded a subsystem capturing the original set of equations defining EMTANK for comparison purposes (cf. the blue box in Figure 9). Parameter values were set for each element according to those presented in Figure 8.

5.6.2. Model Simulation

We simulated the model for t_f=350 units of time, i.e., until steady state is reached.

The next Figure shows the results for the main variables of interest: M, H, EM and Tr simulated at the Storage element in the EcoBG model and also at the EMTANK block that implements the standard equations proposed by Odum (legends squared with dotted lines).

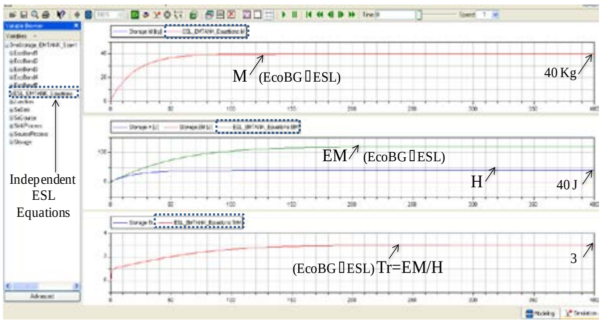


Figure 10: Baseline simulation of EMTANK with EcoBG and standard ESL equations. EcoBG mimics ESL results.

We verify that the EcoBG model mimics exactly the original EMTANK behavior (the trajectories are indistinguishable for M, EM, and Tr). We also display H together with EM. Since all specific enthalpy values were set to 1, the curve of H matches that of M. Yet H differs from EM as the latter remembers all of the energy that was used at the source before discounting losses. The ratio $\mathrm{Tr} = \mathrm{EM}/\mathrm{H}$ is verified to be consistent throughout the simulation. With the given parameter values, the "quality" of each unit of mass available for consumption from the Storage at steady state is 3. In less trivial networks of processes, this number helps to identify, which Storages bear higher energetic quality, indicating that their overall energetic cost is higher.

We can now experiment with different parameter values. E.g. if we change the specific enthalpy of the mass, we should see no changes in the mass dynamics, but we should notice changes in the energy dynamics.

To do so, we set $\mathrm{h_C} = \mathrm{h_S} = 2$, and also $\mathrm{em_S} = \mathrm{h_S}$ so as not to incur changes in the transformity. Results are shown in the next figure.

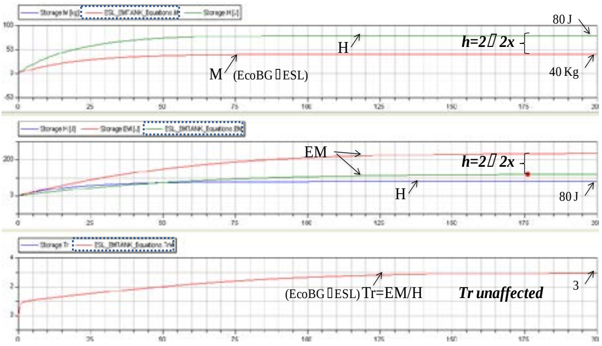


Figure 11: Scenario 1: Baseline with doubled specific enthalpy

All results are as expected. If we now change only the specific *em*ergy at the source, making it e.g. $em_S = 2.h_S = 4$, we should see the dynamics of mass and energy unchanged, whereas now the *em*ergy flows change by a factor of 2. This is shown and verified in Figure 12.

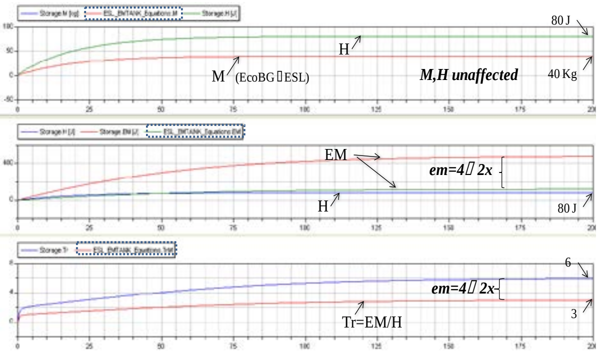


Figure 12: Scenario 2: Scenario 1 with doubled specific emergy

Before coding a less trivial example, an important remark is in order. As discussed before, we use Source elements at the systems' borders. So far we used effort sources, which state how much energy and *em*ergy the requested mass flow shall carry. Yet we know that physical processes are always limited in terms of the maximum power they can deliver. Apparently our ideal sources are able to withstand flows of infinite energy, which is certainly non-physical.

To remedy this situation, we equip Sources with a P_{max} parameter. Should the condition $P_{src}(t) = \dot{H}(t) > P_{max}$ become true, the simulation should stop indicating that the system is requesting more power from the source than can be delivered.

P_{max} represents a coarse-grained abstraction, an assumption made for representing limitations that arise from more complex dynamics at a part of the system that has been lumped together in a single Source element.

In the next example we shall see richer dynamics by replacing the source of effort at the supply side with a submodel that accounts for flow, power, and storage limitations, representing more realistically limitations as they are found in nature.

6. EXAMPLE 2: TWO STORAGES. REPLACING IDEALIZED SOURCES. CHECKING FOR SUSTAINABILITY.

In Figure 13 we show an example that considers a natural process that produces a primary renewable reservoir of matter (C_a), which serves as the actual repository that the Supply Process at the right feeds from.

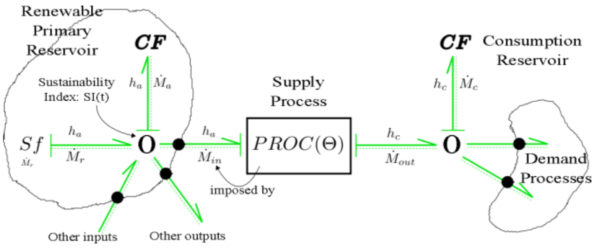


Figure 13: System with two storages: Source deposit (left) and a Consumption reservoir (right).

Now, we use a Source of Flow (Sf) element. Such a source imposes $\dot{M}_r$ while accepting the specific enthalpy imposed by the system it is connected to (in our example h_a, a parameter of C_a).

For Sf, the contributed mass flow is not a consequence of a process demanding material, but rather a known supply parameter. It represents a natural process, whose mass flow can be directly measured (such as the flow of rain filling an underground aquifer).

In this new model, the power limitation will be given by the balance between incoming and outgoing flows at the junction element. Consuming processes that draw more power than that supplied by the donor processes are not sustainable, and checks must be performed for those cases in the same way that we used to check against $P_S > P_{max}$ in our previous example.

We now talk about checking for sustainability instead for instantaneous maximum power, because processes can potentially -though only temporarily- draw more power than is being instantaneously provided by consuming the additional energy from the storage, thereby lowering its level.

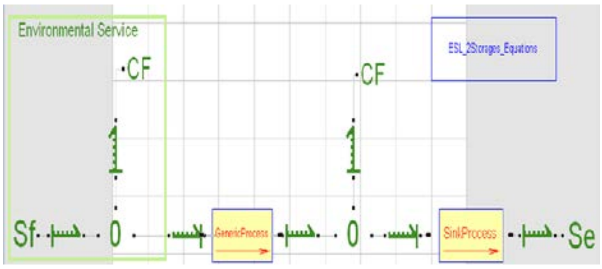


Figure 14: The EcoBG implementation of the Two Storages system in Dymola.

Parameterization for the system in Figures 13 and 14 is as follows:

$$\left\{\begin{array}{c} Rain\ (Sf_r): \dot{M}_r = 2, h_r = em_r = 1 \\ Deposit(C_a): h_a = 1, M_{a,0} = 150 \\ Supply(PR_s): K_s = 0.001, K_s^{irr} = 0.1 \\ Consumption(C_c): h_c = 1, M_{c,0} = 1 \\ Demand(Se_d): K_d = 0.05, K_d^{irr} = 0 \end{array}\right. \quad (3)$$

The equivalent set of equations expressed with the ESL method, taking $M_1 = M_a, M_2 = M_c$ are:

$$\left\{\begin{array}{ll} \dot{M}_1 = J - K_1.M_1.M_2 & \\ \dot{M}_2 = \quad K_1.M_1.M_2 - K_2.M_2 - L & \end{array}\right. \quad (4)$$

$$\left\{\begin{array}{l} E\dot{M}_1 = Tr_J.J - Tr_{M1}.K_1.M_1.M_2 \\ E\dot{M}_2 = \qquad Tr_{M1}.K_1.M_1.M_2 - Tr_{M2}.L \end{array}\right. \quad (5)$$

Parameterization for Eqs. (4) and (5) is as follows: $J = 2, K_1 = 0.001, K_2 = 0.1, L = 0.05, Tr_J = 1$ with initial conditions $M_{1,0} = 150, M_{2,0} = 1, EM_{1,0} = EM_{2,0} = 0$.

6.1.1. Simulations

The next figure shows simulation results for a system configuration yielding oscillatory behavior (a mode possible only with 2 or more storages).

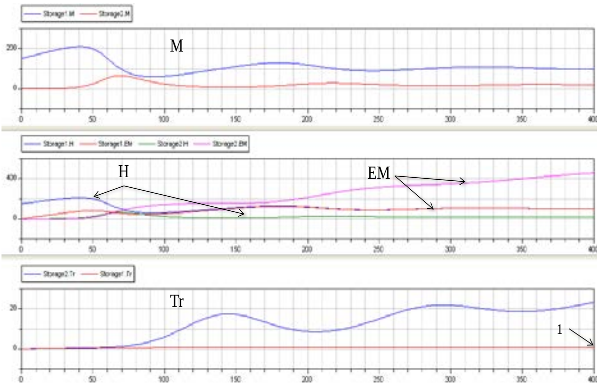


Figure 15: Baseline simulation of the Two Storages model with EcoBG.

All curves overlap those produced by an independent simulation of the corresponding ESL Eqs. (**4)** and (**5)**.

For both storages, the upper graph shows M, the center graph depicts H and EM, and the lower graph displays T_r. All variables reach steady state in the long run (the oscillations die out). We can see how the non-intuitive evolution of H and EM at the second storage produces an oscillatory trajectory for its transformity, indicating that the "quality" measure as defined in the e*m*ergy methodology is indeed a dynamic concept.

E*m*ergy analysis uses flows of e*m*ergy and their transformities along with labels assigned to flows (e.g. "renewable" or "non-renewable"), and then produces several sustainability-related performance indicators.

EcoBondLib provides us with all elements that we require to model and simulate the dynamics of arbitrarily interlinked storage/mass flow systems. Special indicators can be programmed easily to warn us when the simulation enters an operational mode that is not physically feasible.

6.1.2. The Sustainability Index

We shall introduce now a Sustainability Index (SI) indicator for EcoBG.

As mentioned at the beginning of the section, a sustainable balance of power must be observed locally at every source or storage, otherwise the whole system is unsustainable.

For EcoBG Junctions we define:

$$SI(t) = Power_{in}(\mathrm{t})/Power_{out}(t) - 1$$

$SI(t) < 0$ indicates an unsustainable phase, whereas $SI(t) >= 0$ denotes a sustainable phase, $SI(t)$ being the consequence of the (possibly many) simultaneous flows of energy entering and leaving the Junction. The power balance mandates that:

$$Power_{in}(t) - Power_{storage}(t) - Power_{out}(t) = 0$$

For $SI(t)$, we ignore $Power_{storage}(t)$, i.e., how much power is being accumulated by or consumed from the storage, because the condition $Power_{out}(t) > Power_{in}(t)$ is unsustainable regardless of the behavior of the storage.

At a Source, we set $Power_{in}(t) = P_{max}$ (a parameter of the element). Therefore, SI(t) will depend solely on the $Power_{out}(t)$ imposed from the connected processes.

This sustainability concept, local to nodes in a system, is not present in ESL and is not a matter to be captured at the e*m*ergy facet[3].

In the next figure, we show the results of a scenario where we reduced by a factor of four the constant inflow of mass supplied by nature (rain) into the renewable storage (aquifer, C_a). The figure presents the impact of this change on the second storage (consumption, C_c).

---

[3] An E*m*ergy Sustainability Index (ESI) exists that depends in turn on other e*m*ergy-based indices relying on qualitative tagging. While e*m*ergy-based indices are a useful tool, they are of a relative nature: they depend on arbitrary choices made for e.g. the tagging procedure or the system boundary definition. In contrast, our SI indicator is based on energy, and is locally unambiguous for each junction where it is evaluated, regardless of assumptions made elsewhere.

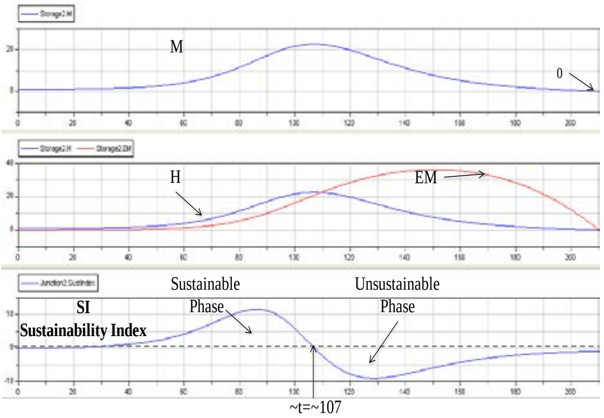


Figure 16: Scenario 1: Baseline with natural inflow reduced by four. Curves are for the second storage.

Contrary to the baseline scenario where we decided to finish the simulation at t_f=400, the simulation stops at t_f=210 in this second scenario, because C_c gets emptied and cannot supply anymore the demanded flow of energy.

In the bottom panel of Figure 16, we plotted SI(t). We can see that for times t_f>107 sec., SI(t) assumes negative values indicating the beginning of an unsustainable phase. The simulation never recovers from this unsustainable operational mode leading to the total depletion of C_c before its donor process can replenish it drawing from C_a. Of course, it can happen that a system experiences temporary phases of unsustainable operation from which it subsequently recovers. Such temporary unsustainable regions should be a reason for concern, but may be acceptable if no better alternative can be found.

$SI(t) < 0$ is an indication of an *instantaneous* mode of operation that *cannot be sustained forever*. This information is not intuitive and cannot be immediately derived from observing independently any of the main variables analyzed so far in any of the three facets considered.

A potential advantage of this indicator is that it can be propagated locally from a Junction to all its connected processes, opening up the possibility of designing rules of decisions to be made by processes reacting to this new knowledge. For example, the process drawing from storage C_a could shut down for a while when the storage level of C_a becomes too low, thereby granting the source enough time to replenish the storage.

7. MODELICA AS THE MODEL ENCODING LANGUAGE

We took advantage of the BG modeling framework as the foundation onto which to build and extend ideas of energy- and e*m*ergy-oriented modeling of CDSMs.

We implemented the core set of EcoBG models in Dymola, a Modelica-based modeling and simulation environment.

There are further relevant implications of having chosen this path.

7.1.1. Modeling aspects

Rather than being a traditional sequential programming language, Modelica is a mathematical modeling language that expresses mathematical relations using an object-oriented declarative textual (eventually also graphically rich) interface. A Modelica compiler checks not only for syntax errors or code completeness, but most importantly also for soundness and solvability of the set of mathematical equations encoded in the model.

Modelica features also model inheritance capabilities that make model development efficient and robust. For example, the Process models used in our examples differ in their laws governing mass and energy, but they all follow the same rule at the emergy facet (namely, they all pass along the emergy flow from input to output). This facet can then be coded once in a base “template” Process model, so that every new specialized process will inherit this functionality. Changes in the template Process will then be automatically inherited by all models that are based on that template, while retaining their specializations.

Benefitting from the latter, full subsystems can also be declared as new self-contained classes hiding away inner intricacies, exposing only selected input and output interfaces, and assigning them with convenient graphical decorators. This feature would make it straightforward to build a library of e*m*ergy models following Odum’s ESL iconography while actually building them using EcoBG as the underlying plumbing technology.

Also very important for productivity, teamwork, and scientific communication, Modelica models are self documentable.

7.1.2. Simulation aspects

Modelica models can be run by any tool adhering to the language specification, which is open and standardized.

Advanced Modelica implementations, such as Dymola, offer robust integration algorithms for simulating models that are potentially difficult to deal with, such as models with a high degree of stiffness and/or heavy discontinuities. Most of the classical ESL implementations are rather weak in this respect, offering e.g. only a fixed-step Forward Euler algorithm as their simulation engine.

The dangers of relying on only one (or a reduced set of entry-level) solvers can be high. Dynamic models of even low complexity can already present serious numerical difficulties[4]. Hence drawing conclusions about sustainability issues in CDSMs by trusting outcomes of simulations tested with only one primitive numerical method is not recommended.

In this same context, having a mathematical encoding language that allows a piece of code to be

---

[4] E.g. a simple second-order model, such as a predator-prey model, whose trajectory solution is known to enter a stable oscillation (i.e., it exhibits a limit-cycle solution) can end up showing unstable behavior if a too large step size is chosen.

interpreted by different tools with different strengths is a considerable advantage, as models can gain more credibility and acceptance in a potentially wider community of users.

The clean separation between the modeling aspects and the simulation aspects embraced by Modelica offers an important advantage of our approach in the analysis of complex systems.

8. CONCLUSIONS

We presented EcoBG, a novel energy-based modeling framework for complex dynamic systems with a focus on sustainability and e*m*ergy flows.

By tracking simultaneously flows of mass and their attached specific enthalpy and e*m*ergy, EcoBG can check for the thermodynamic feasibility of the models, pinpointing physically unfeasible phases that cannot be detected in advance via static inspections of the model's definition.

EcoBG offers a low-level, domain-independent plumbing technology useful for building higher-level components tailored for specific application domains or modeling communities.

EcoBG was specifically designed with generality and scalability in mind. Models of increasing complexity can be built hierarchically while preserving all energy self-checking features. With EcoBG we offer a sound framework into which to embed the basic ideas behind e*m*ergy tracking, naturally lending to a mathematical formulation of emergy dynamics that circumvents the physically awkward original proposition of switching differential equations.

Although not demonstrated in this article, also available in EcoBG is the ability to simulate models with only partial knowledge about the specific enthalpy values associated with flows of masses. By only stating specific enthalpy values at sources, EcoBG will automatically choose values for unknown specific enthalpy values throughout the inner system that do not violate energy conservation principles. This can be very helpful at the early exploratory stages of a modeling process.

An EcoBG model can also be connected with other types of Modelica models. This makes it possible to mix sustainability models with other model types based on first principles in different physical domains (e.g. mechanic, electric, hydraulic, etc.) drawing from the Modelica Standard Library (MSL) (Modelica 2013b), which offers a rich palette of sophisticated models covering many physical phenomena from a wide range of energy domains.

Also benefitting from the Modelica underlying technologies, a wealth of optimization/automatic control techniques becomes easily accessible and applicable in EcoBG. An example of this could be designing processes that self-adapt their consumption/production rates according to (possibly sophisticated combinations of) dynamically calculated sustainability indices.

This is very appealing for studying sustainability of systems involving interactions between natural and industrial processes, as for the latter we can readily inherit a vast knowledge base of models developed within the Modelica community over many years.

9. NEXT STEPS

We are still one important step away from claiming EcoBG to be a full-fledged technology in terms of its emergy accounting capabilities.

There exist definite rules, called Emergy Algebra (Brown and Herendeen 1996) to assign e*m*ergy to flows of energy in special situations, such as e.g. a process generating more than one output (by-products), an output being split after it left a process (flow splits), etc. Among these, the most relevant in our view is the rule stating that emergy shall not be counted twice when recirculating through a process that it had passed through already once after completing a feedback loop - e.g. material recycling-.

In EcoBG, we are currently forced to manually deactivate the emergy carried by flows passing through a feedback loop. This implies that the user needs to detect in advance all looping flows, an approach that is clearly error prone (or even unfeasible when the size of the system grows). Yet, human-assisted approaches to feedback loops are the de facto norm in most ESL implementations today (with the EmSim simulator (Valyi and Ortega 2004) being an exception to the rule). We shall make EcoBG capable of dealing with automated loop detection rules in the next version of the formalism. We shall also supply a richer set of higher-level customized models, in particular PROC elements implementing well known functional relationships in sustainability science.

REFERENCES

Allen, T.F.H., Hoekstra, T.W., 1990. The confusion between scale-defined levels and conventional levels of organization in ecology, *Journal of Vegetation Science*, 1(1), 5–12.

Allen, T.F.H., Starr, T.B., 1982. *Hierarchy Perspectives for Ecological Complexity*. Chicago: The University of Chicago Press. XVI, 310 p.

Baral, A., Bakshi, B.R., 2009. Thermodynamic metrics for aggregation of natural resources in life cycle analysis: insight via application to some transportation fuels, *Environmental Science & Technology*, 44(2), 800–807.

Borutzky, W., 2010. *Bond Graph Methodology: Development and Analysis of Multidisciplinary Dynamic System Models*, London: Springer-Verlag. XXII, 662 p.

Breckling, B., Jopp, F., Reuter, H., 2011. Historical background of ecological modelling and its importance for modern ecology. In: *Modelling Complex Ecological Dynamics*, 29–40.

Brown, M.T., Herendeen, R.A., 1996. Embodied Energy Analysis and Emergy analysis: a comparative view. *Ecological Economics*, 19, 219–235.

Brown, M.T., Ulgiati, S., 1997. Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation, *Ecological Engineering*, 9(1-2), 51–69.

Campbell, D.E., 2000. Using energy systems theory to define, measure, and interpret ecological integrity and ecosystem health. *Ecosystem Health*, 6(3), 181–204.

Cellier, F.E., Greifeneder, J., 2008. ThermoBondLib, a new Modelica library for modeling convective flows, *Proceedings of the 6th International Modelica Conference*, Bielefeld, Germany. Vol. 1, 163–172.

Cellier, F.E., Nebot, A., 2005. The Modelica bond graph library, *Proceedings of the 4th International Modelica Conference*, Hamburg, Germany. Vol. 1, 57–65.

Cellier, F.E., 1991. Continuous system modeling. New York: Springer-Verlag. XXVIII, 755 p.

Dymola Homepage. Available from: http://www.dynasim.se/ [accessed 15 July 2013]

Fischlin, A., 1991. Interactive modeling and simulation of environmental systems on workstations. In: Möller, D.P.F., Richter, O. (eds.) *Analysis of Dynamic Systems in Medicine, Biology, and Ecology*. Berlin: Springer-Verlag, 131–145.

Fritzson, P., et al., 2002. The open source Modelica project, *Proceedings of the 2nd International Modelica Conference*, Oberpfaffenhofen, Germany, 297–306.

Haberl, H., et al., 2006. The energetic metabolism of the European Union and the United States: decadal energy input time series with an emphasis on biomass. *Journal of Industrial Ecology*, 10(4), 151–171.

Hau, J.L., Bakshi, B.R., 2004. Promise and problems of emergy analysis. *Ecological Modelling*, 178(1–2), 215–225.

Modelica Homepage. Available from: https://modelica.org/ [accessed 15 July 2013]

Modelica Association. The Modelica Standard Library. Available from: https://www.modelica.org/libraries [accessed 15 July 2013]

Odum, E.P., 1954. *Fundamentals of Ecology*. Reprinted ed., Philadelphia: Saunders. 384 p.

Odum, H.T., 1971. *Environment, Power and Society*. New York: Wiley-Interscience, 331 p.

Odum, H.T., 1983. *Systems Ecology: An Introduction*. New York: Wiley. XV, 644 p.

Odum, H.T., 1988. Energy, *Environment and Public Policy: A Guide to the Analysis of Systems*. UNEP Regional Seas Reports and Studies. The Hague: UNEP. 109 p.

Odum, H.T., 1994. *Ecological and General Systems*. 3rd ed., Niwot: University Press of Colorado, XV, 644 p.

Odum, H.T., 1996. *Environmental Accounting: Emergy and Environmental Decision Making*. New York: Wiley. IX, 370 p.

O'Neill, R.V, Deangelis, D.L., Waide, J.B., Allen, G.E., 1986. *A Hierarchical Concept of Ecosystems*. Monographs in Population Biology, 23. Princeton University Press. 253 p.

Rockström, J., et al., 2009. Planetary boundaries, a safe operating space for humanity. *Nature*, 461(7263), 472–475.

Tilley, D.R., 2011. Dynamic Emergy Accounting: A review, mathematical revisions, and implications for modeling emergy recycling. *Emergy Synthesis 6: Theory and Applications of the Emergy Methodology*, Center for Environmental Policy, Gainesville, FL.

Valyi, R., Ortega, E., 2004. Emergy Simulator: An open source simulation platform dedicated to systems ecology and emergy studies. *Proceedings of the IV International Biennial Workshop Advances in Energy Studies*, Brazil, 349–360.

Zimmer, D., Cellier, F.E., 2006. The Modelica multi-bond graph library, *Proceedings of the 5th International Modelica Conference*, Vienna, Austria. Vol. 2, 559–568.

AUTHORS BIOGRAPHY

Rodrigo Castro received his Electronic Engineer (MASc-EE) (2004) and PhD (2010) degrees from the National University of Rosario (UNR), Argentina. Since 2007 he is a Lecturer at the Computer Science Department, School of Exact and Natural Sciences, University of Buenos Aires (UBA), Argentina. In 2011, he was appointed an Assistant Researcher at the National Scientific and Technical Research Council (CONICET), Argentina. Since 2008 he visits regularly the Carleton University in Ottawa, Canada, and since 2012 he is a postdoc visiting researcher at ETH Zurich, Switzerland. He received an Emerging Leaders in the Americas award in 2008 from the Government of Canada and in 2013, and he was awarded the DEVS Best Ph.D. Dissertation Award by the Society for Modeling and Simulation International (SCS).

François E. Cellier received his BS degree in electrical engineering in 1972 and his PhD degree in technical sciences in 1979 from the Swiss Federal Institute of Technology (ETH) Zurich. Dr. Cellier worked at the University of Arizona as professor of Electrical and Computer Engineering from 1984 until 2005. He then returned to his home country of Switzerland and his alma mater. He has authored more than 200 technical publications. He published a textbook on Continuous System Modeling in 1991 and a second textbook on Continuous System Simulation in 2006, both with Springer-Verlag, New York. He is a fellow of the Society for Modeling and Simulation International (SCS).

Andreas Fischlin studied Biology and Systems Theory and did ecological research in Canada. He returned to Switzerland ETH Zurich to teach systems ecology and computer science. He played a leading role in the design and formation of the novel curriculum and department Environmental Sciences at ETH Zurich. He was presented the Peace Nobel Prize 2007 as awarded to IPCC for his work as coordinating lead author in the 2nd and 4th Assessment Report of IPCC. He represents Swiss scientists in the Swiss delegation in UNFCCC negotiations and has published numerous scientific works, notably on climate change impacts on Ecosystems.

ENVIRONMENTAL PERFORMANCE OF GLOBAL SUPPLY CHAINS OBSERVED THROUGH EXTENDED MATERIAL REQUIREMENTS PLANNING SIMULATION MODEL

Danijel Kovačić(a), **Marija Bogataj**(b)

(a)Danijel Kovačić s.p., Grič 4, SI-1000 Ljubljana, Slovenia
(b)MEDIFAS, Mednarodni prehod 6, SI-5290 Šempeter pri Gorici, Slovenia

(a) kovacic.danijel@gmail.com, (b)marija.bogataj@guest.arnes.si

ABSTRACT

Every economy in the globalized world consists of a network of different supply chains. Supply chain is a complex system of various activity cells. Some of them correspond to production and others to distribution and consumption activities. The loop is closed when consumption and production subsystems are connected – used items enter a new production cycle as recycled/reused inputs. Outputs of such system are waste products and pollution which is a result of any of the activities inside the supply chain. Extended Material Requirements Planning (EMRP) Theory provides a powerful tool capable of describing all of the relations in such complex systems. Theory uses input-output analysis for characterization of the structures; Laplace transforms for proper incorporation of lead times; and Net Present Value (NPV) calculation for proper evaluation of supply chain's economic performance. This paper presents an analytical tool for simulations, which are essential to a deeper understanding of global supply chains, with emphasis on the environmental component.

Keywords: Extended Material Requirements Planning (EMRP) Theory, environmental factors, energy, input-output analysis.

1. INTRODUCTION

Material Requirements Planning (MRP) Theory rapidly developed during the last two decades of the 20th century as a scientific answer to practical success of MRP in multi-stage, multi-level production systems (Orlicky 1975). The theory is inspired by many famous scientific approaches, such as input-output analysis (Leontief 1970), activity analysis (Koopmans 1951), scientific programming (Vazsonyi 1958) and Laplace transforms. It proves that using a set of input-output matrices **H** and **G** is the most convenient method for mathematical description of products' complex structures. In practice, structures are usually presented schematically in the Bill of Materials (BOM). Lead times are assigned to these structures using Laplace transforms. This combination gives us a sufficient basis for calculation of Net Present Value (NPV), and thus allows for economic analysis of complex production/inventory systems. A good overview of the evolution of MRP Theory can be found in Grubbström and Tang (2000). The first practical application of Theory's scientific approach to the MRP production systems was successfully done in the case of Paper mill company (Grubbström 1990).

MRP Theory has been recently recognized as an extremely useful method for in-depth studies of not only production systems but also complete supply chains. The so-called Extended Material Requirements Planning (EMRP) Theory extends the model to distribution and consumption activities and to reverse logistics at the end of the chain. Integration of additional subsystems forms a closed loop where some elements are circulating inside the grid, and the rest are lost (usually as waste or any kind of pollution). These lost elements have to be replaced with additional purchases if we want to complete the next production cycle and maintain the system closed.

Production is usually treated as an assembly system where components on a particular level are assembled using elements from a previous assembly level, according to the BOM. On the other hand, products are distributed from one location to several distribution centres and end consumers. This type of system can be presented using reverse BOM and is called arborescent system. Bogataj, Grubbström, and Bogataj (2011) introduce lead times as an integral part of a system at any activity cell, belonging either to assembly or arborescent subsystem. A generalized output matrix is introduced to cover arborescent activities, such as distribution or disassembly/recycling (Bogataj and Grubbström 2012).

Such complete examination of supply chains allows us to integrate different environmental factors as essential parts of the system. Long-term general welfare of the human race cannot be measured only in terms of economic benefits of production and consumption activities. It is also significantly affected by limited natural resources, sources of energy and pollution caused by production, transportation and consumption activities. Bogataj and Grubbström (2013) model the cyclical system consisting of 4 subsystems: production, distribution, consumption and recycling. Cyclical flow of elements in the system between any pair of system's activity cells is captured using input-output matrices **H** and **G**. Special attention is given to the recycling subsystem, where:

- Consumption subsystem appears as an output of used final products. Final products at the end of their lifecycle are therefore inputs into recycling subsystem.
- Reusable outputs of the recycling subsystem are successfully recycled items. They are distributed to production activity cells at the start of the next production cycle.
- Unusable outputs of the recycling subsystem are waste elements. They have to be disposed of at landfills. In order to start the next production cycle, these missing lots of elements have to be replaced with additional purchases on the market.
- Lead times appear inside every activity cell (i.e. production or recycling lead times) or between a pair of activity cells (transportation lead times).
- NPV of such a system can be calculated. This allows us to observe the effect of different parameters on overall economic performance of the system, such as environmental taxes, transportation distances between the nodes, etc.

Such a cyclical system is illustrated in Figure 1. Detailed structure of input-output matrices **H** and **G** and relations between the nodes have been analysed by Kovačić and Bogataj (2011). They show that every activity cell of the system can serve as an input into the recycling subsystem and that every element of the system can be traced over several cycles. Further, Kovačić and Bogataj (2013) show how optimal location of recycling activity cell can be determined using EMRP Theory. Among other environmental factors, they point out availability and prices of energy, which can, in some cases, also act as an usable output of the system.

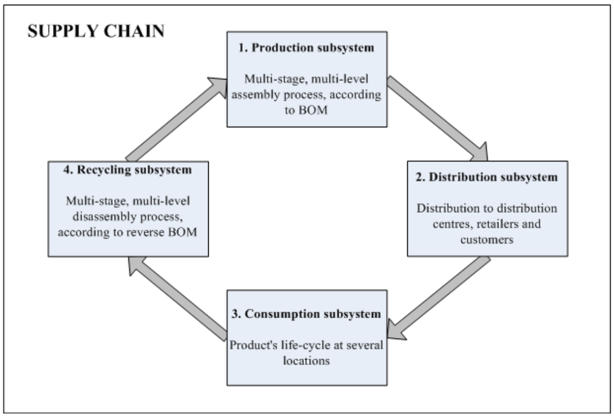


Figure 1: Supply Chain consisting of 4 Subsystems

An environmentally inappropriate structure of a supply chain can lead to a long-term negative overall NPV of the system. Investments into infrastructure which reduces pollution and/or energy consumption or, on the other hand, decreases the volume of scrap and waste, can radically change the overall performance of a supply chain. The integrity, complexity and richness of information in the EMRP Theory make the model an extremely powerful tool for various simulations (Kovačić and Bogataj 2012). The idea of simulating the performance of a supply chain using EMRP Theory stems from Köchel's works on simulating production and inventory systems (Köchel 2009). Simulations based on EMRP Theory can deepen our understanding of supply chains. We can simulate macroeconomic factors and try to find optimal decisions for global, regional or local ecological balance: i.e. optimal environmental taxation can be determined for a specific geographical area. On the other hand, simulations can also be a powerful and useful tool to assist managers in the decision making process. A practical example of usability in the industry can be found in Kovačić, Hontoria, Bogataj, and Ros (2012), where authors use EMRP Theory for economic-ecologic optimization of production processes in a Spanish baby food company. Using simulations, they show how investments into optimisation of the production process, which result in lower volumes of scrap materials, affect long-term NPV. The result is a set of possible solutions, not all of which are technologically feasible. Optimal investment decisions should be made according to feasible solutions found in the set of possible solutions. The solution with the highest long-term NPV is the optimal one.

The purpose of this paper is to present some of the possible simulations of complete supply chains. We will show that EMRP Theory provides an excellent basis for such in-depth research and also decision making. The main advantage of EMRP Theory approach is that research is not isolated only to a part of the problem, but takes into consideration the entire supply chain with all activity cells. This enables us to observe the entire system when any of the input parameters is changing.

2. METHODOLOGY

The structure of global supply chains can be roughly described through 4 main subsystems: 1 - Production, 2 - Distribution, 3 - Consumption and 4 - Recycling, according to Figure 1. The input requirements of the system (**x**) can then be written as:

$$\mathbf{x} = \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \mathbf{x}_3 \\ \mathbf{x}_4 \end{bmatrix} = \begin{bmatrix} \mathbf{H}_{11}\mathbf{H}_{12}\mathbf{H}_{13}\mathbf{H}_{14} \\ \mathbf{H}_{21}\mathbf{H}_{22}\mathbf{H}_{23}\mathbf{H}_{24} \\ \mathbf{H}_{31}\mathbf{H}_{32}\mathbf{H}_{33}\mathbf{H}_{34} \\ \mathbf{H}_{41}\mathbf{H}_{42}\mathbf{H}_{43}\mathbf{H}_{44} \end{bmatrix} \begin{bmatrix} \mathbf{P}_1 \\ \mathbf{P}_2 \\ \mathbf{P}_3 \\ \mathbf{P}_4 \end{bmatrix} = \mathbf{HP} \qquad (1)$$

In the above notation, input matrix **H** consists of several sub-matrices $\mathbf{H}_{ij}$, each of them representing item requirements of subsystem *i* from running processes in subsystem *j*. Each sub-matrix $\mathbf{H}_{ij}$ consists of several technological coefficients h_{kl}^{ij}, describing input requirements for each activity cell in the system. Detailed analysis of the sub-matrices' complex structures can be found in Kovačić and Bogataj (2011). Further, **P** is activity vector. Its sub-vectors $\mathbf{P}_1$, $\mathbf{P}_2$, $\mathbf{P}_3$ and $\mathbf{P}_4$ belong to each of the 4 subsystems and represent constants: i.e. they describe the total volumes of elements at each activity level of the system during each cycle. Similar, $\mathbf{x}_i$ can be interpreted as input requirements of subsystem *i*, where $i = 1, 2, 3, 4$. When the *l*-th process is run on activity level P_l^j inside subsystem *j*, the amount of required inputs (x_k^i) of item *k* is $h_{kl}^{ij} P_l^j$.

We can present outputs of the system (**y**) in a similar manner:

$$\mathbf{y} = \begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \\ \mathbf{y}_3 \\ \mathbf{y}_4 \end{bmatrix} = \begin{bmatrix} \mathbf{G}_{11}\mathbf{G}_{12}\mathbf{G}_{13}\mathbf{G}_{14} \\ \mathbf{G}_{21}\mathbf{G}_{22}\mathbf{G}_{23}\mathbf{G}_{24} \\ \mathbf{G}_{31}\mathbf{G}_{32}\mathbf{G}_{33}\mathbf{G}_{34} \\ \mathbf{G}_{41}\mathbf{G}_{42}\mathbf{G}_{43}\mathbf{G}_{44} \end{bmatrix} \begin{bmatrix} \mathbf{P}_1 \\ \mathbf{P}_2 \\ \mathbf{P}_3 \\ \mathbf{P}_4 \end{bmatrix} = \mathbf{GP} \tag{2}$$

Output matrix **G** coincides in dimension with input matrix **H**, and its sub-matrices $\mathbf{G}_{ij}$ represent outputs of subsystem *j* because of activities in subsystem *i*. The amount of produced outputs (y_l^i) of item *k* is $g_{kl}^{ij} P_l^j$.

Overall net production (**y**) of such system is then:

$$\mathbf{z} = \begin{bmatrix} \mathbf{z}_1 \\ \mathbf{z}_2 \\ \mathbf{z}_3 \\ \mathbf{z}_4 \end{bmatrix} = \mathbf{y} - \mathbf{x} = \begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \\ \mathbf{y}_3 \\ \mathbf{y}_4 \end{bmatrix} - \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \mathbf{x}_3 \\ \mathbf{x}_4 \end{bmatrix} = (\mathbf{G} - \mathbf{H})\mathbf{P} \tag{3}$$

where $\mathbf{z}_i$ is net production of subsystem $i = 1, 2, 3, 4$.

To facilitate understanding, the presented model can be illustrated as numerical example. Figure 2 shows a closed cyclical system where the final product A is assembled according to the BOM: 2 units of elements B and E are used to assemble 1 unit of A; 4 units of element C and 2 units of element E are used to assemble 1 unit of B; 2 units of element D are used to assemble 1 unit of C. Elements D and E can be interpreted as raw materials. They can be extracted during recycling activities and reused in the next production cycle or bought on the market. We assume that 20% of lots of any produced component (B, C) or final product (A) never reach higher assembly or distribution levels. These are scraps from production, components or products of insufficient quality, damaged components or products, lost production, etc. These elements all enter the recycling subsystem from where they can be either recycled or treated as. Remaining 80% of produced final amount of product A enters distribution subsystem: we assume that 75% is distributed to location 1 and another 25% to location 2. Again, 20% is lost during the distribution and enters the recycling subsystem. 80% of distributed products reach end customers. From the consumption subsystem, all used products are sent to the recycling subsystem at the end of their lifecycle. Recycling is a disassembly process where components and final products are disassembled according to reverse BOM. In this numerical example, we suppose that all elements are totally disassembled, therefore outputs of recycling are primary raw materials which can be reused in the next production cycle. The missing amount of raw materials has to be replaced with additional purchases on the market. We assume that 14.2% of all elements E, which are used directly in the assembly of the final product A, are successfully recycled. Further, 19.6% of element E, which is used in assembly of component B, is successfully recycled. We can also reuse 55.6% of element D.

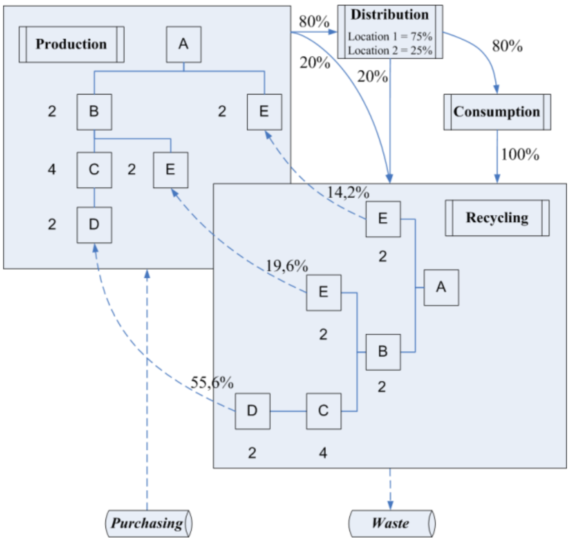


Figure 2: Numerical Example of Production, Distribution, Consumption and Recycling of Product A

The system shown in Figure 2 can now conveniently be written in mathematical form of input and output matrices **H** and **G**:

$$\mathbf{H} = \left[\begin{array}{ccc|c|c|ccc} & & & 0.8 & & & & \\ & & & & & 0.2 & & \\ 2 & & & & & & & \\ & & & & & & 0.2 & \\ & 4 & & & & & & \\ & & & & & & & 0.2 \\ & & 2 & & & & & \\ 2 & 2 & & & & & & \\ \hline & & & & 0.8 \ast 0.8 \ast 0.75 & & & \\ & & & & 0.8 \ast 0.8 \ast 0.25 & & & \\ & & & & & 0.8 \ast 0.2 & & \\ \hline & & & & & 0.8 \ast 0.8 & & \\ \hline & & & & & & & \\ & & & & & & & \end{array} \right] \tag{4}$$

$$\mathbf{G} = \left[\begin{array}{ccc:c:c:ccc}
0.8 & & & & & & & \\
0.2 & & & & & & & \\
 & 0.8 & & & & & & \\
 & 0.2 & & & & & & \\
 & & 0.8 & & & & & \\
 & & 0.2 & & & & & \\
 & & & & & & & 2*0.142 \\
 & & & & & 2*0.556 & 2*0.196 & \\
\hdashline
 & & & 0.8*0.8*0.75 & & & & \\
 & & & 0.8*0.8*0.25 & & & & \\
 & & & 0.8*0.2 & & & & \\
\hdashline
 & & & & 0.8*0.8 & & & \\
\hdashline
 & & & & & & & 2*0.858) \\
 & & & & & 2*0.444 & 2*0.804 &
\end{array}\right] \tag{5}$$

In each production cycle, 1000 units of the final product A are assembled, which requires 2500 units of component B and 12500 units of component C. Activity vector **P** can therefore be written as:

$$\mathbf{P} = \left[\begin{array}{c}
1000 \\
2500 \\
12500 \\
\hline
1000 \\
\hline
1000 \\
\hline
1000 \\
2500 \\
12500
\end{array}\right] \tag{6}$$

Another main pillar of the EMRP Theory is lead times. Proper incorporation of lead times into the model can be done with transformations of time functions into Laplace transforms in the frequency domain. Time function *f*(*t*) can only exist in non-negative time, and its Laplace transform is defined as:

$$\tilde{f}(s) = \pounds\left\{f(t)\right\} = \int_{t=0}^{\infty} f(t)e^{-st}dt \tag{7}$$

where s is the complex frequency. Function is transformed back to time domain with inverse Laplace transformation:

$$f(t) = \pounds^{-1}\left\{\tilde{f}(s)\right\} \tag{8}$$

In MRP as well as EMRP Theory we usually use the following theorems in main analyses:

- Time integration theorem:

$$\pounds\left\{\int_0^t f(\beta)d\beta\right\} = \pounds\left\{f(t)\right\}/s \tag{9}$$

- Time average theorem:

$$\lim_{t\to\infty}\frac{1}{t}\int_0^t x(\tau)d\tau = \lim_{s\to 0} s\tilde{x}(s) \tag{10}$$

- Net present value theorem, where complex frequency s is replaced with continuous interest rate ρ:

$$\mathrm{NPV} = \int_0^\infty a(t)e^{-\rho t}dt = \tilde{a}(\rho) \tag{11}$$

- Time translation theorem, where function is translated uniformly forward in time:

$$\pounds\left\{f(t-\tau)\right\} = \pounds\left\{f(t)\right\}e^{-s\tau} = \tilde{f}(s)e^{-s\tau} \tag{12}$$

- Time translation theorem, where function is translated uniformly backward in time:

$$\pounds\left\{f(t+\tau)\right\} = \pounds\left\{f(t)\right\}e^{s\tau} = \tilde{f}(s)e^{s\tau} \tag{13}$$

We denote τ_j as a lead time before the start of production *t*, when $h_{ij}P_j(t)$ units of elements *i* are needed for production of a batch $P_j(t)$ of elements *j*. Production lead time matrix can be written as:

$$\tilde{\boldsymbol{\tau}}(s) = \begin{bmatrix} e^{s\tau_1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & e^{s\tau_m} \end{bmatrix} \tag{14}$$

and the generalized input matrix consisting of both product structures and production lead times as:

$$\tilde{\mathbf{H}}(s) = \mathbf{H}\tilde{\boldsymbol{\tau}}(s) \tag{15}$$

In global supply chains, not only production but also other types of lead times make a significant contribution to the overall performance of a system. Especially noteworthy are transportation lead times which can differ between any pair of neighbouring activity cells. In this case, further generalisation of the input matrix is required:

$$\breve{\mathbf{H}}(s) = \tilde{\mathbf{H}}^{tr}(s)\tilde{\boldsymbol{\tau}}^{pr}(s) \tag{16}$$

Individual lead times can be assigned to each technical coefficient h_{ij} inside $\tilde{\mathbf{H}}^{tr}$: $h_{ij}e^{s(\tau_{ij})^{tr}}$. Similar assumptions can be made concerning generalized output matrix $\breve{\mathbf{G}}(s)$.

Generalized input and output matrices thus consist of all physical structures and transitions together with all lead times in the system, which appear at any of its stages (production, distribution and recycling lead times, lead times in energy distribution, lead times of waste decomposition, etc.):

$$\breve{\mathbf{H}}(s)=\begin{bmatrix}\breve{\mathbf{H}}_{11}(s) & \breve{\mathbf{H}}_{12}(s) & 0 & \breve{\mathbf{H}}_{14}(s)\\ 0 & 0 & \breve{\mathbf{H}}_{23}(s) & \breve{\mathbf{H}}_{24}(s)\\ 0 & 0 & 0 & \breve{\mathbf{H}}_{34}(s)\\ 0 & 0 & 0 & 0\end{bmatrix} \tag{17}$$

$$\breve{\mathbf{G}}(s)=\begin{bmatrix}\breve{\mathbf{G}}_{11}(s) & 0 & 0 & \breve{\mathbf{G}}_{14}(s)\\ 0 & \breve{\mathbf{G}}_{22}(s) & 0 & 0\\ 0 & 0 & \breve{\mathbf{G}}_{33}(s) & 0\\ 0 & 0 & 0 & \breve{\mathbf{G}}_{44}(s)\end{bmatrix} \tag{18}$$

Note that not all of the flows inside and between subsystems are physically feasible, so many of sub-matrices $\mathbf{H}_{ij}$ and $\mathbf{G}_{ij}$, as denoted in (1) and (2), are zero in real life.

Input and output matrices (4) and (5) from the numerical example can now be extended with lead times:

$$\breve{\mathbf{H}}(\rho)=\tilde{\mathbf{H}}^{tr}(\rho)\tilde{\boldsymbol{\tau}}^{pr}(\rho)=$$

$$\left[\begin{array}{ccc|c|c|ccc}
 & & & 0.8e^{2\rho} & & & & \\
 & & & & & 0.2e^{5\rho} & & \\
2e^{(3+3)\rho} & & & & & & & \\
 & & & & & & 0.2e^{3\rho} & \\
 & 4e^{(1+2)\rho} & & & & & & \\
 & & & & & & & 0.2e^{4\rho}\\
 & & 2e^{(5+1)\rho} & & & & & \\
2e^{(1+3)\rho} & 2e^{(3+2)\rho} & & & & & & \\
\hline
 & & & & 0.48e^{3\rho} & & & \\
 & & & & 0.16e^{5\rho} & & & \\
 & & & & & 0.16e^{6\rho} & & \\
\hline
 & & & & & 0.64e^{7\rho} & & \\
\hline
 & & & & & & & \\
 & & & & & & &
\end{array}\right] \tag{19}$$

$$\breve{\mathbf{G}}(\rho)=\tilde{\boldsymbol{\Delta}}^{pr}(\rho)\tilde{\mathbf{G}}^{tr}(\rho)=$$

$$\left[\begin{array}{ccc|c|c|ccc}
0.8e^{-5\rho} & & & & & & & \\
0.2e^{-4\rho} & & & & & & & \\
 & 0.8e^{-6\rho} & & & & & & \\
 & 0.2e^{-3\rho} & & & & & & \\
 & & 0.8e^{-6\rho} & & & & & \\
 & & 0.2e^{-4\rho} & & & & & \\
 & & & & & & & 0.284e^{(-5-3)\rho}\\
 & & & & & 1.112e^{(-4-2)\rho} & 0.392e^{(-4-3)\rho} & \\
\hline
 & & & 0.48e^{-2\rho} & & & & \\
 & & & 0.16e^{-2\rho} & & & & \\
 & & & 0.16e^{-2\rho} & & & & \\
\hline
 & & & & 0.64e^{-5\rho} & & & \\
\hline
 & & & & & & & 1.716e^{(-4-8)\rho}\\
 & & & & & 0.888e^{(-3-7)\rho} & 1.608e^{(-3-6)\rho} &
\end{array}\right] \tag{20}$$

For example, coefficient $1.112e^{(-4-2)\rho}$, which appears inside sub-matrix $\breve{\mathbf{G}}_{14}(\rho)$, describes successfully recycled element D. During the recycling process, two types of lead times are present: 4 time units are needed for disassembly process and another 2 time units for distribution back to the production subsystem. On the other hand, only 3 time units are needed when disassembly process of element D is not successful, and, due to the considerable distance to a landfill, another 7 time units are needed for distribution (coefficient $0.888e^{(-3-7)\rho}$ inside sub-matrix $\breve{\mathbf{G}}_{44}(\rho)$). Similar assumptions can be made for all other activity cells inside the input-output matrices, but most of them contain only distribution lead times.

Overall NPV of the supply chain can be calculated using equation:

$$\begin{aligned}\mathrm{NPV}=\mathbf{p}\left(\breve{\mathbf{G}}(\rho)-\breve{\mathbf{H}}(\rho)\right)\tilde{\mathbf{P}}(\rho)-\hat{\mathbf{K}}\tilde{\mathbf{v}}(\rho)-\\ -\mathbf{U}^{\mathrm{T}}\left(\tilde{\mathbf{\Pi}}_{\mathrm{G}}(\rho)+\tilde{\mathbf{\Pi}}_{\mathrm{H}}(\rho)\right)\tilde{\mathbf{P}}(\rho)-\\ -\mathbf{c}_{\mathrm{L}}\tilde{\mathbf{L}}(\rho)-\mathbf{U}^{\mathrm{T}}\left(\breve{\mathbf{E}}_{H}(\rho)-\breve{\mathbf{E}}_{G}(\rho)\right)\tilde{\mathbf{P}}(\rho)\end{aligned} \tag{21}$$

Calculation consists of all revenues from produced elements $\mathbf{p}\left(\breve{\mathbf{G}}(\rho)-\breve{\mathbf{H}}(\rho)\right)\tilde{\mathbf{P}}(\rho)$; setup costs for each production cycle $\hat{\mathbf{K}}\tilde{\mathbf{v}}(\rho)$; transportation costs $\mathbf{U}^{\mathrm{T}}\left(\tilde{\mathbf{\Pi}}_{\mathrm{G}}(\rho)+\tilde{\mathbf{\Pi}}_{\mathrm{H}}(\rho)\right)\tilde{\mathbf{P}}(\rho)$; labour cost $\mathbf{c}_{\mathrm{L}}\tilde{\mathbf{L}}(\rho)$; and energy costs $\mathbf{U}^{\mathrm{T}}\left(\breve{\mathbf{E}}_{H}(\rho)-\breve{\mathbf{E}}_{G}(\rho)\right)\tilde{\mathbf{P}}(\rho)$, where:

- **p** is price vector. p_j^i is the price of the element at stage j of subsystem i. p_1^3 is the average price of used item at the end of its life cycle and can be either positive or negative. p_j^4 can be interpreted as environmental taxes for unrecycled elements, which have to be disposed of (negative price).

$$\mathbf{p}=\left[\,p_1^1\,p_2^1\cdots p_m^1\,\middle|\,p_1^2\,p_2^2\cdots p_{(r+1)}^2\,\middle|\,p_1^3\,\middle|\,p_1^4\,p_2^4\cdots p_{(m-2n)}^4\,\right] \tag{22}$$

- $\tilde{\mathbf{v}}(\rho)$ are given timings, calculated from initial times $\tilde{\mathbf{t}}(\rho)$ and cycle lengths $\tilde{\mathbf{T}}(\rho)$:

$$\tilde{\mathbf{v}}(\rho)=\tilde{\mathbf{t}}(\rho)\tilde{\mathbf{T}}(\rho) \tag{23}$$

- $\tilde{\mathbf{P}}(\rho)$ is activity vector with given timings (cycles):

$$\tilde{\mathbf{P}}(\rho)=\tilde{\mathbf{v}}(\rho)\mathbf{P} \tag{24}$$

- $\hat{\mathbf{K}}$ is a vector of setup costs.
- $\mathbf{U}^{\mathrm{T}}$ is a unit vector.
- $\tilde{\mathbf{\Pi}}_{\mathrm{H}}(\rho)$ and $\tilde{\mathbf{\Pi}}_{\mathrm{G}}(\rho)$ are matrices consisting of transportation costs for each activity cell. They coincide in dimension with input and output matrices **H** and **G**.

- $\mathbf{c}_{\mathrm{L}}$ is a vector of manpower costs per unit for each activity cell.
- $\tilde{\mathbf{L}}(\rho)=\hat{\mathbf{L}}\tilde{\mathbf{v}}(\rho)$ where $\hat{\mathbf{L}}$ is a vector of needed workforce for each activity cell.
- $\breve{\mathbf{E}}_H(\rho)$ and $\breve{\mathbf{E}}_G(\rho)$ are generalized energy input and output matrices, respectively. They coincide in dimension with input-output matrices **H** and **G**, and consist of both technical coefficients and lead times. Note that the model allows energy to appear as an output of recycling activities, which is extremely important from the environmental point of view and for long-term sustainability of supply chains.

Using above notation, initial values for numerical example are:

$$\mathbf{p}=\left[2500\ \ 800\ \ 150\ \ 100\ \ 30\ \ 20\ \ 10\ \ 5\,|\,2700\ \ 2600\ \ 250\,|\,20\,|\,-5\ \ -4\right] \tag{25}$$

$$\hat{\mathbf{K}}=\left[5600\quad 3000\quad 2500\,|\,1100\,|\,1150\,|\,800\quad 6700\quad 5800\right] \tag{26}$$

$$\tilde{\mathbf{v}}(\rho)=\left[6956\quad 4034\quad 2397\,|\,3369\,|\,2535\,|\,5310\quad 3940\quad 1316\right]^T \tag{27}$$

$$\mathbf{c}_{\mathrm{L}}=\left[0,03\quad 0,04\quad 0,05\quad 0,07\quad 0,08\quad 0,01\quad 0,02\quad 0,01\right] \tag{28}$$

$$\tilde{\mathbf{\Pi}}_H(\rho)==\left[\begin{array}{ccc|c|c|ccc}
 & & & 16.000 & & & & \\
 & & & & & 12.000 & & \\
26.260 & & & & & & & \\
 & & & & & & 4.200 & \\
 & 0.000 & & & & & & \\
 & & & & & & & 8.000 \\
 & & 10.305 & & & & & \\
6.565 & 12.742 & & & & & & \\
\hline
 & & & & 0.000 & & & \\
 & & & & 0.000 & & & \\
 & & & & & 0.000 & & \\
\hline
 & & & & & 0.000 & & \\
\hline
 & & & & & & & \\
 & & & & & & &
\end{array}\right] \tag{29}$$

$$\tilde{\mathbf{\Pi}}_G(\rho)=\left[\begin{array}{ccc|c|c|ccc}
0.000 & & & & & & & \\
0.000 & & & & & & & \\
 & 0.000 & & & & & & \\
 & 0.000 & & & & & & \\
 & & 0.000 & & & & & \\
 & & 0.000 & & & & & \\
 & & & & & & & 8.800 \\
 & & & & & 3.945 & 2.086 & \\
\hline
 & & & 7.680 & & & & \\
 & & & 2.240 & & & & \\
 & & & 1.280 & & & & \\
\hline
 & & & & 19.200 & & & \\
\hline
 & & & & & & & 24.351 \\
 & & & & & 28.405 & 44.088 &
\end{array}\right] \tag{30}$$

$$\breve{\mathbf{E}}^H(\rho)=$$

$$\left[\begin{array}{ccc|c|c|ccc}
 & & & & & & & \\
 & & & & & 3.7*0.2e^{5\rho} & & \\
1.2*2e^{(0+3)\rho} & & & & & & & \\
 & & & & & & 2.9*0.2e^{3\rho} & \\
 & 1.3*4e^{2\rho} & & & & & & \\
 & & & & & & & 2.7*0.2e^{4\rho} \\
 & & 1.1*2e^{1\rho} & & & & & \\
1.4*2e^{3\rho} & 1.7*2e^{2\rho} & & & & & & \\
\hline
 & & & & & & & \\
 & & & & & & & \\
 & & & & & 2.2*0.16e^{6\rho} & & \\
\hline
 & & & & & 2.3*0.64e^{7\rho} & & \\
\hline
 & & & & & & & \\
 & & & & & & &
\end{array}\right] \tag{31}$$

$$\breve{\mathbf{E}}^G(\rho)=$$

$$\left[\begin{array}{ccc|c|c|ccc}
 & & & & & & & \\
 & & & & & & & \\
 & & & & & & & \\
 & & & & & & & \\
 & & & & & & & \\
 & & & & & & & \\
 & & & & & & & 3.9*0.284e^{(-5-3)\rho} \\
 & & & & & 3.9*1.112e^{(-4-2)\rho} & 4.5*0.392e^{(-4-3)\rho} & \\
\hline
 & & & & & & & \\
 & & & & & & & \\
 & & & & & & & \\
\hline
 & & & & & & & \\
\hline
 & & & & & & & 0.9*1.716e^{(-4-8)\rho}e^{-3\rho} \\
 & & & & & 0.7*0.888e^{(-3-7)\rho}e^{-2\rho} & 0.5*1.608e^{(-3-6)\rho}e^{-4\rho} &
\end{array}\right] \tag{32}$$

If continuous interest rate is set to ρ = 0.025%, NPV of the system is positive and economically viable:

$$\begin{aligned}
\mathrm{NPV} &= \mathbf{p}\left(\breve{\mathbf{G}}(\rho)-\breve{\mathbf{H}}(\rho)\right)\tilde{\mathbf{P}}(\rho)-\hat{\mathbf{K}}\tilde{\mathbf{v}}(\rho)- \\
&-\mathbf{U}^{\mathrm{T}}\left(\tilde{\mathbf{\Pi}}_G(\rho)+\tilde{\mathbf{\Pi}}_H(\rho)\right)\tilde{\mathbf{P}}(\rho)- \\
&-\mathbf{c}_{\mathrm{L}}\hat{\mathbf{L}}\tilde{\mathbf{v}}(\rho)-\mathbf{U}^{\mathrm{T}}\left(\breve{\mathbf{E}}_H(\rho)-\breve{\mathbf{E}}_G(\rho)\right)\tilde{\mathbf{P}}(\rho)= \\
&=3288815.23-128072.94-2730782.89- \\
&-238660.31-164930.15=26368.94
\end{aligned} \tag{33}$$

Using the above NPV equation, we can evaluate economic performance of the whole system. Wide aspect of input parameters is covered in the model, which gives us opportunity for detailed research on supply chains and their sensitivity to common economic-environmental issues. The large number of details included in the model makes the matrix system complex, thus it is difficult to perform accurate numerical analysis. This fact makes EMRP Theory the perfect basis for conducting in-depth research with the use of simulations.

3. SIMULATIONS

We can show the usability of simulation approach in analysing environmental impacts on a supply chain using the above numerical example. Below we present some of the possible environmentally oriented analyses, but we are not limited to them. Wider aspect of research can be done in practical applications.

First, we simulate isolated impact of changes in the return rates and environmental taxation on the NPV of the system. We distinguish between two different situations:

- Recycling on a particular level is not economically viable. In the numerical example, such situation appears when element D is recycled (Figure 3).
- Recycling on a particular level is economically viable. In the numerical example, such situation appears when element E is recycled from the final product A (Figure 4), and element E is recycled from component B (Figure 5).

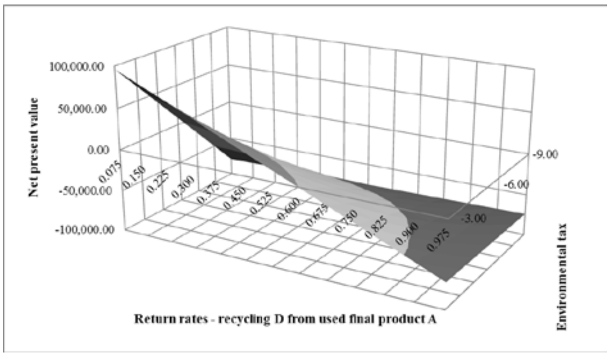


Figure 3: Recycling Element D from A is not Economically Viable

When recycling on a specific micro level is not economically viable, actors in the supply chain will have little incentive to increase recycling activities. Supply chain in such situations creates maximum profit when there are no recycling activities at all, which results in poor long-term environmental balance. Increase in recycling activities leads to a reduction of the NPV of the system. In other words, such a situation means that additional external impulses are required for a shift to more environmentally sustainable behaviour of that particular activity cell. In cases when return rates are low, any environmental tax increase will move the entire supply chain towards negative NPV. Negative overall NPV will encourage actors to change the structure of their supply chains towards more ecologically acceptable behaviour: they will either attempt to substitute element D with a more rational element; invest into research and development of technology with higher recycling efficiency; or geographically reallocate activity cells. On the other hand, if return rates in such situations are already on a high level, changes in environmental taxation will not result in a significant decrease of the overall NPV of the supply chain. Most likely, actors in a supply chain would try to cut return rates in order to generate higher profits, which would bring about negative side effect on the environment. Policy makers can prevent such negative trends or even encourage an increase of return rates with relevant legislation prescribing minimum return rates (an example is the EU Directive 2000/53/EC which prescribes minimum return rates in the automobile industry). In such situations, conflict of interest can be expected:

- Managers of activity cells will try to maximize profits (which is reflected in the maximisation of NPV of supply chains), even for a price of poor environmental balance (low return rates).
- There is a public interest in long-term sustainability of supply chains; this is reflected in the minimization of the industry's impact on the environment (low emissions, reuse of natural resources, etc).

Political leaders are responsible for achieving sustainable long-term balance. Simulating supply chains under different decisions can significantly help in finding long-term optimal solutions which will keep economy competitive and ensure nature conservation.

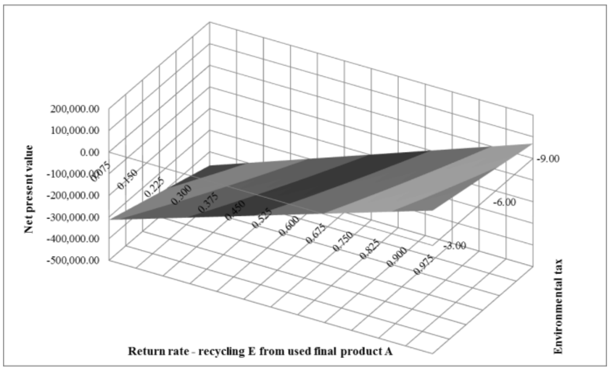


Figure 4: Recycling Element E from A is Economically Viable

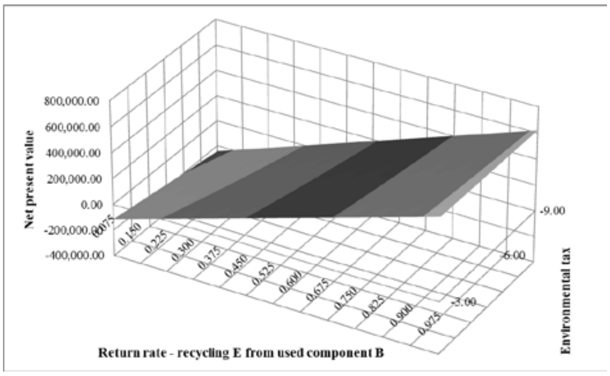


Figure 5: Recycling Element E from B is Economically Viable

A different situation is shown in Figures 4 and 5, where recycling on a specific micro level is economically viable without additional interventions of environmental policy. Economic interest of managers of activity cells coincides with the public interest in long-term sustainability. We can expect such situations to occur in a high-tech environment where recycling activities are already at a high level of development and are highly cost-effective. Similar cases can be expected when input components of the system (raw materials or components) are very rare in nature, or their extraction is difficult and associated with high costs. An environmental tax increase will not encourage recycling activities significantly if return rates are already high. However, if return rates are relatively low despite economic viability of reverse logistics, such tax increase might accelerate the transition of activity cells towards more environmentally friendly business. If we assume that the NPV of a supply chain will remain constant, we can predict achieved return rates after an environmental tax increase if we move along the area with same NPV on the graph (Figures 4 and 5).

In both of the above situations, it is essential that measures used to strengthen economic and environmental balance are proportionate to the level of technological development of the economic environment. Disproportionate measures with which technology is not able to comply can lead to sudden significant reduction in the NPV, which could result in the collapse of the supply chain.

Energy is another crucial environmental factor with a significant impact on the performance of a supply chain. High prices of energy and its irrational consumption can in many cases turn a supply chain from a profitable into an unprofitable one. A lot of energy is stored inside the products, and it can sometimes be restored to some extent. Increases in quantities of recycled energy result in increased NPV of the revenues, which is associated with the sale of that energy on the market (sometimes at a subsidised price). Such increases in recycled quantities usually require investments into appropriate infrastructure. Investments can be studied through setup costs $\hat{\mathbf{K}}$. An investment is economically viable when additional revenues from recycled energy exceed investment costs, which results in an increase of the NPV of the entire system. Figures 6, 7 and 8 show the areas of possible investment decisions for recycling energy during disassembly or incineration of element D; element E, recycled from component B; and element E, recycled from the final product A.

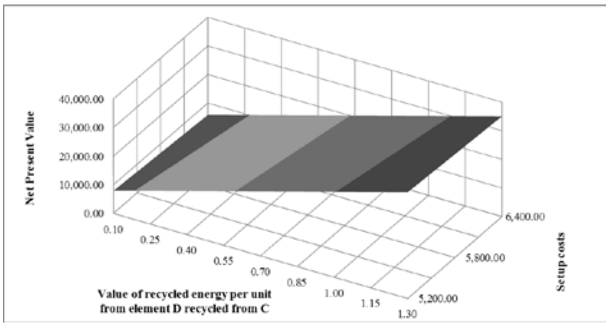


Figure 6: Area of Possible Solutions – Investments into Energy Recycling from Element D

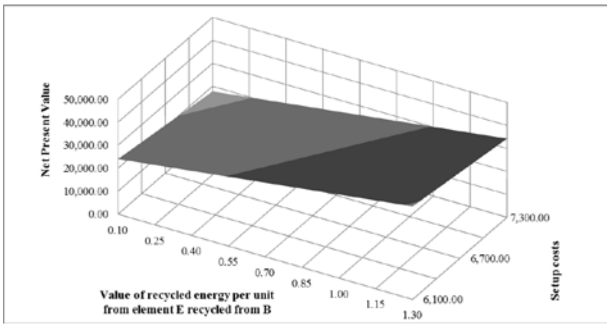


Figure 7: Area of Possible Solutions – Investments into Energy Recycling from Element E, recycled from B

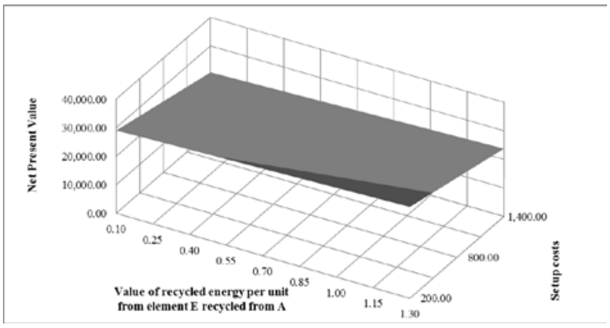


Figure 8: Area of Possible Solutions – Investments into Energy Recycling from Element E, recycled from A

It is clearly evident in the simulation that not all activity cells are equally attractive from an investment perspective. The slope of the graph in Figure 6 is steeper compared to Figure 7 and Figure 8; thus we can expect element D to be more attractive from energy recycling point of view. However, not all solutions on the graphs are feasible, since they are limited by available technology. A comparison of technically feasible solutions between graphs would show the best investment opportunity, which is the one with the highest NPV of the system.

The process of recycling and distribution of successfully recycled elements back to the next production cycle causes time delays. Reduction of lead times has mostly positive effects on the NPV of a system (Figure 9). These positive effects can be interpreted as results of quicker entry of elements into a new production cycle, which reduces the price of capital tied in the stocks of these elements on the way from recycling back to production. For elements that are rare in nature, or whose primary extraction is difficult (therefore their prices on the primary raw materials market are high), we can expect steeper slopes (element D with a lead time $\Delta_{\mathrm{CD}}^{14}$ in Figure 9). On the other hand, amounts of recycled elements also affect the slope of the curve on the graph. If return rates are higher, contingents of recycled elements are bigger and the decrease of lead times back to production has a greater impact to the NPV of the system.

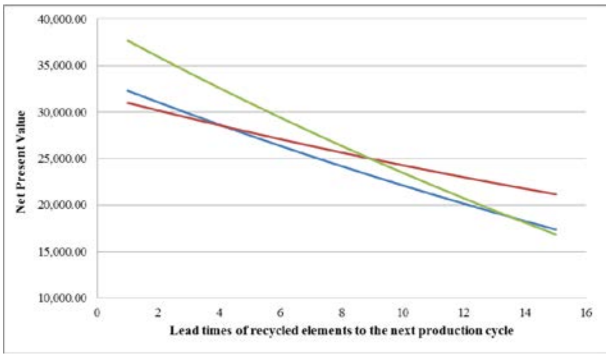


Figure 9: Impact of Lead Times from Recycling to Next Production Cycle

4. CONCLUSION

In this paper, we describe and clearly show that EMRP Theory forms a strong basis for advanced simulations of supply chains. EMRP Theory model has proven to be capable of describing complex structures of supply chains in many previous works. This paper shows that it can also be valuable in practical applications where we can observe the performance of a system by simulating changes in any of the input parameters. Analysis includes environmental factors as an important part of modern supply chains. Such simulations can be helpful, as they can be used in decision making by both managers in the industry and political leaders.

REFERENCES

Bogataj, M., Grubbström, R.W., 2012. On the Representation of Timing for Different Structures within MRP Theory. *International Journal of Production Economic*, 140 (2), 749–755.

Bogataj, M., Grubbström, R.W., 2013. Transportation delays in reverse logistics. *International Journal of Production Economics*, 143 (2), 395–402.

Bogataj, M., Grubbström, R.W., Bogataj, L., 2011. Efficient location of industrial activity cells in a global supply chain. *International Journal of Production Economics*, 133 (1), 243–250.

Grubbström, R.W., 1990. The distribution of an additive in a chemical process - an application of input-output theory. *Engineering Costs and Production Economics*, 19 (1-3), 333–340.

Grubbström, R.W., Tang, O., 2000. An Overview of Input-Output Analysis Applied to Production-Inventory Systems. *Economic Systems Research*, 12 (1), 3–25.

Koopmans, T.C., ed., 1951. Activity Analysis of Production and Allocation. *Proceedings of a Conference*. New York: Wiley & Sons.

Kovačić, D., Bogataj, L., 2011. Multistage reverse logistics of assembly systems in extended MRP Theory consisting of all material flows. *Central European Journal of Operations Research*, 19 (3), 337–357.

Kovačić, D., Bogataj, M., 2012. Simulating the impact of environmental factors on the extended MRP model. In: A. Chikán, ed. *17th International Symposium on Inventories, Book of Abstracts*, pp. 144-145. August 20-24, Budapest: Diamond Congress Ltd.

Kovačić, D., Bogataj, M., 2013. Reverse logistics facility location using cyclical model of extended MRP theory. *Central European Journal of Operations Research*, 21 (1), 41–57.

Kovačić, D., Hontoria, E., Bogataj, M., Ros, L., 2012. Application of the Extended MRP Theory to a baby food company. In: Z. Babić, ed. *Croatian operational research review (14th International conference on operational research, Trogir, Croatia, September 26 - 28, 2012)*, 3, 41–51.

Köchel, P., 2009. *Simulation Optimisation: Approaches, Examples, and Experiences*. Chemnitz: TU Chemnitz, Fakultät für Informatik.

Leontief, W.W., 1970. Environmental Repercussions and the Economic Structure - An Input-Output Approach. *Review of Economics and Statistics*, 52 (3), 262–271.

Orlicky, J.A., 1975. *Material Requirements Planning*. New York: McGraw-Hill.

Vazsonyi, A., 1958. *Scientific Programming in Business and Industry*. New York: Wiley & Sons.

EMERGY TRACKING – SAFE TRANSITION FROM A WORLD OF EXPONENTIAL GROWTH TO ONE OF SUSTAINABILITY

François E. Cellier

Computer Science Dept., ETH Zurich, Switzerland

FCellier@Inf.ETHZ.CH

ABSTRACT

This article proposes introduction of an emergy (embodied energy) label to be associated with all technological items sold for more than $100 a piece on the market. This is different from today's energy labels. Whereas the energy labels in use today account for the energy efficiency in using an appliance, the emergy label accounts for the energy efficiency in producing it. The concept of emergy (or energy footprint) as a measure of total production energy is introduced, and a procedure for tracking emergy throughout the production chain of a technological item is proposed.

Keywords: emergy, emergy tracking, grey energy, sustainability

1. INTRODUCTION

150 years ago, at the beginning of the industrial revolution, precious minerals were lying around openly on the surface of this planet. Now we need to dig ever deeper to still discover new sources of minerals, and soon, they will mostly be gone. The planet is reaching its limits to growth, and we have no choice but to transition from a world (an economy) of exponential growth to one of sustainability (Meadows, Randers, and Meadows 2004).

This transition will take place irrespective of what we do. We cannot prevent it. It is the predicament of a species living on a finite planet. However, we may be able to shape the way in which this transition occurs, thereby reducing the pain and agony that invariably will accompany this transition to some degree (Martenson 2011).

We may be asking ourselves, how much energy each of us will have available after the transition. In Switzerland, people are frequently talking about a *2000 Watt Society* (Morrow Jr. and Smith-Morrow 2008). Why 2000 Watt? There are two ways to arrive at this number.

Method one adds up the total annual energy being consumed for whatever purpose by all humans living on this planet, divides that figure by the number of people currently alive, and divides the result by the number of seconds in a year. This results in an average per capita power consumption of 2000 Watt. So, this must be our fair share. We want to grant every human being on this planet the same quality of life, and consequently, highly developed countries, such as Switzerland, must reduce energy consumption so that other nations can increase theirs.

Method two starts with our current energy consumption of roughly 5500 Watt per person here in Switzerland (Swiss Federal Office of Energy 2013; Cellier 2009). It recognizes that, after Fukushima, Switzerland will most likely decide to get out of nuclear power. Furthermore, we all know that the total supply of fossil fuels is finite and consequently, fossil fuels cannot be supplied in a sustainable fashion. If we deduct from our current energy availability the portion that is being generated from nuclear power stations and from imported fossil fuels, the remaining available per capita power is roughly 2000 Watt.

Thus, both the idealists and the realists among us have every reason to buy into the concept of the 2000 Watt Society. Unfortunately, both calculations are deeply and utterly flawed. Let me explain.

What is wrong with method #1? First of all, not every person on this globe needs the same amount of energy. People living at a high latitude or high altitude require much more energy to heat their homes. Also, since the vegetation period is short, they need additional energy to store their food during the long and cold winters. People living on a tropical island can grow their food all year round for immediate consumption, and they don't truly require any energy to heat or cool their homes. Yet much more importantly, the method assumes that we shall always be able to generate the same amount of energy. This assumption is unfounded. If we invest heavily in renewable energy (solar, wind, geothermal), we may be able to generate much more energy locally than we currently do. Unfortunately, we are at the current time consuming world-wide more than 80% of our total energy mix by burning fossil fuels (British Petroleum 2013). When these fossil fuels are getting scarce, the sum of our overall produced energy will drop dramatically. All renewable energy sources combined will be unable to compensate for this drop.

What is wrong with method #2? We need to check how the current 5500 Watt per person have been calculated. The energy balance does not take into consideration any goods that we import or export. Thus, if I buy a car that has been produced in Japan, the energy that went into the production of that car is counted in the energy balance of Japan and not in the energy balance of Switzerland. Method #2 assumes that import/export patterns, with the exception of fossil fuels and nuclear fuel rods, will continue at the same level at which they are now. Yet, what if Japan can no longer produce my car, because the Japanese economy runs out of sufficient energy to do so as it undoubtedly will?

The shortcomings of method #2 are thus related to so-called “grey energy.” Although everybody talks about grey energy, there are no solid figures available as to the amount of net grey energy that Switzerland imports. All we know is that it is substantial.

Method #1 does not suffer any inaccuracies due to grey energy not being calculated correctly. If I calculate the total energy generation/consumption planet-wide, there is no grey energy. All grey energy imported into Switzerland is real energy produced and accounted for elsewhere. If one nation is a net importer of grey energy, another nation must be a net exporter. Globally, the total grey energy adds up to zero.

We read frequently these days that China’s energy consumption is growing at a phenomenal rate. This is only partly due to an increase in living standard of the Chinese people. A large percentage of the perceived increase in Chinese energy consumption has to do with the fact that China is producing lots of goods for export these days. They have become the largest net exporter of grey energy world-wide.

A country that does not produce anything and imports everything that its people need will look excellent in terms of its energy consumption statistics, and yet, those people may be the biggest energy wasters on the planet. If we wish to calculate fairly and adequately our fair share of energy consumption, we need to get a better estimate of the massive amounts of grey energy that we import and export.

As energy resources become scarce, the international trade both in terms of energy and goods will suffer. The net energy exporters will satisfy the needs of their own constituents first and export less energy, and the nations with large population densities and few energy resources of their own, such as Japan, which in today’s world are among the biggest exporters of goods, will become energy starved. Thus, they will no longer be able to produce as many goods for export, but will rather use up the few energy resources that they can master to satisfy the needs of their own people (Brown 2007).

When food gets scarce, governments introduce food budgets. The same happens with energy. During the Second World War, Switzerland was able to feed each inhabitant 1800 calories per day (food rationing), and no buildings private or public were allowed to be heated to more than 16 degrees Centigrade (energy rationing). At that time, Switzerland counted half of its current population, seven times as many farmers, and double the current farm land (half of it has meanwhile been paved over).

Similar restrictions will be imposed again on a world-wide scale once the fossil fuels are depleted. The future looks bleak for countries with high population density and few energy and food resources of their own. The only countries that will fare a bit better are countries with low population density and large reserves of food and energy resources, such as Argentina and Australia. Switzerland currently imports roughly 80% of its energy and 60% of its food. In contrast, Argentina produces roughly five times as much food as the country requires to satisfy the needs of its own population. Argentina still has the capacity of being self-sufficient w.r.t. energy.

2. EMERGY

How much energy am I consuming while driving from home to work in my car? On the one hand, I might count the thermal energy contained in the fossil fuel that I burn. On the other hand, I might focus on the mechanical energy that I consume for propelling my car, a number that is certainly smaller than the former, because some of the thermal energy gets converted to heat (entropy production).

Energy is thus not equal to energy. This dilemma is well known. British Petroleum converts all forms of energy to *tons of oil equivalent (toe)* (British Petroleum 2013). For example, Switzerland gets “punished” with a conversion factor (efficiency factor) of 3 for producing electricity from hydroelectric and nuclear power rather than by burning fossil fuels. For this reason, the Swiss energy consumption statistics (Swiss Federal Office of Energy 2013) show lower consumption numbers than the BP statistics, because the Swiss Federal Office of Energy focuses on the electricity generated rather than converting the energy to toe first.

Howard T. Odum suggested in his seminal publication on *System Ecology* (1983) to convert all forms of energy to *solar equivalent Joules (sej)*, as the sun is the primary source of energy on this planet.

Let us consider the case of a type of biofuel. In order to produce one Joule worth of this type of biofuel, I need biomass containing 10 Joules worth of thermal energy. However, in order to produce this amount of biomass, I require 1000 Joules of solar radiation. The example (Baral and Bakshi 2010) is depicted in Figure 1.

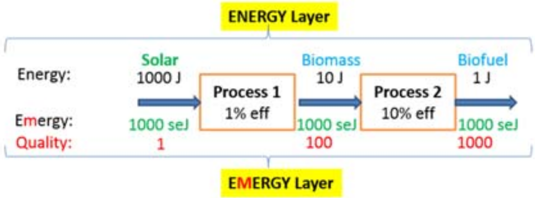


Figure 1: Efficiency of production of biofuel

Whereas BP would consider biofuel a primary source of energy, not assigning any conversion factor to it, Odum takes the analysis two steps further back to the solar radiation needed to generate the biomass from which the biofuel is produced, and therefore would assign a conversion factor (a so-called *transformity*) of 1000 to this type of biofuel.

Although the same technique could be applied to fossil fuels as well, this is probably irrelevant, because with all of the sunshine in the world, fossil fuels cannot be regenerated on a human time scale. These are non-recoverable resources for all practical purposes. Once they are gone, they are gone for good.

Yet in all of this analysis, we have not accounted for the grey energy that went into the production of my car.

I cannot drive my car to work, unless it has been produced first, a process that consumes a massive amount of energy.

The energy that goes into the production of a manufactured good has been coined *embodied energy*, or *emergy* in short (Scienceman 1987). When I buy a new car (when I import a car into my model (Castro, Cellier, and Fischlin 2013)), it comes with an emergy tag representing the total amount of energy that went into its production, including an attributed percentage of the energy that went into the production of the factory, in which my car was produced.

When I calculate, how much it costs me to drive my car around for 1 km, it is insufficient to account for the gas that it uses (although most people do precisely that). I need to factor in taxes, insurance premiums, and maintenance cost, and I should also think ahead and remember that, in a few years' time, I'll need to replace my car by a new one, i.e., I need to put money aside for that future purchase. Thus, I should also factor in the cost of amortizing my car. It turns out that the cost of the gas in all likelihood accounts for less than 50% of the overall cost of driving my car.

Similarly, when I calculate how much energy I am consuming, I need to factor in a percentage of the emergy that came with the car, i.e., I need to amortize my car not only financially, but also energetically. I should also account for maintenance, i.e., I need to factor in the emergy coming with replacement parts and the energy used in the process of repairing my car.

3. EMERGY ACCOUNTING

In order to distribute scarce resources fairly, we need a tool to quantify the amount of grey energy (emergy) that is contained in all of the goods that we consume. This can be easily obtained.

When I buy today a wedge of Camembert cheese in the supermarket, it comes not only with a price tag. It also carries a label that tells me precisely, what that cheese contains percentagewise in terms of fat, proteins, and carbohydrates. If I wish to live sustainably, i.e., without gaining weight, I need to add up my total energy intake in terms of food calories, and balance it against my energy expenditure as dictated by my life style. Thus before eating my Camembert cheese, I should look at the label and decide whether I can afford to eat that cheese or not.

On the other hand, when I buy a new hammer, it comes only with a price tag. There is no label on that hammer telling me how much energy went into its production. Consequently, I have no way of knowing whether I can buy and own that hammer in a sustainable fashion. When I decide to buy a new Japanese car, can I do this without depleting resources of this planet, both in terms of energy and materials?

As our energy resources are becoming increasingly scarce due to depletion of the remaining fossil fuels that currently make up 80% of the energy mix planet-wide, we shall all have to become more energy-conscious, whether we like it or not. At some point in time, our governments will be forced to ration energy. Each inhabitant of a country will be given a monthly energy allowance. At that time, whether or not I can buy my new hammer at the hardware store will depend on two things: whether there is enough money in my bank account and whether there is enough energy credit left in my monthly energy budget.

In order to implement this idea, the hammer will need to carry not only a *monetary* price tag, but also an *energy* price tag, i.e., it needs to exhibit a tag that shows how much energy went into its production, i.e., it needs to document the total amount of emergy that the hammer has accumulated so far.

The producers of Camembert cheese only place a label on the package indicating how much fat, proteins, and carbohydrates are contained in that cheese, because they are legally required to do so. Similarly, no producer of any goods will voluntarily indicate how much energy has been used in the production of his merchandise. They will do so only if this is a legal mandate. It should thus be made a requirement that all new items sold at a price above $100 carry a tag indicating how much energy has been used in their production. The burden of quantifying the energy footprint of each item should consequently be passed on to the producers of these goods.

To the producers, this is not much of a burden. Each producer of goods needs to know how much it costs him to produce his merchandise. To this end, he sums up the cost of all the components that he buys and adds to it the price of producing his sales item.

In a similar fashion, if each component that he buys comes with its own energy price tag, he can sum up all of those partial emergy amounts and add to it the energy consumed in the production of his item. This is the energy price tag, i.e., the amount of emergy that needs to accompany his produced good when sold either to an end user or to the next producer in the chain.

Tools used in the production of goods will need to get amortized both monetarily and energy-wise. The approach is identical in both cases.

Just like in today's markets, producers of goods try to produce their items as cheaply as they can to be competitive on the market, these same producers would also become more energy-conscious in my imagined future market, as producers will have commercial advantage if they can produce their goods in a more energy-efficient way.

Yet, although this measure can be implemented quite easily, it won't happen unless it gets legislated. No producer will voluntarily undertake this effort, and in fact, even if a producer were interested in doing so, he would not be able to, because he would have no way of knowing the emergy content of the components that he buys. This only works if the entire production chain labels its goods in this way.

That this is perfectly feasible is evidenced by another labeling effort that was legislated only a few years ago.

When I buy today a steak at my local butcher store, the butcher should be able to tell me exactly where this steak is coming from. He must be able to follow the steak back all the way through the production chain to the meadow somewhere in the Argentinian Pampa where the cow was raised that is at the origin of my steak. How is this possible?

Food safety is of much concern to the people and therefore also to the governments representing the people. In biblical times, the authorities in the Mideast forbade the eating of pork, because they recognized that people often got sick after consuming this type of meat. They didn't have microscopes yet to check for parasites that frequently befall pigs (trichinosis, brucellosis, ascarid worms). In more modern societies, these diseases can be easily recognized, but the potential of food disease is still omnipresent. Consider for example the outbreak of Creutzfeld-Jakob disease (CJD) in recent times.

For these reasons, the EU regulated that all meat products sold within the EU must be traceable back to their origin. As no country can afford to ignore the EU market, all countries meanwhile bought into the concept, and all meat products world-wide are now labeled in this fashion. This was a huge success story that, however, would not have been possible without a large market (the EU) buying into this concept.

Emergy labeling of technological goods is considerably simpler and cheaper than what is already done to meat products today. All it takes is a large market, such as the US or the EU, to buy into this idea.

Although such a tool will be an important asset in fairly distributing the available goods and services in a future energy deprived world, it would offer important advantages already today, as this information could be used by economists in their market models to predict, which technologies will be able to survive in a future energy scarce world.

Also, emergy labeling is important in the context of decision making concerning measures for improving energy efficiency. For example, we may be able to reduce our energy consumption for heating our home substantially by replacing single-pane windows by triple-pane windows. Yet the decision, whether or not to replace the windows in our home, should take into account the (non-negligible) emergy content of the new windows and how long it will take to energetically amortize them. This is rarely done.

The emergy content of an average new house is roughly equivalent to the total amount of energy spent while living in that house for 50 years. Thus, ignoring the emergy content of manufactured goods may lead to decisions concerning energy efficiency that are not meaningful.

4. EROEI vs. total life cycle assessment

Whereas no attempts have yet been made to quantify in practice the emergy content of all types of general goods produced, methodology is already in place to assess the energy-efficiency of producing one particular type of goods, namely energy.

This all started in the oil business. We can ask ourselves: how many barrels of oil can we produce while burning one barrel of oil in the process? This is called the *Energy Returned on Energy Invested (EROEI)*. Some authors also refer to this concept as EROI (Hall 2008a).

Clearly, the EROEI of oil depends both on the location of the oil well (how easy is it to get to it) and on the quality of the crude (how much energy needs to be invested in transforming (refining) the crude oil to a usable product).

The EROEI of oil has decreased over time as the oil that was easiest to produce was produced first. The EROEI of Pennsylvania crude in the 1930s was above 100. The EROEI of today's conventional oil has already decreased to a value of 20 or less (Hall 2008b). The EROEI of unconventional oil and gas, such as shale oil or oil made from tar sands, is much lower, usually around 5 (Wikipedia 2013).

The concept of the EROEI can be easily abstracted to other types of energy as well, and this has indeed been done. Some energy resources have higher EROEI values than others, but most of them exhibit EROEI values that decline over time.

Obviously, when the EROEI of an energy resource passes through one, the game is over, irrespective of how much energy could still be produced in this fashion. At least, it makes *energetically* no sense whatsoever to produce a type of energy that requires spending more energy in the process than is getting generated. It may, however, still make *economic* sense to do so, if the local government decides to subsidize this energy resource, e.g. in order to reduce its dependence on energy imports or for the purpose of local job creation.

The EROEI is, however, still not a conservative measure, because it takes into account only the true (direct) amount of energy expended in the production of energy while ignoring the hidden (indirect) energy that went into the production of the tools used to produce the energy. It does not take into account the emergy content of the tools.

For this reason, researchers such as Charles A. Hall postulate that an energy resource needs to have an EROEI value of at least 5 in order to survive in a post-carbon world (Hall 2008b). The safety margin of 5 accounts for all types of hidden energy cost. However, the proposed margin of 5 is not a very solid number.

Will an energy generation technology, such as photovoltaic solar power, with an EROEI value of somewhere around 6 or 7 using the current generation of photovoltaic panels according to Inman (2013) be able to survive in a post-carbon world? The photovoltaic panels in place would certainly continue to generate electricity for a while longer, i.e., until they die, but new panels may no longer get produced to replace them once this has happened. The reason is that the EROEI of photovoltaic technology does not account for the emergy content of the plants producing these panels. Depending on whether Hall's safety factor of 5 is ample or insufficient, this technology may be sustainable or not.

I am somewhat optimistic in this respect, because the EROEI of photovoltaic technology is *increasing* over time. It suffices to build photovoltaic panels with a life span that is twice as long as that of current generation panels to double the EROEI.

In contrast, the EROEI of shale oil is rapidly *decreasing* (in fact, more rapidly than that of conventional oil), because the most easily accessible deposits were exploited first, and each new well gets exhausted very quickly.

Also, the safety factor needed for sustainability is not constant but rather depends on the technology in use. Hall's factor of 5 represents an average across all technologies. Yet there is no reason to believe that the emergy content of a photovoltaic production plant is the same as that of a shale oil production plant.

It would thus be very useful if all tools used in energy production were to carry an emergy tag. This would allow us to perform a *quantitative total life cycle assessment* of the energy production plant instead of only looking at its EROEI. In this way, we could do away with Hall's safety margin and answer questions about the sustainability of an energy production technology confidently and reliably.

The concept of the EROEI is limited to assessing energy production plants. In contrast, system analysis involving emergy measures is much more general and generic. This type of analysis can be applied to all kinds of human technological processes.

Using such a tool, we would be able to assess ahead of time and in a reliable fashion (through simulation (Castro, Cellier, and Fischlin 2013)) whether a production technology is sustainable or not, i.e., whether it can survive in a post-carbon world. The quality of life of our children may depend on this knowledge.

5. CONCLUSIONS

In this article, the concept of emergy (Odum 1983) was introduced as a means to account for the energy that is "embodied" in a manufactured good, i.e., the energy that went into its production.

The emergy content of manufactured goods has been demonstrated as being able to help us reach informed conclusions about their sustainability in an energy deprived (post-carbon) world.

An emergy tracking procedure has been introduced as a means to form better decisions about the inevitable and imminent transition from an economy of exponential growth to one that is sustainable within the confines of a finite planet.

REFERENCES

Baral, A., Bakshi, B.R., 2010. Thermodynamic metrics for aggregation of natural resources in life cycle analysis: insight via application to some transportation fuels. *Environ. Sci. Technol.*, 44(2), 800–807.

British Petroleum, 2013. *BP Statistical Review of World Energy, June 2013*. Available from: http://www.bp.com/content/dam/bp/pdf/statistical-review/statistical_review_of_world_energy_2013.pdf [accessed July 14 2013]

Brown, J.J., 2007. The export land model. *The OilDrum Archives*. Available from: http://www.theoildrum.com/tag/export_land_model [accessed July 14 2013]

Castro, R.D., Cellier, F.E., Fischlin, A., 2013. Eco-bond graphs: an energy-based modeling framework for complex dynamic systems with a focus on sustainability and embodied energy flows, *Proceedings SESDE Conference*, Athens, Greece, Sept. 25-27, 2013.

Cellier, F.E., 2009. Is the 2000 Watt society sustainable in Switzerland? *The OilDrum Archives*. Available from: http://www.theoildrum.com/node/5316/ [accessed July 14 2013]

Hall, C.A., 2008a. Why EROI matters. *The OilDrum Archives*. Available from: http://www.theoildrum. com/node/3786 [accessed July 14 2013]

Hall, C.A., 2008b. Economic implications of changing EROI values. *VII Annual International ASPO Conference*, Barcelona, Spain, October 20–21. Available from: http://www.aspo-spain.org/ aspo7/presentations/Hall-EROEI-ASPO7.pdf [accessed July 14 2013]

Inman, M., 2013. The true cost of fossil fuels: as oil becomes more expensive, determining where to invest energy to get energy is increasingly important. *Scientific American*, April 2013, 41–42.

Martenson, C., 2011. *The Crash Course: The Unsustainable Future of our Economy, Energy, and Environment*. New York: John Wiley & Sons.

Meadows, D., Randers, J., Meadows, D., 2004. *Limits to Growth: The 30-Year Update*. 3rd ed. White River Junction, Vermont: Chelsea Green Publishing.

Morrow Jr., K.J., Smith-Morrow, J.A., 2008. Switzerland and the 2,000-Watt society. *Sustainability*, 1(1), 32–33.

Odum, H.T., 1983. *Systems Ecology: An Introduction*. New York: Wiley-Interscience.

Scienceman, D., 1987. Energy and emergy. In Pillet, G., Murota, T. (eds.) *Environmental Economics – The Analysis of a Major Interface*. Geneva, Switzerland: Roland, Leimgruber, 257–276.

Swiss Federal Office of Energy, 2013. *Energy Consumption in Switzerland 2012*. Available from: http://www.bfe.admin.ch/php/modules/publikationen/stream.php?extlang=en&name=en_310114823.pdf [accessed July 14 2013]

Wikipedia, 2013. *Energy Returned on Energy Invested*. Available from: https://en.wikipedia.org/wiki/Energy_returned_on_energy_invested [accessed July 14 2013]

AUTHOR'S BIOGRAPHY

François E. Cellier received his BS degree in electrical engineering in 1972 and his PhD degree in technical sciences in 1979 from the Swiss Federal Institute of Technology (ETH) Zurich. Dr. Cellier worked at the University of Arizona as professor of Electrical and Computer Engineering from 1984 until 2005. He then returned to his home country of Switzerland and his alma mater. He has authored more than 200 technical publications. He published a textbook on Continuous System Modeling in 1991 and a second textbook on Continuous System Simulation in 2006, both with Springer-Verlag, New York. He is a fellow of the Society for Modeling and Simulation International (SCS).

COMPLEMENTING LIFE CYCLE ASSESSMENT BY INTEGRATED HYBRID MODELING AND SIMULATION

Bochao Wang[(a)], Séverin Brême[(b)] and Young B. Moon[(c)]

(a)Department of Mechanical and Aerospace Engineering, Syracuse University, Syracuse, NY 13244, U.S.A.
(b)Institut Supérieur de l'Aéronautique et de l'Espace (ISAE), Toulouse, France
(c)Department of Mechanical and Aerospace Engineering, Syracuse University, Syracuse, NY 13244, U.S.A.

(a)bwang07@syr.edu, (b)severinbr@gmail.com, (c)ybmoon@syr.edu

ABSTRACT

This paper presents a new complementary life cycle assessment (LCA) approach to address several limitations of the standard LCA methodology thus enhancing the functionalities of environmental impact analysis. The research demonstrates that the hybrid modeling and simulation method can address some of the limitations of the standard LCA, which were results of the assumption that parameters and relationships are constant regardless of local uniqueness. Also, the method is demonstrated to have a potential to address social and economic aspects as well. The hybrid simulation model was developed as a proof-of-concept system, which was validated using a case study of bottled water and alternative drink products.

Keywords: Sustainability, Life Cycle Assessment (LCA), Agent-Based Modeling, System Dynamics, Discrete-Event Simulation

1. INTRODUCTION

Sustainability issues are being addressed by a variety of different activities ranging from creating environmental-friendly products to changing habits to reduce waste. While such initiatives deserve commendations, there is a danger of narrowly focusing on local optimization thus unintentionally worsening the whole situation unless a holistic systems thinking guides those executions. One of the tools available to assess overall environmental impacts throughout a product's entire life is life cycle assessment (LCA). LCA is the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040, 1997). In a LCA study, many aspects throughout a product's lifecycle can be considered ranging from production, transportation, distribution, usage and ultimately to the end-of-life activities.

However, the standard LCA method has a number of limitations and some of these problems are critical (Reap et al., 2008). For example, the LCA method takes a static viewpoint that its parameters and internal relations among entities remain constant. Therefore dynamics among entities cannot be addressed. Also, the social and economic impact, local environmental uniqueness, effects of dynamic environment, and temporal perspectives are not easily considered in the LCA. In other words, the standard LCA is useful as a high level tool, but not for necessarily dealing with dynamics, uncertainties and broader perspectives.

This research demonstrates that a hybrid simulation model can address these limitations of the standard LCA approach. All the steps in LCA, goal and scope definition, inventory analysis, and impact assessment, including interpretation are considered in our research. However, the focus is placed on the third step of the standard LCA, that is, impact assessment. A hybrid simulation model combining agent-based modeling, system dynamics and discrete-event simulation methods was developed as a proof-of-concept system. The validity of the developed approach was done on comparing bottled water alternatives such as tap water and vitamin water along with different bottle options. The case study drew necessary data from the Nestlé report (Nestlé Waters North America, 2010).

The paper is organized as follows. First, the integrated hybrid modeling and simulation method developed for this research is presented. Drinking water and beverages is chosen to illustrate how the framework is developed and modeling is carried out. Impact analysis based on the simulation results is explained to show the value and potential of the new complementary LCA approach. Conclusion and future work is provided at the end.

2. INTEGRATED HYBRID MODELING AND SIMULATION METHOD

The hybrid model integrates three commonly used modeling and simulation methods: i) Discrete Event Modeling and Simulation (DEMS), ii) System Dynamics (SDMS), and iii) Agent-based Modeling and Simulation (ABMS). These are integrated to simulate the life cycle process and study the feasibility of complementing the functionalities of the standard LCA method. The integrated hybrid model combine the uniqueness and advantages of each of the above three methods into a single model while taking their differences into consideration.

Discrete Event Modeling and Simulation (DEMS) can simulate multiple events in a time sequence (Zeigler, Kim and Praehofer, 2000). Basic elements are entities, flowcharts and resources. DEMS is a natural choice when linear processes in a complex environment is modeled and an entity's action is triggered by other entities or at a certain time.

System Dynamics Modeling and Simulation (SDMS) is a methodology used to model and simulate a system from a higher system-level viewpoint (Forrester, 1968; Doebelin, 1998; Sterman, 2001). Stocks, flows and unique feedback loops are their basic elements. Aggregates are linked through aggregated mechanisms implemented as flows in SDMS. Feedback loops link each module of the system with defined relations and influence. The state of the whole system could be observed from various stocks at any given time.

Agent-based modeling and simulation (ABMS) is a methodology to model and simulate individual actions and interactions of agents in a complex adaptive system, focusing on their effects on the system as a whole (North and Macal, 2007). They are constructed in the form of active objects, individual behavior rules, and direct or indirect interaction within a dynamic environment.

The most promising part of the integrated modeling approach is its flexibility that can handle dynamic and evolving requirements of a system. SDMS can deal with aggregates at the highest abstraction level while DEMS can be used at middle level of abstraction and possible at lower level as well. ABMS can be used across all levels of abstraction. In our research, we utilized the flexibility of the integrated hybrid modeling and simulation and developed a proof-of-concept system that can complement the standard LCA method.

3. LIFECYCLE ASSESSMENT OF DRINKING WATER AND BEVERAGES

Tap water is still one of the major drinking sources in daily life. However, the bottled water market in developed countries such as United States and Japan has grown rapidly. For health, quality and convenience reasons, bottled water has become a popular choice in drinking water and beverage market. The rise in popularity of bottled water has created a burden on the sustainability (Gleick, 2010), however. For example, bottled water produces wastes during its production, transportation, distribution, refrigeration and recycling. So the basic questions to address by a LCA study are:

i) which one of the available options (e.g. tap water, bottled water, and other drinking alternatives) is the most sustainable?
ii) will consumers' choice make a difference?

Normally, a LCA study consists of three distinct steps with associated interpretation of results. The three steps are: i) goal and scope definition, ii) inventory analysis, and iii) assessment of impacts associated with these inputs and outputs.

3.1 Goal and Scope

The goal of our study is to measure the environmental impacts of beverage consumption habits under different scenarios. In this study, the critical environmental issues and responsibilities were identified along the entire life cycle chain of five specific drinking alternatives:

1. Tap water in glass bottle,
2. Tap water in reusable aluminum bottle,
3. Ecoshape bottled water,
4. Sport drink, and
5. Vitamin water.

Consumer behavior is also taken into consideration. Consumers are allowed to choose freely from drinking alternatives and switch among them over time to reflect the trend of consumers. Two particular impacts, energy consumption and global warming potential, are assessed to reveal the practicality of the new methodology.

3.2 Inventory Analysis

a) System Boundary

The whole lifecycle of drinking alternatives will be covered. For the sport drink as an example, its lifecycle consists of beverage production, package production, transportation, distribution, refrigeration to recycling or landfilling disposal. The boundary of the system and stages are shown in Figure 1. There are five stages in the sub-model of sport drink.

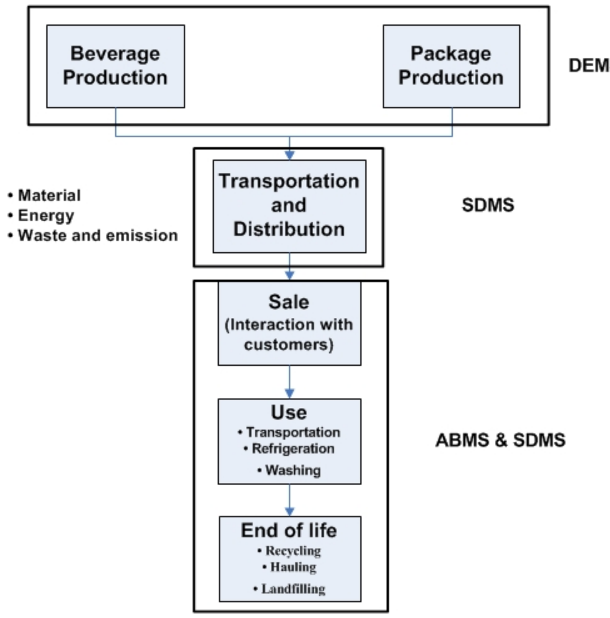


Figure 1: The boundary of the system and the stages of sport drink systems

b) Functional Unit and Emission Data

A reasonable water/beverage consumption amount is chosen as 3 liters (L) per day per person. This is equivalent to 6 bottled water volumes or vitamin water bottles. Data for material/energy consumption, water usage, waste generation, greenhouse gases emissions, distribution selection, quantitative relations between entities and parameters are collected from the Nestlé study paper (Nestlé Waters North America, 2010), GaBi databases (LBP, 2009) and published LCA papers (Azoulay et al., 2001; Keoleian et al., 2009).

c) Assumptions

In order to effectively reflect and compare the results of each product in different scenarios, the most commonly used and important two impact categories are chosen:

i) Energy that is the amount of energy used during each phase of the life cycle and Global Warming Potential (GWP) for each phase of the life cycle (Pasqualino, Meneses & Castells, 2011).

ii) Global-warming potential (GWP) is a relative measure of how much heat a greenhouse gas traps in the atmosphere. It compares the amount of heat trapped by a certain mass of the gas in question to the amount of heat trapped by a similar mass of carbon dioxide. GWP is expressed as a factor of carbon dioxide (the GWP numbers are standardized to 1).

Additional assumptions were made to simplify the model constraints and set a reference standard.

4. MODELING AND SIMULATION

System dynamics is used to model the workflow and calculate energy consumption and GWP. Since the overall process is a continuous procedure in straightforward workflow that involves plenty of feedbacks, such as material flow and energy usage, system dynamics is a natural choice. It is best suited to analyze a system with dynamic stocks, flows and feedbacks. However, the detail work processing procedure and the connection linking consumer behaviors with actions are modeled by discrete-event and agent-based methods.

4.1 Scenarios

Scenario 1 is the "reference scenario". This scenario represents the base pattern of beverage consumption in New York State assuming that only the five kinds of beverages are available. All beverages are assumed to be refrigerated for 2.4 days on average, except tap water, which is not refrigerated. The glass used for tap water and the reusable bottles are washed in a dishwasher.

Scenario 2 is similar to the reference scenario, but during the winter no beverage is assumed to be refrigerated by the consumer.

Scenario 3: In this scenario, tap water is somehow unavailable during this period, such as pollution or disaster. "tap water in glass bottle" and "tap water in reusable aluminum bottle" are then replaced by "ecoshape bottled water". All drinks are refrigerated.

Scenario 4: Under this scenario, bottled water is banned.

Scenario 5: Same as the reference scenario, but refrigeration conditions are different. It is assumed that refrigeration takes place for 7.2 days instead of 2.4, in a 20-year-old refrigerator that consumes three times more energy. Furthermore, it is assumed that the beverage occupies about 1/10 of its refrigerator content.

Scenario 6: Same as the reference scenario, but glasses and bottles are washed by hand with cold water.

4.2 Framework and Modeling

a) Overall hybrid modeling framework

The model is developed in two main parts: i) modeling the life cycle of each beverage and ii) modeling the behavior of each consumer of the population. The life cycles of the five beverages are first modeled in SDMS, followed by the consumer behavior modeled in ABMS and DEMS. The integrated model is then established in order to compare the environmental impacts of beverage consumption under the different scenarios.

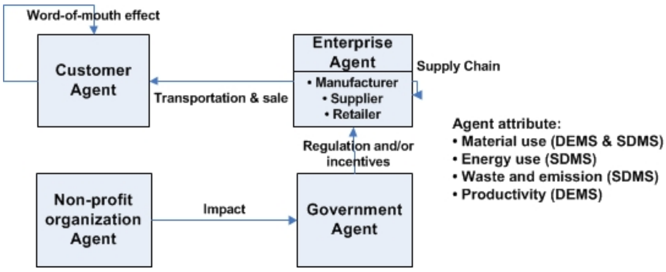


Figure 2: Hybrid model structure

b) SDMS part

Bottles, glasses and cardboard used to produce bottled water can be recycled into new containers as a feedback system illustrates in Figure 3. This increases the production rates of beverages and containers. Four kinds of raw materials are needed to manufacture bottles and their packaging: packaging cardboard, PPlid, PET Resin, and Pallet. The production rate of each beverage and each container is based on average consumer consumption (6 servings a day for one consumer) and on average losses (some bottles and glasses are stolen or damaged in the supermarkets or during manufacturing and transportation).

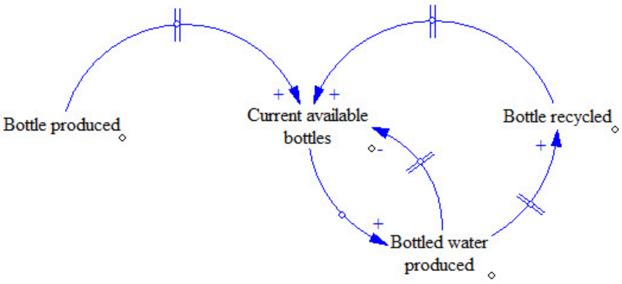


Figure 3: Bottled water production feedbacks in system dynamics

After the production stage, the beverages are transported to the marketplace such as a supermarket. There, bottles beverages are refrigerated before being sold to the consumer. After people drink the beverages, there are 3 ways to dispose all materials: i) landfilling, ii) waste-to-energy, iii) or recycling. The recycle rates depend on the container used.

For the tap water as well as the bottled beverages (ecoshape bottle, sport drink and vitamin water), the SDMS diagram is composed of two independent SDMS diagrams: one for the tap water and the other for the containers. Tap water is processed and generated at a municipal water plant, then distributed through pipes to the consumers. The tap water consumption is determined by adding: i) the tap water that is drunk by the consumer, ii) the tap water that is used for dishwashing and, iii) the losses during the production and distribution processes. The production rate of tap water is determined to meet customer's demand. On the other hand, glass bottles are produced from raw materials and reusable aluminum bottles are from recycled materials. Their production rates are chosen with respect to the consumer demand. They are then distributed to the marketplace, bought by consumers, used and then discarded.

c) ABMS and DEMS part

Starting with potential users, when they go to the supermarket to shop for their favorite products, and every purchase transaction is based on the availability of their favorite products. Customers will recycle used products and buy new products after a certain period, such as the product’s lifecycle length or any replenishing time. DEMS is embedded in the statechart of agent behavior, where the state of agent will change to another state when time elapse or by certain rate depended on variables. The state such as purchase or discard may happen even by triggering certain requirements, such as word-of-mouth effect, favorite product is unavailable, etc. The sequence of discrete events is usually one-way and follows time sequence, while two-way conversion is comprised of two one-way discrete events.

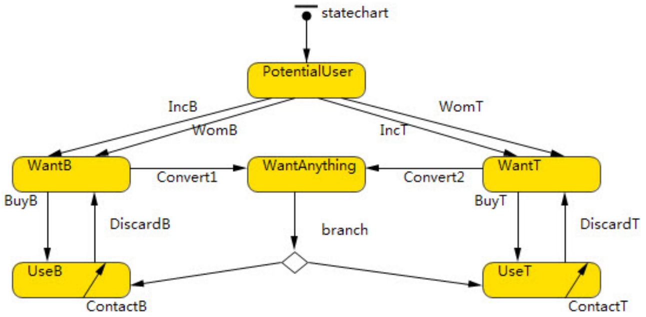


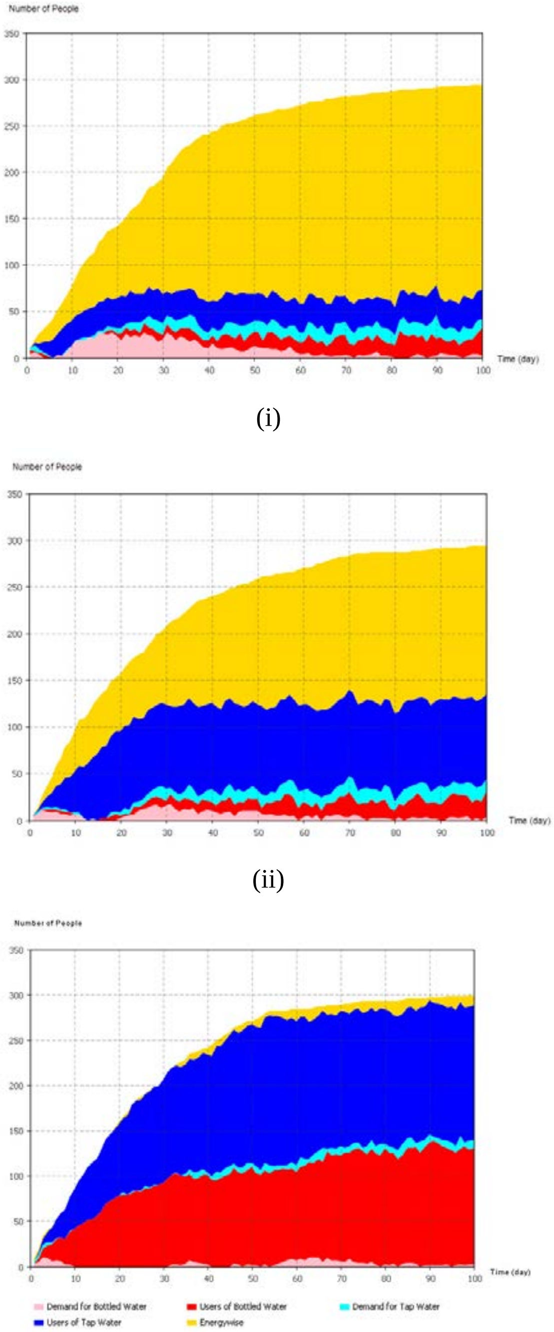
Figure 4: State chart of customer behaviors on two competing alternative products

4.3 Results and Validation

a) Observations

Three most important factors affecting the simulation outcomes are supply chain capability, customer involvement impact and market specialty. In the model, environment-sensitive behaviors were considered. There are a certain adjustable percentage of customers who prefer energy-efficient products over alternative choices. The energy efficiency calculation is based on the ratio of each product’s energy consumption over total consumption amount, which leads some people to make a conversion when a more energy-efficient product becomes available.

First, the characteristic of supply chain capability is studied. Figure 5 shows the market share of each product in different colors. It compares three scenarios, the replenishing period time changes from the shortest in scenario (i) to the longest in scenario (iii) while keeping all other parameters constant. X-axis represents the timeline of simulation. Y-axis represents the number of customers. The total numbers of customers reaches 300,000, which is the asymptotic value of total number of customers who would make the purchase. Customers waiting replenishment are represented in yellow color. They are potential customers in the market but without a decision to purchase any product. The yellow zone shrinks from left to right when the replenishing time increases, indicating the supply chain is capable of meeting the customer demand in longer replenishment time scenarios. The supply chain, especially manufacturer is a bottleneck in terms of production and transportation when they need to meet customers' demands in faster pacing situations. It is interesting to note that tap water in blue and bottled water in red become favorite choices at steady state situations, while sport drink in cyan and vitamin drink in pink come to represent smaller segments of the market.



(i)

(ii)

(iii)

Figure 5: Comparison of market share in three different replenishment time scenarios: (i) the shortest time, (ii) the average time, (iii) the longest time

b) Verification and Validation

The results obtained from our hybrid model for the three bottled beverages (ecoshape, sport and vitamin) are reasonably close to those reported in the Nestle report (Nestlé Waters North America, 2010), for both Energy and GWP. Table 1 lists the LCA problems addressed in this paper and corresponding verification and validation methods adopted to caliber the hybrid model and make sure it reflects the characteristics of the competitive bottled water market.

Table 1: Verification and Validation methods

Traditional LCA problems addressed in the paper	**Modeling method**	**Result verification and validation**
Social and economic impacts	ABMS	Customer behaviors, regulation or incentives and competitive Market
Alternative scenario considerations	DEMS, SDMS & ABMS	Different local uniqueness, season and preference, customer behaviors
Local environmental uniqueness	DEMS & ABMS	Different input represents various local environments
Dynamics of the environment	SDMS & ABMS	Customer-driven market and agents make decisions on feedback
Time horizons	DEMS, SDMS & ABMS	The trend alters according to different time span
Uncertainty in the decision process	DEMS, SDMS & ABMS	Most parameters and relations have certain uncertainty range with robust analysis

c) Summary

Bottled water is regarded as a major pollution source given its energy consumption and after-use disposal method such as landfill. It was found that bottled water, which is a very common choice for users in the USA, is the third best choice overall after tap water with glass and reusable aluminum bottle. It is the second best choice as a beverage source for the environment. Water production takes a large portion of energy consumption in bottled water production (larger than distribution and transportation consumption), while other soft drinks production take extra steps to produce beverage or packaging and recycle steps, which makes them less energy-efficient or environmentally friendly if the recycling rate is the same for all products except tap water.

Word-of-mouth effect is non-negligible. However, initial customer inclination is not sensitive according to market share and energy usage, since the conversion from one product to another along with customer's influence is complementarily strong. It was also found that having a regional supply chain helps national or international manufacturers to bring down cost and environmental impact and also attract more loyal customers.

5. CONCLUSION

Usually, bottled water is not thought of as an environmentally friendly choice, the results from this study affirms it, given that energy consumption and GWP of ecoshape bottled water are 32 times and 10 times larger, respectively, than those of tap water in glass bottle. However, it is also indicated that although falling far behind the best two choices, bottled water is a good (third-best) choice. This is way better than sports drink and vitamin water both in energy efficiency and GWP emission.

Energy and greenhouse gas emission are found to be positively correlated. So energy usage can be used as a gauge to measure and evaluate efficiency and environment friendliness. The results of the hybrid DEMS-SDMS-ABMS model are good and promising, which not only matches published reports but also extend further to incorporate customer's behaviors and market responses.

For future work, other factors such as customer behavior comparison, reusable product introduction and model validation can be included to provide more comprehensive results. Washing glasses and bottles plays an important role in the life cycles, as water needs to be heated whether dishwashing takes place in a dishwasher or in a sink. It is interesting to compare the reference scenario with this one in which the dishwashing water is not heated. Customer behavior comparison is another potential subject of study. Some customers may choose the least expensive products only, while others prefer to follow the current fashion from time to time. Such customer behaviors are interesting to recognize and compare.

When more accurate data become available, more quantitative analysis beyond Design-Of-Experiment can be implemented. Products such as sports drinks, coffee, and tea can be added to study a more complete beverage market. Cost analysis could be done when pricing data is available. Parameters such as transportation distance variance were not taken into consideration. There are critical values of some parameters that exist which optimize the performance. To minimize the impact to the environment, public advertising and broadcast is effective due to the word-of-mouth effect. Government environmental and/ or production policy can impact environmental issues by limiting certain products and promoting others via incentives if they are more environmentally friendly and energy wise.

REFERENCES

Azoulay A., Garzon P. and Eisenberg M.J., 2001. Comparison of the mineral content of tap water and bottled waters. *Journal of General Internal Medicine*, 16 (3), 168-175.

Doebelin, E., 1998. System Dynamics: Modeling, Analysis, Simulation, Design. *CRC Press*.

Forrester, J. W., 1968. Principles of Systems. *MIT*, Cambridge, Mass.: Wright-Allen Press.

Gleick, P.H., 2010. Bottled and Sold: The Story Behind Our Obsession with Bottled Water. *Island Press*.

Keoleian, G., Bulkley, J., and Dettore, C., 2009. Comparative Life-Cycle Assessment of Bottled Versus Tap Water Systems. *Deep Blue Library-University of Michigan at Ann Arbor*.

GaBi databases 2006. *PE International GmbH; LBP-GaBi, University of Stuttgart: GaBi Software System*, Software or database.

Nestlé Waters North America, 2010. Environmental Life Cycle Assessment of Drinking Water Alternatives & Consumer Beverage Consumption in North America. Research performed for NWNA. Available from: http://beveragelcafootprint.com/?page_id=203 [Accessed 20 Febuary 2012].

North, M.J. and Macal C. M., 2007. Managing Business Complexity: Discovering Strategic Solutions with Agent-Based Modeling and Simulation. 1st edition, *Oxford University Press*, USA.

Pasqualino, J., Meneses, M., & Castells F., 2011. The carbon footprint and energy consumption of beverage packaging selection and disposal. *Journal of Food Engineering*, 103, 357–365.

Reap J., et al., 2008. A survey of unresolved problems in life cycle assessment. *The International Journal of Life Cycle Assessment*, 13, 374-388.

Sterman, J. D., 2001. System Dynamics Modeling: Tools For Learning In A Complex World. *California Management Review*, 43 (4), 8-25.

THE 2006 STATS, Source: Commentary and content provided by Beverage Marketing Corporation.

Zeigler, B. P., Kim, T. G. and Praehofer, H., 2000. Theory of modeling and simulation: integrating discrete event and continuous complex dynamic systems, 2nd edition, *Academic Press*.

Policy Function Approximation for Optimal Power Flow Control Issues

Stephan Hutterer[(a)], Michael Affenzeller[(b)]

University of Applied Sciences Upper Austria, School of Informatics / Communication / Media, Softwarepark 11, 4232 Hagenberg, AUSTRIA

[(a)] stephan.hutterer@heuristiclab.com, [(b)] michael.affenzeller@heuristiclab.com

ABSTRACT

In nowadays operations research, dynamic optimization problems build a central and challenging research topic. Especially in real-world systems such as electric power grids, dynamic problems occur where robust solutions need to be found that enable (near-) optimal control over time in volatile as well as uncertain power grid operation. The authors of this work identified the application of policy function approximation for suchlike problems, where an analytic functions needs to be found that takes an arbitrary state of the dynamic system and outputs appropriate control actions aiming at system-wide goals. Such an approach is very fruitful for robust optimization over time.
Applying this approach to two different problem classes in power grid research, this work aims at summarizing this work and identifying potential future issues.

Keywords: simulation optimization, power flow control, dynamic stochastic optimization, policy-function approximation

1. INTRODUCTION

Taking a look at power grid optimization, tasks that necessitate fast and robust dynamic control lie on hand. Taking exemplarily the general optimal power flow (OPF) problem, the aim is to find the optimal configuration of all controllable units for satisfying a given load situation, using steady-state representation of the power grid. Thus, the solution of this problem addresses exactly one stationary state J_t, disregarding possible states in the near future or eventual uncertain conditions in the system. Considering the system one time step later (J_{t+1}) due to changing conditions of weather, customer behavior or any other influence, the power flow in the system would change, hence, requiring a new solution to the optimal power flow problem further necessitated by the non-linear behavior of an electric power distribution system. Such a new computation would require a robust and fast-converging solution method, that guarantees quick support with a new optimal solution, independent of system complexity and starting point, which cannot be guaranteed by traditional steady-state OPF methods (Wang, 2007). This concern is further complicated by the steady increase of the number of control variables in smart grid applications (Hutterer, 2013b).

Thus, electric power systems fundamentally represent applications that require dynamic optimization techniques, respectively methods that enable optimization over time. The general scheme of approximate dynamic control with policy function approximation builds a fruitful ground for suchlike issues (Powell, 2012).

The rest of the paper is organized as follows: Section 2 proceeds with discussing the principles of simulation-based policy function approximation using evolutionary algorithms. Therefore, genetic programming (GP) can be identified as suitable metaheuristic search technique for evolving powerful control policies. In order to demonstrate the application, Sections 3 and 4 continue with illustrating two empirical studies when applying GP-based policy evolution to two practical scenarios, namely dynamic optimal power flow control for generation unit scheduling on the one hand, and a demand-side management related scenario for controlling distributed electric vehicle charging processes on the other side. Section 5 finally concludes the work und gives outlook to future issues.

2. SIMULATION-BASED EVOLUTIONARY POLICY FUNCTION APPROXIMATION

Policy function approximation can be understood as the general principle of providing an anticipatory policy $P(J_t)$, that outputs (near-) optimal control actions at runtime. The great advantage of such policy-based control schemes is the avoidance of any reoptimization during runtime after change of some state variables. Thus, instead of computing a static optimal solution, the policy function is optimized such that it leads to minimal expected costs in each possible state. This principle is illustrated in Figure 1. The authors of this work already identified the usage of policy function approximation techniques for the sake of optimizing power flow related tasks in smart grid engineering. A special scheme was applied in (Hutterer, 2013a; Hutterer 2013c) that uses evolutionary simulation optimization to evolve optimal policies that are trained within a dynamic simulation model and minimize some expected cost function. The application of simulation therefore enables the integration of systems' uncertainties (like uncertain weather or customer conditions) into the optimization process. This simulation-based policy optimization shall now be applied to highly relevant scenarios in power grid engineering.

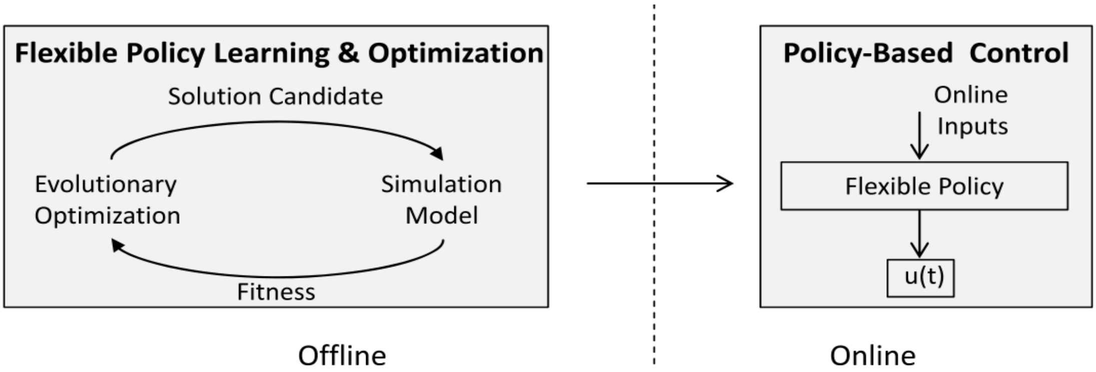


Figure 1: Principle of Policy Function Approximation

2.1. Formulating Simulation-Based Evolutionary Policy Function Approximation

As already discussed, policy function approximation is a method for dynamic optimization and seeks finding a generic function (policy) *P(x)* that returns a (near-optimal) action given a state. Most often, finding this function is the crucial step, where this technology usually gets applied when the structure of the policy is obvious (Powell, 2012). Equation 1 additionally aims at illustrating the principle of policy based control:

$$P = \arg\min_{P \in \Theta} [E(\sum_{t=1}^{K} F(P(J_t)))], \quad (1)$$

where J_t gives the system state at time *t, P* is the general denotation of a policy, *F(P(*J_t*))* gives the fitness of a policy's action at time t and *E()* indicates that usually an estimate (over uncertain states) needs to be obtained. Since the aim is to find the best performing policy *P* (without knowing how this policy shall look like), it has to be optimized over the space of potential policies Θ.

Assuming that a sufficient description of a state is achievable (which serves as input to the aspired policy), the issue is now to find this policy. As already discussed and being illustrated by (Powell, 2012), policy-function approximation is especially attractive when the structure of the policy is obvious. However, what if we do not know about the structure a policy could take? What if we only know that a certain policy takes several input variables (that come from J_t) and combines them to a more complex analytic function (using manifold mathematical operators) in order to derive a control action? In this case, genetic programming (GP) provides a fruitful method for function approximation that does not need for a-priori knowledge on the aspired mathematical structure, but only knows about the input variables as well as a specific grammar for combining them. Applying a metaheuristic search process (genetic algorithms), GP finally searches for performant policies within Θ.

2.2. Function Approximation with Genetic Programming

Extending the principle concept of genetic algorithms, GP uses evolutionary-inspired concepts for the heuristic search process, but is able to evolve computer programs. Within the herein described work, these computer programs take the appearance of trees, where leafs represent input variables describing the system state, that are combined by given mathematical operators which are incorporated by inner nodes. This kind of solution representation allows the evolution of arbitrary analytic functions without knowing their structure beforehand.

This approach has already been applied successfully to diverse applications, a general view on these works shall be provided herein.

3. APPLICATION TO THE GENERAL OPTIMAL POWER FLOW PROBLEM

The optimal power flow (OPF) problem has been stated some decades ago and is still the basic optimization problem in power system engineering. In its original formulation, the OPF considers steady-state situations, i.e. provides a static solution for exactly one considered discrete state. Since in volatile as well as uncertain power grids this consideration is some kind of "too optimistic", policy function approximation can be applied in order to build a general optimal power flow controller within simulated dynamic power grid environments. These simulations will be built based on real-world benchmark models, namely the IEEE distribution grid test cases[1]. For comparison reasons, the evolved approximate control policies will be evaluated with respect to exact interior point OPF solutions within steady-state situations created for testing reasons.

3.1. Policy Formulation

When striving to obtain a general control policy *P(x)*, it needs to be assumed that *x* gives a sufficient representation of the system's state J_t. In order to derive a control action for optimal power flows, *x* would need to consider all dependent variables of a power flow model (see definitions of OPF formulations in order to get an overview of used dependent variables (Hutterer, 2013c)). In such a case, especially for real-world

---

[1] Christie, R. D.: Power systems test case archive, http://www.ee.washington.edu/research/pstca/

systems a policy $P(x)$ would need to consider many hundred or even thousands of input variables.

Therefore, the authors of this work proposed the introduction of abstract information entities, so called "abstract rules", which extract information from a system's dependent variables and provide only the necessary data to a decision making unit that is crucial for this decision. In the case of handling a traditional optimal power flow (OPF) problem, a set of 7 rules (r) has been proposed in (Hutterer, 2013a) that is assumed to be both necessary as well as sufficient for making power flow decisions. Thus, a policy $P(r)$ needs to be approximated, where for most systems $|r|<<|x|$ holds.

3.2. Experiments

In the context of this publication, empirical studies have been performed for different models provided by the IEEE test case archive. For illustration reasons, two of these networks shall be presented herein, namely the 14-bus (the smallest test case) and the 300-bus (the largest test case) problems. Out of these benchmark instances, dynamic problems are built according to (Hutterer, 2013c) for learning policies for dynamic optimization. In order to validate the approximated policies, a test-procedure has been created that is based on randomly created test states. Therefore, within the simulation of the dynamic power grid models, discrete-time states are expressed that represent one single state of the system each. For these states, the deterministic OPF solution is computed with interior point method in MATPOWER and compared to actions that obtained best found policies lead to within these states. This allows the definition of an error term (in means of fitness), hence the quantitative validation of the policies' performance for approximate dynamic OPF.

3.3. Results

Table 1 lists the quality in means of error between the OPF fitness function value of the best found policy compared to the deterministically computed optimal solution within 10 arbitrary and independent test states. For both benchmark instances, it can be shown that the approximate policy-based control leads to near-optimal decisions, that are in mean only 0.6 respectively 0.51 % worse than the reference solutions.

Table 1: Performance Validation of OPF Policies

Time Step	**14-Bus**	**300-Bus**
1	0.0074	0.0160
2	0.0053	0.0201
3	0.0105	-0.0151
4	0.0045	0.0033
5	0.0041	0.0030
6	0.0071	0.0046
7	0.0071	0.0048
8	0.0064	0.0033
9	0.0034	0.0030
10	0.0042	0.0082
Mean Relative Error (MRE)	**0.0060**	**0.0051**

A more detailed discussion on OPF policy approximation can be obtained from (Hutterer, 2013c). This illustration shall demonstrate the power of policy function approximation for dynamic optimization in the context of the OPF-based generation unit scheduling and quantitatively shows its validity.

Further empirical studies applied policy-based control to demand side management; more detailed: to the control of distributed electric vehicle charging processes.

4. APPLICATION TO SMART ELECTRIC VEHICLE CHARGING CONTROL

Various researchers examine the problem of integrating plug-in electric vehicles (EV) optimally into power grids, where the control of charging power is seen as advantageous for reaching optimal power grid operation (Clement, 2008; Clement, 2009; Sortomme, 2011). Central challenge beside formulation and computation of the optimization problem itself is the consideration of the individual behavior that mainly characterizes electric vehicle charging load.

This PEV-charging control problem represents a dynamic optimization task that requires optimal control actions for high amounts of distributed EV-agents. Therefore, building a policy-based approach is the fundament of this show case. Here, each agent (EV) receives a flexible policy rather than static control decisions that makes it react to its environment dynamically, but in a globally optimal manner. This policy is principally the same for all agents, but using individual data from an agent's environment, it leads to agent-specific charging control. The policies will be evolved using the presented policy function approximation approach. Here, a simulation model is built that represents a fleet of EVs within a given power grid area, which will be integrated into the simulation-based evolutionary optimization of PEV charging control policies.

4.1. Policy Formulation

A general policy shall be obtained. Its aim is to output a charging decision to an electric vehicle given the state of the system at a given time step. This optimized policy is derived from input variables that consider agent-specific parameters from its environment. Out of these parameters, the EV's power demand as well as the state of its environment can be described sufficiently in order to derive a valid charging decision. Here, three different data classes can be distinguished from each other:

- Agent-specific data concern the EV's driving behavior, like its residence time at the actual charging station or its likelihood of getting parked at another charging spot later on.
- Local data considers other EVs immediately affecting the local situation in the power grid. For example, if the power grid is stressed locally because of a high amount of EVs

charging at the same bus, their charging power has to be reduced in the next time step in order to avoid critical power flow conditions.

- Global data considers information describing the whole system's state, like the total load to the distribution grid, totally expected supply from renewables or financial aspects considering costs of electrical power supply.

Out of these classes of input data, in the context of this work, the authors defined once more a set of abstract rules *(r)* that gathers all needed information for decision making and provides compressed information to control units (EVs in this case). Out of these rules, the general policy *P(r)* shall be learned that gives the decision on the charging power to a certain EV in the system.

4.2. Experiments

All experiments are based on the IEEE 33-bus distribution feeder. Within this feeder, 300 EVs are simulated to act individually. Additionally, renewable sources (wind-power and photovoltaics) are added to the system in order to create a dynamic and volatile scenario. A finally obtained charging policy has to derive robust charging decisions that provide system-wide near-optimal charging control over time.

Detailed discussions on this problem scenario as well as formal definitions are provided in (Hutterer, 2013b). Here, only the main issue of applying policy-function approximation to suchlike problems shall be illustrated.

4.3. Results

In this scenario, a general policy $P_{EV}(r)$ needs to be computed that derives accurate control actions for each single EV in the system, while considering both the agent's (EV) needs as well as system-wide goals of power grid operation. Equation 1 illustrates such a policy, which has been found in studies on the above mentioned system.

$$\begin{aligned} &P_{EV} = \\ &c_1 * ERT^{10} * AP * AWS * MCR * (PBL - c_2) \quad (1) \\ &+ c_3 * AI \end{aligned}$$

While the used input variables are discussed extensively in (Hutterer, 2012; Hutterer, 2013b), this policy considers an EVs remain time at a charging spot (ERT), the actual electricity price (AP), the actual wind speed (AWS), the mean charging rate of all other EVs during the previous time step (MCR), the past base load (PBL) at the previous time step as well as the actual solar irradiance (AI). Since all input rules are defined to give a value in the range [0,1], with the constants c1=17.86, c2=0.03 and c3=0.11 the policy finally provides a charging power value in the unit [kW].

Figure 2 depicts the mean charging power over all 300 EVs in the simulated system when applying the evolved policy to a test-scenario. From this illustration one can observe the principal functionality that this policy causes during operation, namely the principal shift of charging to time steps at night (where the grid-load is low). While this graph gives the mean charging power, the actual power of each EV differs and considers its individual behavior. However, over all EVs the system-wide constraints are satisfied that enable secure power grid operation, while the objective function considering total costs of energy supply is minimized.

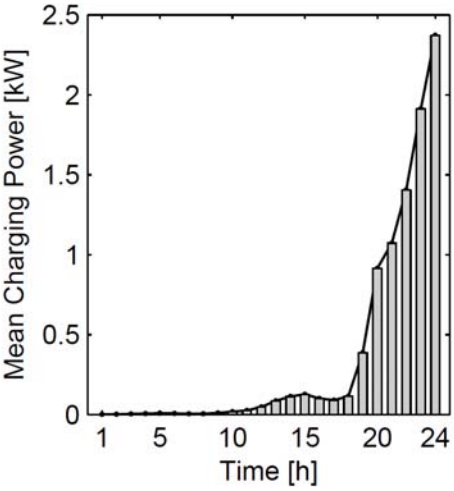


Figure 2: Charging Power in Simulated Test Scenario

However, this example shall demonstrate the evolution of control policies for dynamic optimization to an actual smart-grid relevant problem domain. More detailed discussions can be obtained from the referenced works, while this paper aims at providing a general view on the developed techniques. An outlook shall now depict several open issues.

5. OUTLOOK

Dynamic optimization with policies has the great advantage that it avoids the necessity of computing a specific solution to each state the dynamic system exhibits over time. Hence, dynamic adaptation of solutions seems to be not necessary, which is a major challenge in dynamic evolutionary optimization (Nguyen 2013a, Nguyen 2013b). However, this advantage only holds in a restrictive manner: A policy is able to make accurate decisions within situations that are sufficiently similar to those situations it has been trained to. For other situations, its extrapolation-ability is necessary to still make good decisions. As soon as specific situations are too different from the training simulation, obviously the policy-based control becomes useless. In such a case, the simulation model would need to be adapted in order to correspond to such situations, and the policy would need to be adapted / relearned.

Hence, if being learned accurately, policy-based control is valid for systems where their behavior, dynamics and uncertainty are adequately predictable. If such a system changes over long time, and the simulation no more matches the real-world, special techniques will need to be applied for learning a new policy or adapting the existing one, where numerous approaches already exist in literature, using memories of already evaluated solutions, sub-populations or immigration methodologies in order to adapt the evolutionary search to changing positions of the desired optima over time (Yang 2013). Hence, solution adaptation is avoided on a short-time scale, where the policy is able to derive decisions for uncertain and dynamic states. On a long-time scale, solution adaptation is still necessary in order to meet potential drifts of the system (i.e. a mismatch between simulation model and real-world).

Future work will need to concentrate on the examination of such drifts and needs to apply methodologies for policy adaptation.

5.1. Conclusion

This paper illustrated the application of policy function approximation for the sake of dynamic optimization under uncertainty in power grids. Summarizing related work from the authors and stating new results, two empirical studies have been outlined that show the application to central problem classes in power grid optimization. While policy-function approximation seems to be a fruitful technology for dynamic optimization, open issues have been identified that challenge new research questions in the context of dynamic systems.

ACKNOWLEDGMENTS

The work described in this paper was done within the Josef Ressel Centre for Heuristic Optimization Heureka! (http://heureka.heuristiclab.com/) sponsored by the Austrian Research Promotion Agency (FFG).

REFERENCES

Clement, K., Haesen, E., and Driesen, J. (2008): *The Impact of Uncontrolled and Controlled Charging of Plug-In Hybrid Electric Vehicles on the Distribution Grid*, Proceedings of the European Ele-Drive Conference, (EET-2008).

Clement, K., Haesen, E., and Driesen, J. (2009). *Stochastic Analysis of the Impact of Plug-In-Hybrid Electric Vehicles on the Distribution Grid*, 20th International Conference on Electricity Distribution CIRED, Prague.

Hutterer, S., Affenzeller, M., and Auinger, F., (2012). *Evolutionary Optimization of Multi-Agent Control Strategies for Electric Vehicle Charging*. Companion Publication of the Genetic and Evolutionary Computation Conference, GECCO'12, Philadelphia, PA

Hutterer, S., Affenzeller, M., and Auinger, F., (2013). *Evolutionary Algorithm Based Control Policies for Flexible Optimal Power Flow Over Time*, Proceedings of the EvoStar – EvoEnergy Workshop Workshop, Vienna, Austria

Hutterer, S., Auinger, F., and Affenzeller, M., (2013). *Evolutionary Computation Enabled Controlled Charging for E-Mobility Aggregators*, IEEE CIS Symposium Series on Computational Intelligence, Workshop: CIASG, Singapore

Hutterer, S. and Affenzeller, M., (2013). *Genetic Programming Enabled Evolution of Control Policies for Dynamic Stochastic Optimal Power Flow*, Companion Publication of the Genetic and Evolutionary Computation Conference, GECCO'13, Amsterdam, Netherlands

Nguyen, T.T, Yang, S., and Branke, J. (2012). Evolutionary dynamic optimization: A survey of the state of the art. *Swarm & Evol. Comput.* 6, pp. 1–24.

Nguyen, T. T. and Yao X. (2012). Continuous Dynamic Constrained Optimization-The Challenges. *IEEE Transactions on Evolutionary Computation*, 16(6), pp. 769-786.

Powell, W. B., Simao, H. P., and Bouzaiene-Ayari, B. (2012). Approximate dynamic programming in transportation and logistics: A unified framework. *European Journal of Transportation and Logistics, 1(3),* pp. 237-284.

Sortomme, E., Hindi, M. M. , McPherson, J. & Venkata, M. (2011). Coordinated Charging of Plug-In Hybrid Electric Vehicles to Minimize Distribution System Losses. *IEEE Transactions on Smart Grid, 1(1).*

Wang, H., Murillo-Sanchez, C. E., Zimmerman, R. D., and Thomas, R. J. (2007): On computational issues of market-based optimal power flow. *IEEE Transactions on Power* Systems, 22(3).

Yang, S. and Yao, X. (2013). *Evolutionary Computation for Dynamic Optimization Problems.* Studies in Computational Intelligence Vol. 490, Springer Berlin Heidelberg

AUTHORS BIOGRAPHY

Stephan Hutterer received his Diplomingenieur (FH) (graduate engineer) in Automation Engineering at the University of Applied Sciences Upper Austria. Since 2009, he is PhD candidate at the Johannes Kepler University Linz, Austria, working in the field of evolutionary optimization for intelligent power grids. His special research interests are simulation-based optimization for the integration of distributed renewable supply as well as electric vehicle fleets into power grids. He is member of the Heuristic and Evolutionary Algorithms Laboratory at the University of Applied Sciences Upper Austria.

Michael Affenzeller has published several papers, journal articles and books dealing with theoretical and practical aspects of evolutionary computation, genetic algorithms, and meta-heuristics in general. In 2001 he received his PhD in engineering sciences and in 2004 he received his habilitation in applied systems engineering, both from the Johannes Kepler University of Linz, Austria. Michael Affenzeller is professor at the University of Applied Sciences Upper Austria, Campus Hagenberg, and head of the Josef Ressel Center Heureka! at Hagenberg.

SIMPLIFIED STRATEGY FOR MODELING THE PERFORMANCE OF A NOVEL MULTI HOUSE HEATING SCHEMES

John Geoffrey Rogers [(a)],

[(a)]The Department of Mechanical Engineering, University of Bath, Bath, BA2 AY2, UK

mailto:j.g.rogers@bath.ac.uk,

ABSTRACT

Low carbon heating schemes frequently consist of a number of heat sources with different emission factors, a thermal store and heat distribution network. These need detailed models with short update periods to accurately predict their performance. However if you wish to establish the running patterns associated with the different heat source it can be assumed that tradition heat distribution networks work. This simplifies the modelling as the run period is dependent on thermal inertia of the heat store. This approach has been used to model the performance of a micro district heating scheme supplying three houses in the UK from a combination of a micro CHP unit, condensing gas boiler and solar water heaters. The model allowed each house to have variable heat loads and it was found that this combination of technologies produced a considerable reduction in annual CO_2 emissions.

Keywords: micro district heating, emission estimation, multi house heat load modelling, micro CHP with boiler and solar water heating,

1. INTRODUCTION

The need to reduce greenhouse gas emissions has now been generally accepted. This can be done by replacing some fossil fuelled power station by renewable generators and nuclear power station. An alternative approach is to improve the utilisation of our use of fossil fuels. The use of waste heat from electricity generation for space heating (combined heat and power CHP) is well established as a method of improving energy utilisation. A large industrial heat load or district heating scheme is needed to utilise the rejected heat from traditional utility scale generators. Micro CHP units designed to supply single households have been used as a way of over-coming the need for a district heating network. These have found to be effective in a number of countries. An extensive field trial carried out by the Carbon Trust in the UK found that they would only produce significant emission savings in houses with a high heating load (Carbon Trust 2007, 2011). An alternative would be to use a single micro CHP unit to heat a few houses in a micro district heating scheme. It is common practice in district heating CHP schemes to use a combination of a CHP engine and auxiliary boiler. With the CHP plant sized to supply a typical load and the auxiliary boiler rated to top up the capacity on the coldest days. This arrangement improves the capacity factor (the ratio of equivalent full load running hours to hours in a year) of the CHP plant and hence the economics of the scheme. The advantages of using thermal stores to improve micro CHP unit efficiency has been well reported (Haeseldonckx, Peeters, Helsen, and D'haeseleer 2007; Beyer and Kelly 2008). Traditionally in the UK the critical load for sizing boilers is the need to replenish domestic hot water (DHW) tanks after a bath is taken. A well insulate modern thermal store can store sufficient water for several baths can be taken in succession (The Hot Water Association, 2010). This allows the store to be reheated over a longer period which enables a smaller heating system to be used. Consequently the heating system can be sized for its longer term space heating duties rather than short duration DHW ones.

Thermal stores are also key components in solar heating systems so it was decided to look at the impact of adding solar water heaters to the system to see if this would meet requirements for 10-15% of primary energy generated from onsite renewable energy generation in the "Code for Sustainable Homes" (DLCG 2006).

Studies that have looked at the energy used in identical houses have shown wide variation between properties (Kane, Firth, Lomas, Allinson, and Irvine 2011; Carbon Trust, 2011). Although some of the variation can be accounted for by factors like degree of shading much of it appears to be a matter of occupier's lifestyle and preference. To take account of this it was decided to model three houses with average heat loss coefficients then independently vary the coefficient by ±30% to see what the performance is likely to be in a real installation.

It was decided to model the performance of one of the micro CHP unit used in the Carbon Trust field trial to heat three average houses with the assistance of a natural gas booster boiler for use on cold days. Each house had its own thermal store. The stores were connected in series and each store had a bypass value. The bypass valves were automated such that the two warmest stores were bypassed (Figure 1).

It was found that this arrangement coped well with unbalanced heat demands and could produce primary energy savings of 20-23% when compared to heat supplied by a condensing boiler and electricity generated by a gas fired combined cycle gas turbine (CCGT) supplied through the electricity grid. The savings could be increased to 30% by the addition of solar water heating and seasonal adjustment of heating system running temperatures. Large solar water heating installations can also meet the onsite renewable generation requirements of the UKs sustainable homes standard.

2. DESCRIPTION OF MODEL

It is possible to produce detailed models of building using tools like ESP-r and TRNSYS but this requires detailed information about the building being modelled. Although these tools can give accurate results for a single building they may be unnecessarily complex to estimate the performance of average houses with conventional heat distribution systems. We know that householders are satisfied with the performance of conventional heat distribution systems so it is only really necessary to consider the heat flows in and out of the thermal store. As the thermal inertia of the thermal store is much higher than that of the air enclosed in the house a lower model update rate can be used when compared to a full building simulation programme.

For the multi house model each house has its own thermal store. This means that any heat loss from the store heats the house and is not necessarily wasted. The micro CHP and boiler plants are run if any of the stores is below the appropriate cut in temperature and will run until all the stores are above the cut out temperature.

The three houses were initially modelled with a simple series connection but this was found to produce unacceptable thermal store temperature with some load distributions. This was overcome by including store bypass valves which were operated so that the coldest store received all the heat in a given period as shown in Figure 1.

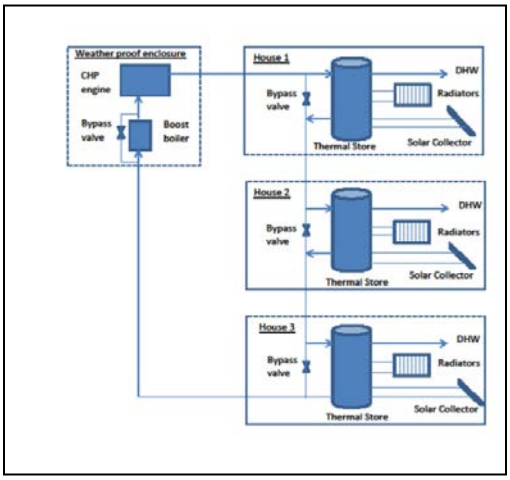


Figure 1: arrangement of micro district heating scheme

This arrangement maintained all the stores at an acceptable temperature throughout the year over the tested permutations of heat loads. It would also enable the running cost to be apportioned according to the total length of time that each houses bypass valve was closed thus removing the requirement for individual heat meters.

The model operates at a 6 minuet time interval for every fifth day throughout a year using the Weather data for Cardiff a city has an average UK climate (Exeter University 2011). The model follows typical UK practice of switching off the heating systems are overnight. This means that the inherent discontinuities associated with not considering every day occur when the heating system is off. It has been assumed that the houses are occupied throughout the year.

When the heating system is enabled it is assumed that the internal air temperature is maintained at a uniform 20°C. This is used to calculate the losses. The houses are assumed to have brick faced cavity walls with solid block inner skins. Each house is considered to have a thermal mass equal to the total thermal mass of the building structure within its insulated envelope. This is assumed to be the inner skin of the cavity wall which has a thermal mass of 8,333 kJ/K. The heat stored in the thermal mass is calculated from the inside air temperature and the thermal conductivity of the inner skin of the cavity wall (this assumption is only valid for this type of construction). The heat required to satisfy the losses and heat storage requirements for each period is subtracted from the heat accumulated in the store.

When the heating is switched off the internal temperature is assumed to be the mid wall temperature of the thermal mass and this is used to calculate the losses for the period. These are subtracted from the heat stored in the thermal mass.

For the solar heating option each thermal store is connected to a bank of vacuum insulated heat pipe thermal collectors which can operate at elevated liquid temperatures. To maximise the heat collection from the solar collectors the operating temperatures of the micro CHP engine and boiler are reduced during the summer.

2.1. Heating system input

2.1.1. µCHP unit

In the proposed arrangement the micro CHP engine is housed in a separate enclosure and is not in any of the houses. This means that it is possible to use a unit based on an internal combustion engine rather than a quieter but less efficient commercially available Stirling engines.

It was decided to use the commercially available Senertec Dach micro CHP unit for the model as its performance is typical for commercial IC engine based micro CHP unit and it has been widely studies (Beausoleil-Morrison and Kelly 2007). In its low NO_x form this engine can produce 12.3 kW of heat and 5 kW of electricity. It was assumed that the engine would take 6 minutes to warm up to a temperature where it produces utilisable heat (Beausoleil-Morrison, Kelly 2007).

2.1.2. Boiler

The micro CHP unit cannot supply all the heating or electricity demands of the houses. Additional heat is provided by a 12 kW condensing boiler. The boost boiler is connected in the return line to the micro CHP engine; this ensures that the inlet temperature to the boiler is low enough for it to operate in condensing mode.

2.1.3. Distribution system losses

An allowance of 5% was made for heat loss in the distribution system between the 3 houses. An allowance of 300W was made for the pumping power required by the distribution system.

2.1.4. Back up heating

The heating capacity of the radiator system is a function of the hot water supply temperature i.e. the thermal store temperature. This was allowed to vary over a wider temperature range than in conventional installations consequently the available heat output from the radiators was calculated for each period. If it was found to be below the thermal load for the period it was assumed that the occupants will switch on electrical heaters. The power that these consume was taken from the net generation of the CHP plant.

2.1.5. Solar water heaters

The model was run for houses with or without solar water heaters. Estimates of hourly beam and diffuse solar irradiation that would have been received at Cardiff for a year in the period 1961 to 1990 have been taken from Exeter Universities (2011). These have been used to calculate the hourly solar irradiation on an inclined solar collector. To maximise the use of solar energy it was decided to collect more solar energy than required for the DHW load on sunny day and store it for use on cloudy ones. This meant that the solar collector would have to operate efficiently with a high collection temperature. A collector that uses vacuum tube heat pipes would be suitable for this duty and it was decided to model the performance of the Sunnpro series of solar collectors as they appeared to be typical of this type of collector (Kramer 2007). The collector was assumed to be optimally mounted and the area adjusted such that the store temperature did not exceed 90°C at any day over the year. This is not a safe temperature for DHW but the building regulations require that thermal stores are fitted with temperature control valves that dilute the stored water so that the DHW is at a safe temperature. The amount of energy that can be stored on a sunny day is naturally a function of the store size. A larger collector area is needed to collect more energy consequently the size of solar collector that can be installed increases with store size.

This style of solar water heater uses a circulating pump. It has been reported that the electricity these use is equivalent to an average of 5% of the energy they collect (Martin, Watson 2001). The annual electricity consumption has been increased for the houses with solar water heating to take account of this increase in load.

2.2. Control Logic

2.2.1. Systems without solar water heating

The heating plant operates following the following control strategy:

- The CHP engine and boost boiler are constrained to only operate between 06:00 and 23:00.
- The CHP engine starts if any of the thermal store temperatures drop below 60°C.
- The CHP engine stops when all the store temperatures are above 75°C.
- The boost boiler operates if the return temperature is below 50°C.
- The boost boiler is bypassed if it is not running.
- The thermal store bypass valves are open except for the thermal store with the lowest temperature where it is closed.

2.2.2. Systems with solar water heating

For the days of the year where space heating is likely to be needed the control setting described in 2.2.1 were used. But solar water heaters should be able to provide most of the DHW demand over the summer period (day 100 to day 250) when there is little demand for space heating. The amount of energy storable in a thermal store depends on the difference between its maximum and minimum operating temperatures. To allow the maximum amount of solar energy to be stored the control temperatures were lowered to so that the CHP would only cut in if the thermal store temperature dropped below the minimally acceptable DHW supply temperature. This gave revised settings of:

- The CHP engine starts if any of the thermal store temperatures drop below 40°C.
- The CHP engine stops when all the store temperatures are above 50°C.
- The boost boiler operates if the return temperature is below 30°C (in practice this would only happen if the CHP engine was not available).

2.3. Individual house energy requirements

2.3.1. Electricity

Electricity consumption varies considerably between households and building types. The standard 30 minute demand profiles for domestic consumers used by the electricity balancing market administrators (UKERC,2012) was used to estimate the hourly electricity consumption which equates to an annual consumption of 3500 kWh.

2.3.2. Heat losses

Loss through the buildings fabric

The most common type of house in Britain is a three bedroom semi-detached or terraced house with a floor area of 82m^2 (Anon 2009, Utley and Shorrock 2008). There is a wide range of construction techniques used so the thermal conductivity and thermal mass will vary between houses. This study considered a typical mid-20th century construction of facing brick, air cavity, and inner cinderblock skin with a plaster facing. There have been a number of government schemes to improve the insulation standard of houses and it has been assumed that the houses would have had the loft insulated to a depth of at least 100mm, cavity wall insulation injected and double glassing fitted over the last 30 years.

It is assumed that a typical house is a cube with a pitched roof that is joined to a similar house by a common wall. Glazing fraction and material U values were taken from the government's Standard Assessment Procedure (SAP) manual for the energy ratings of dwellings (BRE 2011). This gave a heat loss of 167 W/K. An allowance for ventilation loss has also been included. Test on a range of property types in Scotland found ventilation rates in mid-winter ranging from 2.15 to 0.05 air changes per hour (AC/H). Some of this variation can be accounted for by building type, and age however there was also a wide range of values within each type of building indicating differences caused by location, or user preference (Howieson 2003). It was decided to use 1.0 AC/H which corresponds to an average loss of 73 W/K. This gives the total losses for the house as 240 W/K which gives a specific heat loss of 2.93 W/m^{2}K (this is similar to the average value for the UK housing stock of 247 W/K from Utley and Shorrock (2008)).

Domestic hot water

The Energy Saving Trust (2008) carried out a survey of DHW usage in the UK which gave averages for the volume used, delivery temperature, and incoming water mains temperature. This has been used to derive the following equation for the average daily DHW energy requirement:

$$Q_{dhw} = 4.56 + 6.53N \text{ MJ} \tag{1}$$

Where N is the number of occupants.

80% of English households have less than 4 occupants (Anon, 2009) so it was decided to assume an occupancy level of 3 for calculating the metabolic gain and DHW demand. As the houses were fitted with large thermal stores that buffered the DHW demand it was considered acceptable to assume that the DHW load was uniformly distributed between the hours of 07:00 and 23:00.

2.3.3. Heat gains

Solar Gain

The solar energy received per square meter of south facing window for each day has been calculated using the hourly solar data for Heathrow and the following factors from the SAP procedure (BR 2011): frame factor of 0.7, transmittance 0.76, solar access factor 0.9 glazing fraction of 17%. It was assumed that the house would have the equivalent of one south facing wall and that the solar gains through the windows in other walls would be negligible.

Metabolic and cooking

Metabolic gain is the heat given off by the occupants of the dwelling. The SAP procedure (BRE 2011) assumes that 100 Watt per person is dissipation to the surroundings. The SAP procedure uses equation 2 for average cooking gain

$$Q_{cooking} = 35 + 7\,N \text{ kWh/day} \tag{2}$$

It is unlikely that this will be a steady load so it was assumed that cooking only take place in the hours 12:00 to 13:00 and 18:00 to 19:00.

Lighting and appliance gain

It was assumed that eventually all electrical power used in the home would end up as heat.

Thermal Store losses

As the thermal store is assumed to be in the heated area of the house the heat loss from it is a heat gain for the house. The following equation for calculating the maximum permitted 24 hour heat loss is given in The Hot Water Association (2010):

$$Q_{HL\text{-}MAX} = 1.28 \times (0.2 + 0.051\ (VT)^{2/3}) \tag{3}$$

Where $Q_{HL\text{-}MAX}$ is the maximum permitted daily heat loss from a thermal store in kWh and VT is the total storage capacity of a thermal store in litres. It is measured with an initial store temperature of 75°C, and an ambient air temperature of 20°C. This will give the store temperature after 24 hours as:

$$T_{24} = T_0 - \frac{Q_{HL\_MAX}}{C_P VT} \tag{4}$$

Where C_p is the specific heat of water, T_0 is the store temperature at the start of the test and T_{24} is the temperature 24 hours later.

In practice for modern thermal stores the difference between T_{24} and T_0 will be less than 10°C and it is acceptable to assume a linear heat loss such that :

$$T_{Average} = \frac{(T_{24} + T_0)}{2} \tag{5}$$

Consequently a linear heat loss coefficient K can be defined as

$$K = \frac{Q_{HL\_MAX}}{24(T_{Average} - T_{Ambient})} \qquad KW/K \qquad (6)$$

This was used to calculate the heat loss from the thermal stores.

3. RESULTS

3.1. Energy Savings

Comparison of the emission associated with a gas fire CHP scheme with those from an independent heating system and grid electricity are likely to show emission savings simply because gas is being used as a primary fuel rather than the grid mix of coal, gas, nuclear and renewables. To get an assessment criteria which is independent of the grid mix it was decided to compare primary fuel usage by the micro district heating scheme with a benchmark of the same houses using the best economically available gas fired technologies i.e. gas fired condensing boilers and grid electricity from a gas fired combined cycle gas turbine (CCGT) power station. It is worth noting that this benchmark case would emmit 32% less CO_2 than would have occurred for the same load in 1990 (the Kyoto protocol base data) with the 1990 grid mix and non condensing boilers. So a 30% primary fuel saving against this papers benchmark is a 52% saving against the Kyoto protocol baseline.

The heat load for each house was varied for -30% to +30% with different combination of high and low load houses used the resulting energy supplied by the system is shown in Figure 2

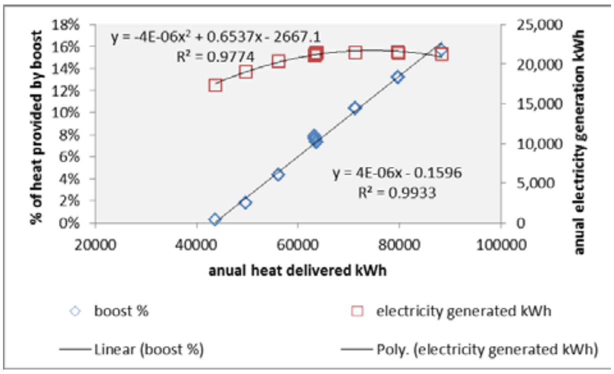


Figure 2: Energy supplied by micro district heating scheme

This gave rise to the primary energy savings shown in Figure 3. The boiler that is used to boost the CHP output has the same efficiency as the base case and so it is to be expected that the primary fuel saving will fall with increase boiler usage.

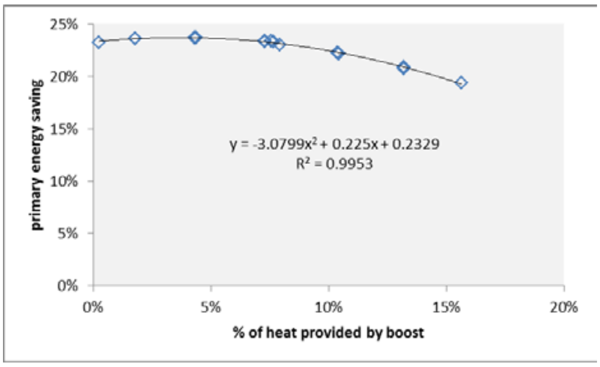


Figure 3: primary energy saving

It was found that changing the loads of the various houses had little impact on the thermal store temperatures of the individual houses. However at higher loads there were a few occasions where electrical back up heating were required. In the worst case when each house was taking 130% of the design heat load 3% of the heating was provided by the backup electrical heaters which would need to have an output of 3kW to cope.

The impact of different size solar collectors was investigated with each house fitted with a 700l thermal store and with equal heat load. The results are shown in Figure 4. There is not much solar energy available in the winter when the booster boiler operates consequently the solar water heating displaces micro CHP operation.

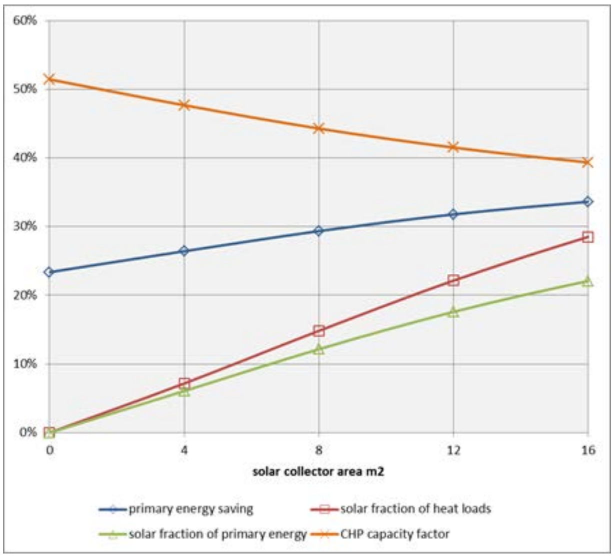


Figure 4: Impact of adding Solar Water Heating

3.2. Economic analysis

A full economic analysis is outside the scope of this study. If it is assumed that all systems have the same operational life and that the energy demand does not change between years a simple payback period calculation should give an indication of the most profitable option. Payback periods are simple to understand and are frequently used in promotional literature. The calculation is not subject to the underlying assumption involved with setting discount rates or valuation of environmental impact used by more sophisticated techniques like net present value and environmental cost benefit analysis.

A simple payback period calculation has been carried out to allow the relative costing of a multi house system to be compared with a single house installation. To do this the model was reconfigured as a single house installation.

It was recognised that the Dach unit is not designed for single households and is oversized for this application. So the single house was also run using a Honda Ecowill unit which is designed for single households and has rated outputs of 1kW electrical and 2.8 kW thermal.

The basic procedure was to estimate the annual gas and electricity bills for the house using a condensing boiler and grid electricity. Calculate the annual net saving made by using the micro CHP systems and their capital costs. Then calculate the simple payback period.

The electricity generated is treated by considering the amount of the CHP generation that would displace grid electricity (own use) and surplus CHP electricity sold to the grid (export). Electricity used when the CHP plant is not running is supplied by the grid. Payments under the UK feed in tariff scheme are allowed for.

Operation and maintenance cost of 0.036 Cent/kWh for the Econwill and 0.026 Cent/kWh were taken from (Pehnt et. Al. 2004). The net impact of electricity sales and imports is calculated and an overall annual operational savings calculated.

The installed costs were taken from the following papers and consumer information sources:

- Micro CHP units - Angrisani, Roselli, Sasso (2012),
- Thermal stores - www.stovesonline.co.uk/wood_burning_stoves/Akvaterm-Standard-Thermal-Stores.html
- Solar water heaters – theecoexperts.co.uk
- Condensing boilers – Wich.co.uk

Prices in pounds Stirling have been converted at the average 2012 exchange rate of 1.1776 €/£ (taken from www.currency.me.uk/convert/gbp/eur). The solar water heater cost is for a collector with an effective area of 12m^2 and is net of a £600 grant available under the government’s renewable heat incentive scheme.

The costs have been taken from single sources to try and eliminate errors resulting from different geographic location, dates, exchange rates and assumptions about installation costs. As such they do not represent a considered estimation of the cost but should only be taken to be indicative of the relative costs that may be experienced in real installations.

Domestic electricity consumption is highly stochastic in nature. A stochastic load estimation tool has been produced by Loughborough University (Richardson I, Thomson, Infield, Clifford, 2010) this has been used to generate load profiles for 3 occupants during January. A sample of these is shown in Figure 5.

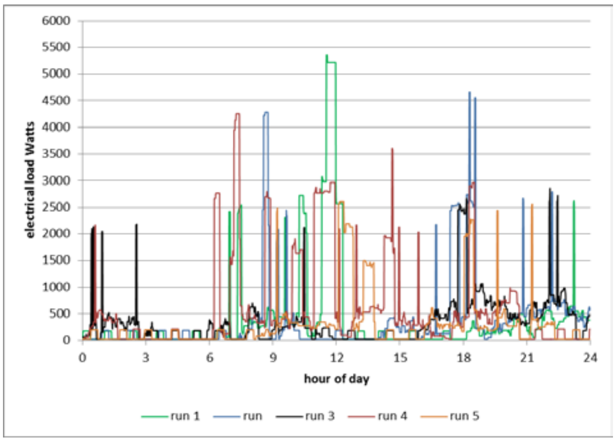


Figure 5: simulated daily electrical load profiles

From analysis of 40 runs it was concluded that 50% of the electricity consumption took place at times when the load was less than 1kW (which was about 92% of the time). The rest occurred in short duration peaks 99% of which were less than 5 kW. A 1kW micro CHP unit will be able to supply all of the loads below 1 kW and 1kW of the peak load this mean that on average overall it can supply 71% of the domestic electricity requirements when it is running. Likewise a 5 kW system can 99% of the domestic electricity requirement. However as the micro CHP plant does not operate all the time the amount they actually produce is dependent on their capacity factor. The operational performances of the systems are listed in Table 1.

Table 1: Operational Parameters

	Ecowill	Own Dachs	Shard Dachs	shared Dachs with SWH
Heat supplied kWh	19,448	19,631	19,516	19,449
boiler %	19.0%	0.0%	7.6%	7.7%
CHP	80.4%	100.0%	92.4%	70.1%
SHW				22.1%
CHP capacity factor	59.4%	18.9%	51.8%	41.5%
hours run / start	14.25	1.52	9.07	8.56
CHP heat efficiency	62.5%	58.7%	58.9%	58.9%
CHP electricty effiency	22.7%	24.9%	23.4%	23.4%
primary energy saving	20.3%	29.2%	23.4%	31.8%
solar % of primary energy				17.6%

The heat supplied is different for the different installations as the heat losses from the thermal store will be a function of its temperature which will differ between the systems. As predicted the use of a Dach unit in a single house results in a lower capacity factor and lower number of running hours per start. The electrical efficiency is higher on the Dach used on a single house as the electrical generation is net of the power used by the installation which is higher for the shared units.

The payback period has been calculated on the basis of current UK feed in tariff (FIT) payments for micro CHP of 0.1289 £/kWh generated and export payments of 0.0464 £/kWh (www.energysavingtrust.org.uk/Generating-energy/Getting-money-back/Feed-In-Tariffs-scheme-FITs). At present the 5 kW systems are too large to qualify for these payments but would be eligible for other subsides however as the aim of this study is to compare systems not support mechanisms it was decided to use the FIT payments in all cases.

The electricity and gas cost of 0.1318 £/kWh and 0.0443 £/kWh are the 2012 average domestic price from DECC (2012).

The key data for the payback calculation are shown in Table 2. The data for the boiler system is shown in order to demonstrate where the additional costs and operational savings are made. As it is the reference system there is no payback period associated with it.

Table 2: payback period

	boiler	Ecowill	Own Dachs	shared Dachs	shared Dachs with SHW
gas used kWh	23504	29229	33418	32356	25994
gas bill €	1226	1525	1743	1688	1356
electricty used kWh	3500	3500	3500	3500	3688
electricty generated kWh		5,345	8,320	7,111	5,705
own use kWh		1476	656	1793	1516
electricty from grid kWh	3500	2024	2844	1707	2172
electricty bill €	543	314	441	265	337
O&M cost €	100	187	216	185	148
FIT payments €		811	1263	1079	866
Electricty export kWh		3,869	7,664	5,318	4,189
Electricity sales €		211	419	291	229
annual operating cost €	1869	1003	719	768	747
Savings €		866	1150	1102	1123
Capital cost per house €					
CHP		6000	15000	5000	5000
thermal store		2341	2341	2341	2341
distribution pipes etc				1000	1000
saving on boilers				-550	-550
Solar water heater					6948
total		8341	17341	7791	14739
payback period years		9.6	15.1	7.1	13.1

The nominal target payback period used to design the UK FIT scheme was 10 – 15 years (Brown, Omom, and Madden 2009). It would appear that the Ecowill and shared Dachs with solar water heating fall inside this target, the single Dachs does not meet it and the shared Dachs exceeds it.

4. DISCUSSION

It has been shown that the use of micro CHP units can give a significant emission saving over separate electricity and heat generation using the best commercially available technology. In common with most generation technologies micro CHP units show a considerable economy of scale (Simader, Krawinkler and Trnka 2006; Angrisani, Roselli, and Sasso 2012). It has been shown that it is possible to take advantage of this by using a micro CHP unit to heat a small number of properties. This is likely to be a more realisable option for retrofitting existing houses to a CHP network than implementing a new large scale district heating scheme.

The control system described in this paper copes with unbalanced loads and has the following features:

- requires very little on site adjustment,
- low data processing requirements,
- no need for heat meters,
- still maintains acceptable store temperature.

There could be an issue with the frequent operation of the bypass valves and further work is needed to optimise the operating period for different thermal store sizes.

The estimation of the optimum size CHP unit is a complex mater (Haeseldonckx, Peeters, Helsen, and D'haeseleer W,2007; Bianchi, De Pascale, and Spina, 2012), too large a unit involves unnecessary capital expenditure and it runs infrequently which can lead to inefficiencies unless large heat stores are used; too small a unit runs efficiently for long periods but requires frequent running of an auxiliary boiler to boost its output. Unfortunately there is a limited range of units on the market so in practice it is a matter of finding one which will do the job rather than the optimum sized unit. The option of sharing a unit between properties increases the size range of systems available for the system designer.

From Table 2 it appears that sharing the load between a micro CHP unit and booster boiler improves the scheme economics but Table 1 indicates that this results in a significant reduction of the primary fuel savings achieved by the scheme. This is due to the fact that although a condensing boiler and a micro CHP unit have similar overall efficiencies the electricity produced by the micro CHP unit is displacing electricity which is generated at a much lower efficiency. This effect can also be seen with the solar water heating where the SWH provides 18% of the primary energy but only increases the primary fuel saving by 8.4%.

As the efficiencies of internal combustion µCHP units are broadly similar a SWH system should provide the same order of primary energy saving on any installation.

The primary energy savings achievable are in the region of those has been targeted for 25 years time which is also close to the end of the life of the micro CHP engine. It should be noted that if the micro CHP engine is replaced with a fuel cell based unit further primary fuel savings will be achieved.

5. CONCLUSIONS

Sharing a micro CHP unit between a number of houses is a realistic option that give flexibility to the system designer to optimise the size of each houses effective CHP unit.

The use of series connected thermal stores with heat distribution controlled by two state bypass valves is a simple method of implementing a robust small scale heat distribution network.

The economic case for micro CHP is dependent on the installation being able to receive FIT payments or other similar value subsidies.

The use of gas fired micro CHP units result in significant primary fuel savings when compared to the best available gas technology for local heating and gas fire centralised generation.

The addition of solar water heating further improves the primary fuel saving but increases the payback period under current subsidy arrangements.

ACKNOWLEDGMENTS

The author would like to thank Prof Geoff Hammond, Dr Marcelle McManus, Dr Adrian Winnett, Mrs Hayley Howard and Dr Samuel Cooper for their advice and support during conducting this research. This research was carried out as part of the UK's SUPERGEN:HiDEF program funded as part of The Energy Programme an RCUK cross-council initiative led by EPSRC and contributed to by ESRC, NERC, BBSRC and STFC.

REFERENCES

Angrisani G., Roselli C., Sasso M.,2012, Distributed microtrigeneration systems, *Progress in Energy and Combustion Science* 38, 502-521.

Anon, 2009, *Housing in England 2007–08, A report principally from the 2007– 08 Survey of English Housing September 2009*. Department for Communities and Local Government, London.

Beausoleil-Morrison I, Kelly N, 2007, *Experimental Investigation of Residential Cogeneration Devices and Calibration of Annex 42 Models*. A Report of Subtask B of FC+COGEN-SIM The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems. Annex 42 of the International Energy Agency Energy Conservation in Buildings and Community Systems Programme.

Beyer D, Kelly, Nick N, 2008, Modelling the behaviour of domestic micro-cogeneration under different operating regimes and with variable thermal buffering. *In: Micro-Cogen,1st International Conference on Micro-Cogeneration Technologies and Applications,* 29 April -01 May 2008, Ottawa, Canada.

Bianchi M., De Pascale A., Spina P., R., 2012, Guidelines for residential micro-CHP systems design, *Applied Energy* 97 (2012) 673–685.

BRE, 2011, *The Government's Standard Assessment Procedure for Energy Rating of Dwellings 2009 edition incorporating RdSAP 2009*, BRE Garston, Watford WD25 9XX.

Brown M., Omom D., Madden B.,2009, *Poyry Energy Consulting and Element Energy, 2009: Qualitative issues in the design of the GB feed-in tariffs*: a report to the department of energy and climate change, Oxford, Poyry Energy Ltd and Element Energy Ltd.

Carbon Trust, 2007. *Micro-CHP Accelerator Interim report*, Carbon Trust report CTC726.

Carbon Trust, 2011.*Micro-CHP Accelerator Final report – March 2011*, Carbon Trust report CTC768.

DECC, 2012, *Quarterly Energy Prices*, downloaded from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65940/7341-quarterly-energy-prices-december-2012.pdf. Accessed June 2011.

DCLG,2006, *Code for Sustainable Homes.* Downloaded from www.communities.gov.uk Accessed December 2012

Exeter University,2011, PROMETHEUS web site www.centres.exeter.ac.uk/cee/prometheus/, accessed October 2011.

Haeseldonckx D, Peeters L, Helsen L, D'haeseleer W,2007, The impact of thermal storage on the operational behaviour of residential CHP facilities and the overall CO2 emissions, *Renewable and Sustainable Energy Reviews* 11(2007),1227–1243.

Howieson S.G., 2003, Domestic ventilation rates, indoor humidity and dust mite allergens - Are our homes causing the asthma pandemic?, *Building Services Engineering Research and Technology*, 24 (3), p 137-147.

Kane T, Firth SK, Lomas KJ, Allinson D, Irvine K,2011, Variation of indoor temperatures and heating practices in UK dwellings, *Proceedings of Buildings don't use energy people do*, Bath 28/06/2011, ISBN: 978-0-86197,2011.

Kramer K., 2007. Test Report: KTB Nr. 2007-07-ac-en for Sunny Pro SP series, Fraunhofer-Institute for Solar Energy Systems ISE, Heidenhofstraße 2, D-79110 Freiburg, www.kollektortest.de. Accessed October 2011.

Martin C., Watson M., 2001, *Side by side testing of eight solar hot water heating systems.* ETSUS/P3/C0275/REP/2, DTI pub URN 01/1296.

Pehnt M., Praetorius B., Schumacher K., Fischer C., Schneider L., Cames M., Voß J,2004, Micro CHP – a sustainable innovation?, interim results of a case study performed within the interdisciplinary research project, Transformation and Innovation in Power Systems, downloaded from http://www.tipsproject.org/DOWNLOAD/Graz_Innovation_Micro_CHP.pdf accessed July 2013.

Richardson I., Thomson M., Infield D. G., Clifford C., 2010, Domestic electricity use: A high-resolution energy demand model. *Energy and Buildings*, 42 (10), p1878-1887.

Simader G., R, Krawinkler R.,Trnka G., 2006, *Micro CHP systems:state-of-the-art*, Deliverable 8 (D8) of Green Lodges Project (EIE/04/252/S07.38608).

The Energy Saving Trust, 2008, Measurement of domestic hot water consumption in Dwellings, available from http://www.decc.gov.uk/publications. Accessed October 2011

The Hot Water Association, 2010, *Performance Specification for Thermal Stores*, Downloaded from www.hotwater.org.uk. Accessed April 2011

UKERC,2012, Energy Data Centre , http://data.ukedc.rl.ac.uk/browse/edc/Electricity/LoadProfile/data/ProfileClass1.csv Accessed March 2012.

Utley JI and Shorrock DL, 2008, *The BRE Domestic Energy Fact File*. Report produced for DECC. Downloaded from http://www.bre.co.uk/filelibrary/pdf/rpts/fact_file_2008.pdf accessed July 2013

OPTIONS FOR SWITCHING MODES OF TRANSPORT IN VIENNA

Gerda Hartl[a], **Gabriel Wurzer**[b]

[a]university assistant, Architectural Sciences, Vienna University of Technology
[b]researcher, lecturer, Architectural Sciences, Vienna University of Technology

[a]hartl@iemar.tuwien.ac.at [b]wurzer@iemar.tuwien.ac.at

ABSTRACT

In city planning, simulation has often been employed for assessing the impact of regulatory decisions. One of the aspects that widely influence the development of a city is the use of different transport modes (motorized individual transport, public transport, pedestrian or bicyclist traffic). In the model we are going to present, we have looked into a reallocation of commuter traffic as means for building a walkable city. Holding commuters' origins and destinations constant, we built an agent-based simulation model in search for opportunities to switch modes of transport. We utilize real network data together with municipal census data (commuters living and working in Vienna, differentiated by transport modes). Our results show possible ways towards sustainable transport mode usage. Being already feasible today, its implications are interesting well beyond the borders of our chosen area.

Keywords: agent-based modeling, traffic simulation, walkable cities, commuter traffic

1. INTRODUCTION

Commuting is an everyday reality for most people nowadays. The key problem is that sustainable infrastructure (bicycle lanes, public transport) that supports people in their daily travel to and from work is not always available, due to the fact that city planning has long evolved around the private car as primary transportation means. This is a pity, because there are multiple transport modes to choose from. In our model, we show that by using a simple approach of mode change, people can get faster to work (and back again) even if residential and workplace locations are distributed as today. Take, for example, the situation shown in Figure 1: a commuter going by car travels along the node network of a city, which takes a defined time. By evaluating additional choices, here: first the alternative route via foot (no decrease in travel time) and then via public transport followed by egress (decrease in travel time), the commuter can decrease his time spent in traffic and at the same time contribute to form the walkable, decarbonized city.

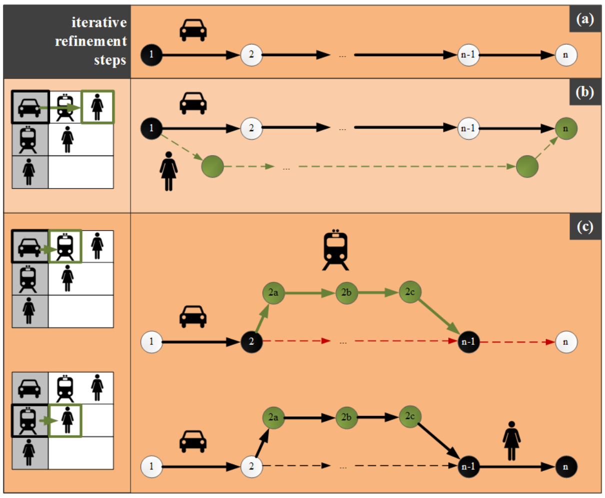


Figure 1: Optimisation of Paths via Mode Switch Evaluation. An initial route by car is first substituted by a pedestrian connection, with no success (increase in travel time). At the next node, a preferable route is found which first uses public transportation before resorting to egress by foot. Note that the choice of subsequent transportation means is done via a look-up-table, as shown left in the graphics.

2. MODEL DESCRIPTION

Our model is based on a directed graph, with allowed modes being attributed to the edges (public transport, motorized individual transport, pedestrian or bicyclist traffic). Furthermore, we attribute maximum speed limits and metric length to each edge. These two characteristics form the weight used during path finding (weight = length / speed).

We have imported this network information into a Netlogo 3D model (Wilensky 1999) extended by a plug-in for shortest path inquiry. Arrival data is loaded from spreadsheets, obtained from municipal census data on commuters from 2009 (Statistics Austria 2009). In more detail, this takes the form of a matrix, in which traffic between each two zones of the city is gives as the number of commuters per transport mode. The network itself is imported from GIS-Data, available from the Viennese transport model of the city of Vienna (Magistrat der Stadt Wien 2012).

The progression of our simulation model is as follows: In the first step, commuters are distributed to a random vertex within their residential zone. This vertex needs to be attached to the circulative network required by the commuter (public transport, motorized individual transport, pedestrian-, or bicycle network). Likewise, a target vertex is selected in the destination zone. Using the described weights on the edges of the network, the commuter now determines his initial shortest path, the duration of which is taken as a baseline. If every commuter acts in this way, we have our first model, the baseline model.

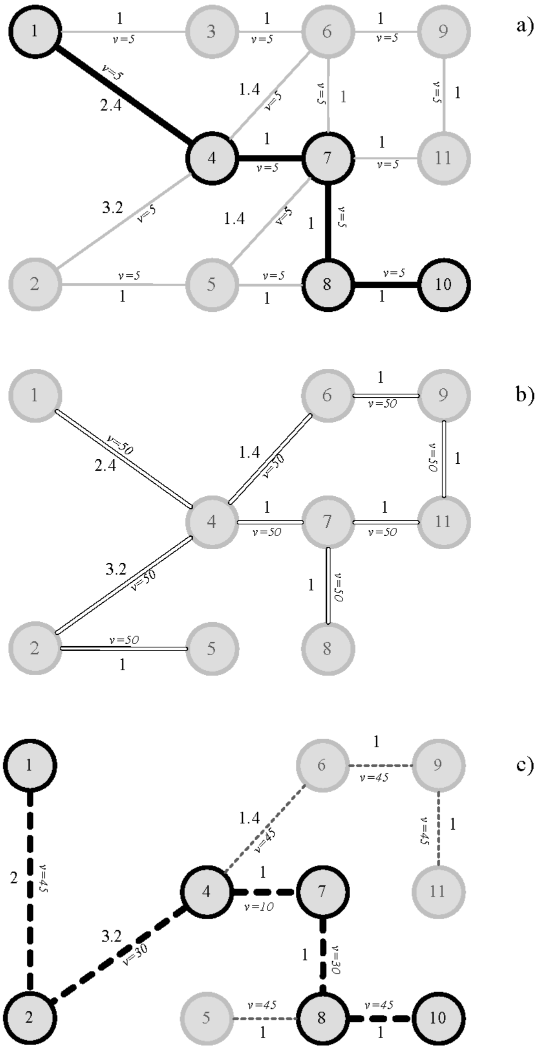


Figure 2: Sample Transport Network Graph for a) pedestrian circulation b) public transport c) motorized individual transport. Highlighted in black: shortest path between nodes 1 and 10.

An example is given in Figure 2: Let us assume that a commuter is to travel from node 1 to node 10. Then, we can look at the graph corresponding to the initial mode choice – pedestrian transport (Figure 2a), public transport (Figure 2b) or motorized individual transport (Figure 2c). Note that we have left out bicycle traffic, as this is largely identical to pedestrian transport except the higher velocities at the edges. For pedestrian and individual transport, there is a suitable route, whereas there is none for the case of public transport. Thus, we can see that the latter is an intermediate choice, which cannot always be properly reflected if we consider a fixed model only, without the use of mode change. A solution to this problem would be to define catchment areas, which we have implemented as straightforward solution. However, we are more interested in the true reallocation of commuters, which we show in due course.

In our reallocation model, we seek to optimize the initial travel time by examining the alternative transport options at each node of the so-far selected path. Starting with the initial node, we subsequently try alternative means of transport as given by the mode of transport switching in Table 1:

- For each mode, there are allowed next modes to try
- A route is optimized by an agent situated at a current node. This agent examines if there are alternative routes with the allowed next modes, in the following manner: if an alternative path from the current node exists that meets the so-far planned route again, the agent switches his transport mode and takes the new route. In case that the last current node is not the destination node of the route, the agent iterates this process: he examines the mode of transport switch table and takes one of the allowed next transportation means in order to arrive at his final node.
- Once the agent is at his destination node, the travel costs of the alternative route are compared to the initial ones. In case there is a benefit, we accept this as new solution. In all other cases, the agent back-tracks to the node at which the fork was conducted. He then continues to the next node along the hitherto existing route and tries again.

Table 1: Mode of Transport Switch Opportunities: an agent entering in a current mode may choose the allowed next modes in the order defined when optimizing his path.

Current Mode	Allowed Next Mode
individual transport	public transport, pedestrian
public transport	pedestrian
pedestrian	pedestrian

The example in Figure 1 shows exactly this case: A given route by car is first optimized by finding an alternative public transport connection, then, a pedestrian path is searched. As there is no public transport available at that node, the agent goes on to determine a pedestrian route, but fails (no benefits), thus, he has to backtrack and advance to the next node. At this node, there is the opportunity of public transport. The agent (now in public transport mode) takes it and arrives at an intermediate node, which is not his final destination. Thus, he consults his mode of transport switch table again and finds that there is the possibility to switch to pedestrian mode for reaching the final goal. The total path taken turns out to be of lower cost than the initial one and is accepted as the optimized solution. Figure 3 gives a merged view of all three networks presented in Figure 2, in which the optimized path is shown. The initial route by car went from node 1 over nodes 2, 4, 7, 8 to 10. The optimized route consists of a switch to public transport for travelling the nodes 1, 4, 7, 8 and after that, to pedestrian transport for reaching the final node 10.

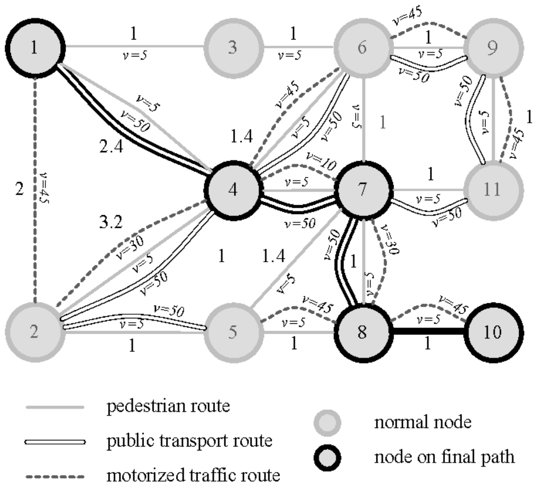


Figure 3: Optimization of paths by switching mode of transport. The highlighted black edges display the optimized path from nodes 1 to 10.

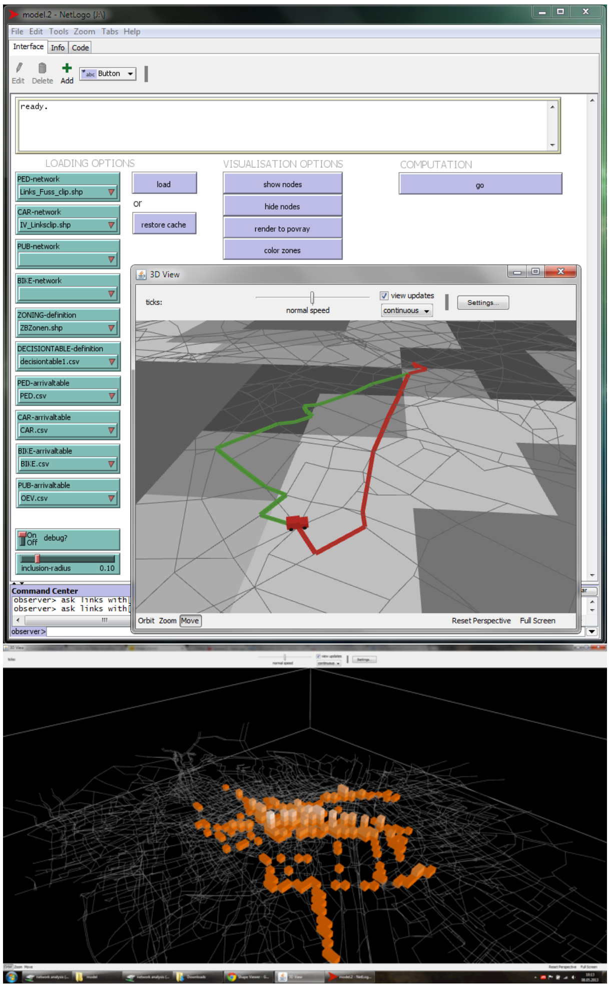
3. DISCUSSION

Average speed values (e.g. pedestrians' speed is 5 km/h, car speed varies according to traffic and congestion) together with segment lengths are used to obtain travel time estimations for found routes. Clearly, this is a snapshot of a situation that corresponds to "interesting" time spans. We could easily make this model more dynamic by importing time series instead of static speed values; however the availability of such data is really the key issue here (future work).

Also, we employ catchment areas for determining when an agent can cross over into another form of transportation. These are of different size (public transport catchment areas are necessarily far greater than for example pedestrian network access radii). However, the radii can also change within one network, which we have still not taken into account.

4. PRELIMINARY RESULTS

We have implemented our approach as a Netlogo 3D simulation in order to test its feasibility on real data (transport networks of Vienna). The results are two-fold: First, we can show that route finding does not simply behave as shortest path problem when looked at from the viewpoint of time and speed (see upper part of Figure 4). Second, we can graph the transport network utilization in each zone for both the baseline model and the reallocation model, in order to be able to visually compare the predicted commuter volumes. Work on the latter has, however, just started (see lower part of Figure 4).



```
ready.
```

PED-network: Links_Fuss_clip.shp
CAR-network: IV_Linksclip.shp
PUB-network:
BIKE-network:
ZONING-definition: ZBZonen.shp
DECISIONTABLE-definition: decisiontable1.csv
PED-arrivaltable: PED.csv
CAR-arrivaltable: CAR.csv
BIKE-arrivaltable: BIKE.csv
PUB-arrivaltable: OEV.csv
debug? On Off
inclusion-radius 0.10

```
observer> ask links with
observer> ask links with
observer>
```

Figure 4: Preliminary implementation. Upper part: Route optimization of an agent traveling by car (red) into a pedestrian route (green). Lower part: Intermediate stage of the simulation, showing utilization of transport in zones.

5. REFERENCES

Magistrat der Stadt Wien MA 18, Stadtentwicklung und Stadtplanung. *Verkehrsmodell Wien der Stadt Wien*. Magistrat der Stadt Wien: VISUM Transport Model. Received in August 2012.

Statistics Austria, 2009. *Abgestimmte Erwerbsstatistik 2009*. Available from: www.statistik.at/web_de/frageboegen/abgestimmte_erwerbsstatistik/ergebnisse/index.html [accessed 24 October 2011].

Wilensky, U., 1999. *NetLogo*. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL. Available from: http://ccl.northwestern.edu/netlogo/ [accessed 13 April 2013]

DEVELOPING A SUSTAINABILITY ASSESSMENT TOOL FOR SOCIO-ENVIRONMENTAL SYSTEMS: A CASE STUDY OF SYSTEMS SIMULATION AND PARTICIPATORY MODELLING

Perez-Mujica Luisa[(a)], Bossomaier Terry[(b)], Duncan Roderick[(c)], Rawluk Andrea[(d)], Finlayson C Max[(e)], Howard Jonathon[(f)]

[(a,d,f)] School of Environmental Sciences, Charles Sturt University
[(b,c)] Centre for Research in Complex Systems, Charles Sturt University
[(c)] School of Accounting and Finance, Charles Sturt Unviersity
[(a,d,e)] Institute of Land, Water and Society, Charles Sturt University

[(a)]lperezmujica@csu.edu.au, [(b)]tbossomaier@csu.edu.au, [(c)]rduncan@csu.edu.au, [(d)]arawluk@csu.edu.au,
[(c)]mfinlayson@csu.edu.au, [(d)]jhoward@csu.edu.au

ABSTRACT

Assessing the sustainability of socio-environmental outcomes, created through wetland restoration, requires a systemic approach. The aim of this paper is to develop a participatory modelling procedure for understanding sustainability in complex socio-environmental systems by combining participatory modelling and systems simulation. This study uses the wetland restoration program at Winton Wetlands (Benalla, Victoria, Australia) as a case study. The systems simulation component, which includes system dynamics and agent-based modelling techniques, is used to identify: i) the main elements and relationships of the system, ii) plausible scenarios for sustainable development, and iii) sustainability indicators for the Winton Wetland socio-environmental system (WWSeS). In addition, the process includes the participation of stakeholders for model validation and better understanding of the system. A nature-based tourism simulation model is developed as an example for the systems simulation method. This novel approach is thought to provide new insights into and guidance for assessing sustainability of complex socio-environmental systems around the world.

Keywords: sustainability, complex socio-environmental systems, simulation modelling, agent-based modelling, system dynamics, wetlands

1. INTRODUCTION

1.1. Sustainability and complex socio-environmental systems

Since it was first introduced, sustainability has been defined and conceptualized on many occasions (Gibson, 2006; Lozano, 2008). This presents difficulty for undertaking assessments of sustainability and ascertaining whether or not it is a practical concept and if it represents more than just good intentions and promises. It has been argued that assessments of sustainability need to consider whether an initiative is: i) based on the underlying principles of sustainability (Table 1), ii) is viewed in the context of the complex system in which it is embedded, iii) is systematic and traceable (Phillis & Andriantiatsaholiniaina, 2001) and iv) includes stakeholders in the decision-making process (Gibson, Hassan, Holtz, Tansey, & Whitelaw, 2005). Many assessments, in particular those which claim to address sustainability systemically, have neglected to truly address these requirements. In particular, they either fail to account for the complexity of the socio-environmental system (SES) of interest or do not include stakeholder participation in the modelling process (Bagheri & Hjorth, 2007a, 2007b).

Table 1: Principles of Sustainability

1. The resources of the system, in terms of sinks and sources, are not deteriorated. a. Substances produced by society must not accumulate in the ecosphere. b. Substances extracted from the Earth´s crust must not systematically increase in nature.
2. The physical basis for productivity and diversity of nature must not be deteriorated.
3. All people should have their basic needs satisfied so that they can live in dignity and in healthy communities.
4. Have a systemic perspective of the world in terms of the social, environmental and economic implications of sustainability.
5. Build collective responsibility through open and informed deliberations.

In the context of assessing sustainability, SESs are acknowledged as complex, however their characteristics have often not been fully taken into account. A common misconception is that complex systems are characterized by having a combination of social, economic and environmental aspects. However, this ignores the important features of complex systems, such as being constantly changing, tightly coupled, history dependent, having emergent phenomena and being governed by feedback (Bagheri & Hjorth, 2005; Borshchev & Filippov, 2004; Sterman, 2000). Efficiently accounting for these features enables the sustainability of complex SESs to be addressed in a more thorough and systemic manner.

It is because of the complexity of SESs that the assessment of sustainability should focus on understanding the processes and dynamics that shape the physical, social and economic environments and establish measures to keep the system working in perpetuity (Bagheri & Hjorth, 2005). However, because complex systems contain a large number of objects (e.g. people, businesses, vehicles, animals, etc.), which interact with each other, building a complete picture of such a system is extremely difficult without the use of systems simulation modelling (Sterman, 2000). Moreover, the unique characteristics of every SES together with the difficulty of gathering all the information necessary to describe it, requires the incorporation of stakeholder participation in the modelling process.

All these previous factors open the field for an integrative study of sustainability, which focuses on the complexity of SES. Because of this, the aim of this study is to develop a participatory modelling procedure for understanding sustainability in complex socio-environmental systems by combining participatory modelling and systems simulation. The case study for this project is the Winton Wetlands site at Benalla, Victoria in south-east Australia.

1.2. The Winton Wetlands as a complex socio-environmental system

The Winton Wetlands is an 8,750 ha transformed wetland site, located in the Goulburn-Broken Catchment in North-East Victoria, approximately 200 km north of Melbourne, Australia. In 1970, it was transformed into an artificial irrigation reservoir, Lake Mokoan, with the construction of a dam. Due to its inefficiency as an irrigation reservoir (increasing turbidity, algal blooms, and water losses), the State Government decommissioned the dam in 2004 (Goulburn Broken Catchment Management Authority, 2012).

After the decommissioning, the state Minister of Water established the Winton Wetlands Committee of Management (WWCoM). This community-based organization was charged with the preparation and implementation of two projects aiming to return the Winton Wetlands to its natural state as an important wetland system (approximately 2,900 ha of Red Gum woodland were destroyed with the construction of the dam) and develop the site as a sustainable nature-based touristic wetland. These are the Winton Wetlands Restoration and Monitoring Plan and the Winton Wetlands Master Plan, respectively (Goulburn Broken Catchment Management Authority, 2012; Taylor Cullity Lethlean et al., 2012). In both documents, sustainable development with the participation of stakeholders is considered a main objective and guiding principle of the restoration project (Taylor Cullity Lethlean, et al., 2012). This makes the Winton Wetlands an ideal case study for the development of a sustainability assessment method such as the one proposed in this paper.

It is recognized that there are many actors and issues involved in the Winton Wetlands SES. These actors have different agendas, interests and knowledge of the system (Taylor Cullity Lethlean, et al., 2012), all of which need to be taken into account in the construction of the system. Some actors have been identified such as, graziers, tourist operators, indigenous communities and local residents in the neighbourhood of the wetland.

In addition to the actors, the main issues identified for the Winton Wetlands socio-environmental system SES include water availability, water quality, biodiversity, economic revenue and the creation of a Winton Wetland tourism brand. Regardless of the different levels of acceptance of the overall restoration project, stakeholders agree that whatever is done, needs to be done well. The interactions among the actors and the environment comprise the Winton Wetlands SES and need to be included in the simulation process.

The Winton Wetlands restoration project is an ideal case for this study because it is currently in the beginning stages of restoration and development of nature-based tourism. Furthermore, sustainable development and inclusion of stakeholders is deemed as important and the community has shown significant interest in taking part in the decision-making process.

2. SYSTEMS SIMULATION TECHNIQUES AND STAKEHOLDER PARTICIPATION IN SUSTAINABILITY ASSESSMENTS

SESs are dynamic, multi-scalar systems, which are so complex that a full description is impossible, prediction of changes is difficult and unexpected changes are likely (Gibson 2006). To overcome these difficulties, systems simulation processes, utilizing qualitative and quantitative methods, are used to incorporate stakeholder participation and approach the study of sustainability along two main axes. First, they address sustainability through the development of a simulation model of the socio-environmental system (Bagheri & Hjorth, 2005; Cockerill, Passell, & Tidwell, 2006). This takes into account the features of complex systems such as feedbacks and non-linear interactions. Second, they make use of a participatory method to include direct input of stakeholders throughout the modelling process

(Andersson, Olsson, Arheimer, & Jonsson, 2008; Stave, 2002; Voinov, 2008).

2.1. Systems simulation modeling

Systems simulation approaches interpret reality through the construction of representative models of a system. These simulation models can be considered as a set of rules (equations or logical rules) that define how the modeled system will change in the future, given its present state (Borshchev & Filipov, 2004). Systems simulation modelling approaches, such as Systems Dynamics (SD) and Agent-Based Modelling (ABM), have been adapted for the study of complex SESs (Borshchev & Filippov, 2004). These approaches not only address the features of complex systems, but also allow the main elements of the system and their relationships to be depicted rigorously and unambiguously, thus making the modelling process traceable (Scholl, 2001).

SD was originally developed for the analysis of complex systems in other areas, such as engineering and business management, while ABM has been applied to fields such as social sciences (Scholl, 2001).

The differences between SD and ABM simulation modelling come from the approach of their respective simulation procedures. SD is a 'top-down' simulation in which the overall structure and interdependencies of the system determines the behaviour of the particular elements. In SD, real world processes are represented in terms of aggregate variables (stocks and flows between stocks) and their interconnections, through feedback loops. Feedback loops represent circular causation among the elements of a system and are the fundamental building blocks of a SD model.

As SD uses differential equations for the modelling process, the modeler has to think in terms of global structural dependencies and has to provide values for them. This makes SD a confirmatory approach. In addition, by working with aggregate variables, the items in each aggregate are indistinguishable from one another.

In contrast, ABM is a 'bottom-up process' where emergent phenomena are derived from behavioural rules of individual agents (Scholl, 200). Emergence, in complexity theory, is understood as the property of complex systems where "much comes from little". Said in other words, complex patterns arise from simple behavioural rules. Compared to SD, the aim of ABM is to look at the global consequences of local interactions in a given space. Therefore global behavior is established at the individual level, and emerges as a result of many individuals following their own behavioral rules. These rules include interactions with other individuals and the environment. ABM, as opposed to SD, therefore has an exploratory nature.

Despite the differences between both modelling techniques, SD and ABM are underpinned by a set of universal principles that support the behaviour of all complex systems and can be modelled over time (Bonabeau, 2002). This is the main reason why recent studies have established that they can be complementary as each technique can potentially account for weaknesses in the other (Borshchev & Filippov, 2004; Scholl, 2001). For example, the exploratory nature of ABM counteracts the confirmatory nature of SD. This is particularly important for the study of complex SES where little is known about the overall dependencies and the modelling team (and in this case the stakeholder group) does not intuitively need to know the specific globalized dependencies of the system (Bonabeau, 2002). Thus, modelling the individual agents in terms of their individual rules, which help them interact with other agents and the environment, results in the emergence of the behaviour of the system (Borshchev & Filippov, 2004). In contrast, certain tools within SD, such as Causal Loop Diagrams (CLD) may be helpful in the qualitative conceptualization of the model, particularly with stakeholders, as they show the relationships among the elements of the system under discussion (Coyle, 2000).

2.2. Stakeholder participation

There is growing consensus that every socio-environmental system is unique within its context (Gibson, 2006). When it comes to studying sustainability of SES, this implies that in order to have all the information necessary to depict a particular system, a large amount of data needs to be collected, and even then, there would still be gaps in knowledge and margins of error (Stave, 2002). In addition, systems that involve human sub-systems are characterized by uncertainties, conflicts of interests and value judgments, making it difficult to find a single "optimal" representation of the system (Stave, 2002). As a result, instead of constructing a socio-environmental system after months or years of exhaustive data collection, a mixture of available data and stakeholder knowledge of the system could be used to understand the main elements and relations within the SES.

Stakeholder participation is often called upon as a means of tackling challenging problems, such as sustainability in natural resource management. Yet, there is much discussion that participation is not a homogenous concept and about the most appropriate form of participation for different contexts and situations. Beginning with Arnstein (1969), the argument has been that not all processes of participation are equal. Using the metaphor of a ladder, participation can range from nonparticipation to full community control along levels of manipulation, therapy, informing, consultation, placation, partnership, and delegated power (Arnstein 1969). Collins and Ison (2006) suggest that community participation is too manipulable and misused, and call for participation as a reflection of social learning. Parkins and Mitchell (2005) suggest that a new direction for public participation is a deliberative democratic approach. Rodela (2012) argues that participation is exercised through learning a deliberation among stakeholders with competing discourses. Drawing on this literature, we are engaging participation from the perspective that it encourages discussion among stakeholders for the understanding of the SES.

Even if participation of stakeholders has been widely used when building models, there is a need to have a more structured way of deliberation and communication between stakeholders and the modelling team (Luna-Reyes & Andersen, 2003). According to Stave (2002), most of the time, public involvement does not involve the use of formal models. At the most basic level, hearings are held to solicit public comment, sometimes with an expert panel to respond to questions, but with the primary purpose of collecting input to be summarized and addressed at a later time. New planning approaches involve cooperative simulation models in which scientists and stakeholders work together to develop a computer simulation model to assist in planning efforts (Cockerill, et al., 2006).

Protocols are available for including stakeholders' knowledge in the modelling process for SD and focus on the use of participation throughout certain stages of the modeling process. Elias & Cavana (2000) consider that participation is important during two stages of the simulation: the qualitative structuring of the system and the scenario planning. In this regard, stakeholders are only expected to provide information on the scope of the system and their vision of plausible scenarios of the future that is validating the results of the model. There is a lack of inclusion of stakeholders in other important stages of the modeling process, such as establishing the interactions of the elements of the system and providing value parameters to feed the model (Stave, 2002). Moreover, there are few studies in the literature that present protocols to incorporate qualitative data derived from stakeholders into the modelling process (Luna-Reyes & Andersen, 2003). This is particularly important because although simulation models are mathematical representations of problems, it is recognized that most of the information available is not numerical in nature and there is a need to establish techniques to record, analyse and incorporate this kind of qualitative data into the model (Luna-Reyes & Andersen, 2003).

In contrast, for ABM, stakeholders have a more active role in the development of the modelling process. They are responsible for the establishment of the behavioural rules of the individual components. This is because people directly tell the modeler what they would do under certain conditions (Purnomo, Mendoza, Prabhu, & Yasmi, 2005), thus allowing the inclusion of on-site decision making (An, 2012).

In terms of sustainability assessments, ABM and SD simulation techniques have been used in combination with stakeholder participation for the study of complex SES. Berman *et al.* (2004) studied the adaptation and sustainability of a small artic community. They modelled, through research and local knowledge, how people interact with each other and adapt to changing economic and environmental conditions. The model outcomes assess how scenarios associated with economic and climate change might affect the local economy, resource harvest, as well as the well-being of the community. As far as SD is concerned, Bagheri & Hjorth (2005, 2007a; 2006) have developed the concept of Viability Loops to address the sustainability of complex SES. They identified different dynamic structures governing real world ecosystems, including human ones. To them, the world can be explained by means of reinforcing and balancing loops. While reinforcing loop are sources of growth and decline, which can bring the system into collapse, balancing loop hamper the reinforcing loops, keeping the system in balance (Bagheri & Hjorth, 2005). Sustainability therefore means to recognize the balancing loops (viability loops) that allow the system to work everlastingly and keep them functional (Hjorth & Bagheri, 2006).

3. MODELLING PROCESS

The modeling process requires the parallel development of the Winton Wetlands Socio-Environmental System (WWSES) through systems simulation techniques (SD and ABM) and the rigorous inclusion of stakeholder participation in the modeling process.

3.1. Modelling procedure

The modelling procedure consists of seven stages, each of which has different levels of input from stakeholders.

3.1.1. System's boundaries

The first step in the process is to determine, through stakeholder involvement and revision of relevant documentation, the spatial and temporal boundaries of the system, which will help delimitate the entire modeling process (Bagheri & Hjorth, 2005; Musters, de Graaf, & ter Keurs, 1998). As the main interest is to define and develop the socio-environmental system surrounding the Winton Wetlands, the spatial boundaries are intended to cover more than the extension of the wetlands and include neighbouring towns, which will influence and be influenced, directly and indirectly, by the restoration project. The temporal boundary of the system will establish the time span in which the model will be simulated. This is particularly important and is a principal deficiency in many "mental models" of the world where the tendency is to think of cause and effects as local and immediate (Sterman, 2000). Therefore, the choice of time horizon dramatically influences our perception of the system.

3.1.2. Main elements and interactions (Factors-Actors-Sectors framework)

The next stage in the modelling process is the identification of the main social, environmental and economic elements of the Winton Wetlands socio-environmental system.

This is achieved through the implementation of the Factors-Actors-Sectors framework (FAS) used to develop participatory-based scenarios in Southern European countries (Kok, Patel, Rothman, & Quaranta, 2006; Kok, Rothman, & Patel, 2006). Within the FAS framework, a factor represents a component of a socio-environmental system around which there are broad issues of concern. An actor represents an individual or organization of individuals with the capacity to affect and/or influence the factors. A sector characterizes a sub-component of a natural or social system, such as agriculture or tourism. For the Winton Wetlands SES, some examples of factors, actors and sectors are water quality of the wetlands, neighbouring households and agriculture, respectively.

During the focus groups, stakeholders will be ask to identify between 3 and 5 of these elements and record them on "post-it notes", which will be later pasted onto a white board. During group discussion these elements will be clustered in similar topics and relations will be indicated among them. The information obtained from stakeholders' will be complemented with published and unpublished documentation about the Winton Wetlands.

3.1.3. Model Formulation I: Causal Loop Diagrams

The next step is to qualitatively capture the interactions among the variables previously established during the discussion of the Factors-Actors-Sectors through the use of Causal Loop Diagrams (CLD).

A Causal Loop Diagram is a graphical tool borrowed from System Dynamics, which shows the relationships among elements in a system (Ford, 2010). It is a helpful reminder during discussions, not only because they explicitly depict the interactions among elements but also because they can help identify the wider context of the modelling task. A correctly drawn Causal Loop Diagram is the basis for a quantified model and is easily transformed into mathematical expressions (Coyle, 2000).

The CLD, as applied in this study, consists of variables, which represent the Factors, Actors or Sectors identified by the stakeholders, and arrows that denote the interactions among the elements (Ford, 2010). In System Dynamics, CLD are used to characterize the feedback processes that determine the dynamics of the system. These dynamics arise for the interaction of two types of feedback loops, reinforcing (or positive) and balancing (or negative) (Sterman, 2000). In a reinforcing loop, an action influences other variables in a way that the result is more of the same action. In contrast, a balancing loop causes change in the current state of a variable, which is affected at the moment that an external or internal input is introduced into a reinforcing loop (Sterman, 2000).

For the construction of the Winton Wetlands SES, the CLD is divided into subsystems, which can be arranged hierarchically in the overall system. Some examples of these subsystems are wetland hydrology, woodland restoration and nature-based tourism.

An example of these subsystems is a model of the dynamics of nature-based tourism (Figure 1), adapted from the work of Lacitignola *et al.* (2007). In this model, tourists visit a site depending on its attractiveness. For nature-based tourism this attractiveness depends on the ecological quality of the site as well as the infrastructure, such as road access, accommodation and facilities. In this sense, if tourists perceive that the ecosystem quality and infrastructure are low (by previous experiences or word of mouth) they will choice another destination to spend their holidays. In contrast, if the ecological quality and infrastructure are above certain threshold, tourists will be more inclined to visit the site. Ecological quality and touristic infrastructure are also affected by the arrival of tourists. This model assumes that even if nature-based tourism differs from mass tourism in its care for the environment, there are certain pressures to the ecological quality such as, generation of waste and use of resources like water and space (Buckley, 2004). In addition, the arrival of tourists also implies that pressures are exerted on the system, which require maintenance of existing and construction of additional infrastructure, such as roads, visitor facilities, accommodation, amenities and essential services. Finally, the arrival of tourists also assumes that there is an increase in capital through tourism revenue. This capital is in turned use for the maintenance and construction of new infrastructure and the restoration of ecological quality of the wetland itself.

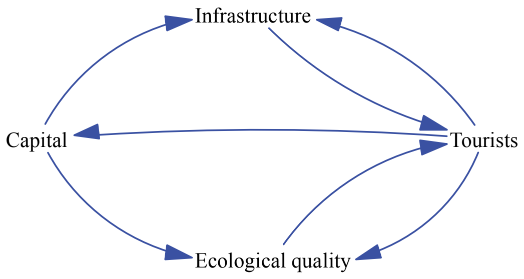


Figure 1. CLD of subsystem nature-based tourism

3.1.4. Model formulation II: Agent-Based-Modeling

Using the Causal Loop Diagrams with the main elements and relation within the SES, the next stage is to translate such relations to an Agent-Based Model. This is achieved through mapping the decision rules of the agents, using a flow chart, and entering them as commands into the ABM software Netlogo.

Continuing with the example of the nature-based tourism subsystem, after the CLD is established, the behaviour of tourists is translated into decision rules (Figure 2). The potential tourists start their journey in the city or hometown. Every turn, they randomly decide if they wish to go to on a holiday or not (based on a probability of recreation). Once they decide to take a holiday, they can choose to go to the wetland or to another destination, (e.g. the beach) depending on their previous experiences of the wetland (experience), as well as the experiences of other visitors of the wetland (word of mouth). The previous experience of the wetland for each tourist is determined by the fulfillment of their expectations of the wetland touristic site in terms of the ecological quality and infrastructure during their previous visit. While some tourists value more the ecological quality of the wetland, others value more that the infrastructure (facilities, restaurants and hotels). If during their visit of the wetland their expectations are met, their experience will be satisfactory. In contrast, if their expectations are not fully met, their experience will decrease. Once the tourists finish their visit to the wetland, they return to the city and exchange experiences with other potential tourists.

While the tourists are in the wetland, they impact environment in one hand and leave revenue for the touristic site on the other hand. As explained in the previous section, because their presence in the wetland and the activities related with nature-based tourism, the ecological quality decreases as well as the infrastructure. In addition to these impacts, tourists bring economic revenue to the site, which in turn can be used for more infrastructure or restoration efforts. Every time a tourists interacts with an ranger of the wetland (builder for infrastructure and ecologists for restoration) they give resources to them in order to improve the overall quality of the wetland.

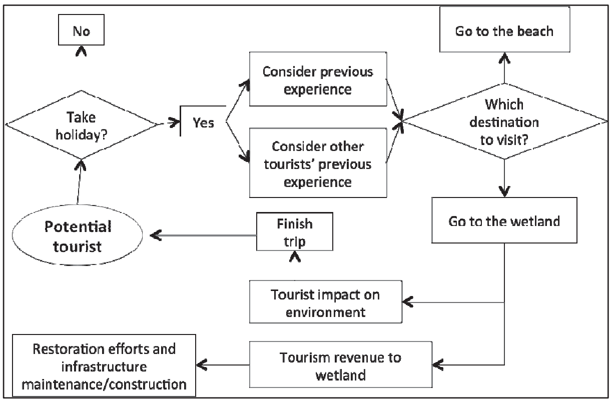


Figure 2. Behavioural rules flow chart of tourists

The agent-based model constructed in Netlogo shows the movement of the tourists from the city to the wetland depending on their travelling decisions (Figure 3). It contains sliders which are used to establish initial conditions, such as the number of tourists, rangers (builders and ecologists), tourist revenue and probability of recreation. The model has three plots, which show the average experience of tourism in the wetland, the average ecological quality and the number of tourists in the wetland at any given time (Figure 4).
The implementation of the decision rules depends on the agent in the model (tourists, ecologists and builders). The ecologist and builders move randomly across the wetland and are able to undertake their activities if they have available resources. These are a result of encountering tourists in the wetland, therefore if a park ranger never gets in touch with a tourist, he would not have enough resources to build new or maintain old infrastructure and to restore the wetlands. In addition, every time he finds himself in a patch of the wetland that could be improved, *i.e.,* where ecological quality and infrastructure could be increased, he allocates part of the resources to that patch.

The other agents in the model are the tourists, which transition from different states depending on their decision rules. Every potential tourist (city residents for this model) has a preference for ecology or infrastructure when it comes to choosing to undertake a nature-based touristic experience. Some people value more the environmental traits of the site and some people value more the infrastructure (restaurants, facilities, etc.). In addition, this model takes into account that there are certain circumstances that diminish the chances of taking a holiday by establishing a random probability of recreation within a range previously established by the modeler. Once they decide to go on a holiday, they base their decision to go to the wetland or another destination (beach) based on their previous experiences and the experiences of other people that have visited the wetland. Those decisions are based on the following rules:

$$E=\left[\left(1-E_d\times E_{t-1}\right)+\left(E_d\times\left(\frac{100}{M}\right)\times\left(P_{ec}+P_i\right)\right)\right] \tag{1}$$

where: E is the experience of each tourist after visiting the wetland; E_d is the experience decay (proportion of the experience that decreases every turn that the tourist does not go to the wetland); E_{t-1} is the previous experience of the tourist; M is the maximum resources that a patch can have (divided into infrastructure and ecology for each patch) and; P_{ec} and P_i are the product of the patch value for ecology and infrastructure and the individual preferences of the tourists for ecology and infrastructure, respectively.

The decision rule upon which a tourist decides to visit a wetland depends not only on each tourists' own experience, but also the degree of influence that others tourists' opinions have on the weight of their previous experience. This decision is represented by the following equation:

$$E_w=\left(1-G_w\right)E_{wt-1}+\left(G_x\times E_o\right) \tag{2}$$

where: E_w is the weighted average experience of each tourist; G_w is the gossip weight (weight of other tourists' opinion); E_{wt-1} is the previous experience of other tourists and; E_o is the average experience of other tourists.

Two different scenarios were constructed, A and B (Figure 3), depending on the amount of resources left by tourists upon their arrival to the wetland and the limit for ecological quality and infrastructure improvement. Limit for ecological quality and infrastructure improvement mean that for each patch, there is a maximum degree of restoration that can be achieved and a maximum amount of infrastructure can be developed or maintained. In Scenario A, the number of rangers (builders and ecologists), the payment of tourists and the maximum resources of patch is set to low values. In scenario B, all those parameters are set to higher values. For both scenarios, the number of tourists, the weight of gossip from other tourists and the probability of recreation stayed the same.

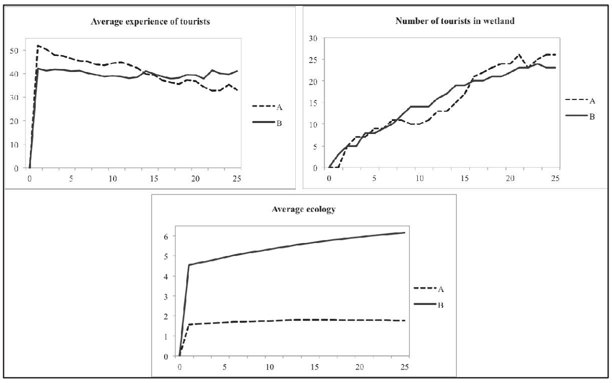
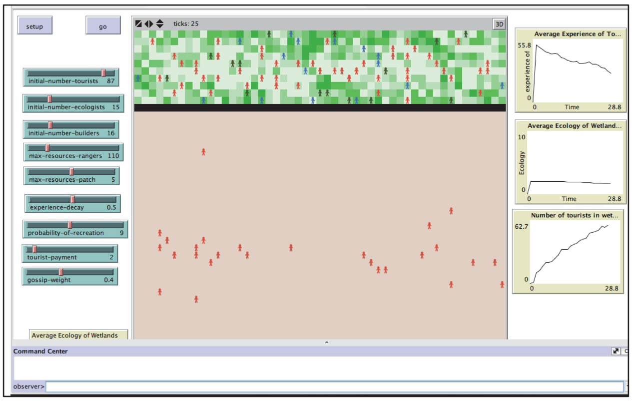


Figure 3. Average Experience of tourists, average ecology of wetland and number of tourists in wetlands in two different scenarios: A and B.

The average experience of tourists for scenario A decreased as opposed to scenario B, which stayed unchanged through out the simulation. Because the number of tourists was the same for both scenarios, the number of tourists in the wetland was the same in both scenarios. Finally, the average levels of ecology of the wetland differ between scenarios. When there are more rangers in the wetland, tourists leave more revenue that is translated into restoration and construction efforts and type of activities undertaken by the rangers are appropriate for the wetland in terms improving the ecological quality of the site, the average experience of tourists does not increase and the average quality of the wetlands increases.

An ABM is constructed for each of the subsystems of the Winton Wetlands SES to represent the interactions of main elements of the SES. Each subsystem is represented in a netlogo interface, with sliders, agents and plots (Figure 4).



initial-number-tourists 87
initial-number-ecologists 15
initial-number-builders 16
max-resources-rangers 110
max-resources-patch 5
experience-decay 0.5
probability-of-recreation 9
tourist-payment 2
gossip-weight 0.4

Figure 4: Window screen of Netlogo showing the tourists moving in and out the city (bottom) to the wetland (top); the sliders which modify the initial conditions of the simulation (left) and the response plots of each simulation (right).

3.1.5. Sustainability principles and questions

During this step, the stakeholder group is introduced to principles of sustainability adapted from several analyses of those principles by (Bagheri & Hjorth, 2005; Gibson, 2006; Holmberg, Robert, & Eriksson, 1996; Peet & Bossel, 2000; Robert, Daly, Hawken, & Holmberg, 1997). In combination with the main elements and relations within the system, these principles are then translated into sustainability questions (Bagheri & Hjorth, 2005). They represent a set core of values that any project, which deems itself to be sustainable, should address (Table 1). These questions assert the general conditions under which the system is considered to be sustainable by the stakeholders. It does not mean that specific indicators are established at this point. Instead, general questions such as “Is the water quality of our system decreasing” are asked.

3.1.6. Parameter estimation

The next step is to estimate the parameters of the model using the best available information. This stage of the process can start at the beginning of the modelling procedure and can continuously be increased. The information can come from numerical, written or mental databases (Forrester, 1991). The range of information is portrayed along the information spectrum from hard sources to soft sources: physical laws, controlled experiments, uncontrolled experiments, statistical information, case studies, expert judgment, stakeholder knowledge, personal intuition. Statistical information such as time series data or cross-sectional data, are common sources of information. Stakeholder knowledge is also gaining in importance as it can take the form of knowledge accumulated in a community (Cockerill, et al., 2006; Stave, 2002).

In some cases the measurement of real values may be difficult or even impossible and the value used in the model, legitimately, may be a guess. In this case, such a value cannot be regarded and treated in the same way as other parameters in the model. It must be treated tentatively and its role evaluated using sensitivity analysis (Kitching, 1983).

A database of parameters and assumptions is kept, recording the source of information and the degree of uncertainty.

3.1.7. Sustainability Indicators and scenarios of sustainable development

The indicators of sustainability come as a result of the entire modelling procedure and translation of the sustainability questions into quantifiable indicators. These could be used in the future monitoring of the system and to establish scenarios of development. As sustainability is seen as a process instead of an end state (Bagheri & Hjorth, 2005), preference will be given to process indicators as opposed to performance indicators. For example, if one of the questions of sustainability is; is the water quality decreasing? The indicator could be the rate of change of water quality.

Values of different stakeholders are incorporated through future scenarios of development. This can be achieved using Q-methodology (van Exel and de Graf, 2005) to produce groups of highly correlated opinions. Each group of opinions is representative of different viewpoints within the broader stakeholder group. These viewpoints represent the stakeholders desired visions for the system. Plausible scenarios of development are incorporated into the model by modifying certain parameters based on the desired visions for the Winton Wetlands established earlier.

3.2 Stakeholder participation procedure

The overall goal of the stakeholder participation procedure is to be able to incorporate the knowledge and values of stakeholders at different stages of the simulation process. Stakeholder knowledge and values will be incorporated through the use focus groups with two stakeholder groups: a General Stakeholder Group (GSG) and a Modelling Stakeholder Group (MSG) (Stave, 2002). The MSG is actively included in the different stages of the modelling process while the GSG is included only in the general process of model validation, as well as in the inclusion of stakeholder values in the development of scenarios for the future.

4. SUMMARY

The assessment of sustainability in socio-environmental systems requires the understanding of complex systems as well as the inclusion of stakeholders. The outcomes of this project could be use as guidelines for future decision-making processes in the Winton Wetlands and could also provide a framework to assess the sustainability of initiatives or programs in other parts of the word. In the particular case of modelling nature-based tourism for nature-based tourism, it was found that experience of the tourists and the average ecological quality of the wetlands (in terms of biodiversity, which is attractive to nature-based tourists) depends on the amount of resources allocated to restoration and infrastructure efforts, as well as the type of activities undertaken by the rangers are appropriate for the wetland in terms improving the ecological quality of the site. The current modelling procedure presented in this paper demonstrates the functionality of an approach combining multiple systems simulation paradigms and participatory modelling, which provides a base upon which to develop models of complex SESs. However, this model will be further elaborated upon in terms of complexity of decision rules for the ABM component and number of variables incorporated into the overall model.

REFERENCES

Andriantiatsaholiniaina, L.A., Kouikoglou, V.S., & Phillis, Y. A. (2004). Evaluating strategies for sustainable development: fuzzy logic reasoning and sensitivity analysis. Ecological Economics, 48(2), 149-172.

Arnstein, S.R. (1969). A Ladder Of Citizen Participation. Journal of the American Institute of Planners, 35(4), 216-224.

Bagheri, A., & Hjorth, P. (2005). Monitoring for sustainable development: A systemic framework. International Journal of Sustainable Development, 8(4), 280-301.

Bonabeau, E. (2002). Agent-based modelling: Methods and techniques for simulating human systems. Proceedings of the National Academy of Sciences of the United States of America, 99(Suppl 3), 7280-7287

Borshchev, A., & Filippov, A. (2004). From SD and discrete event to practical AB Modelling: reasons, techniques, tools. Proc. of the 22nd Int. SD Conf.

Gibson, R. B. (2006). Sustainability assessment: basic components of a practical approach. Impact Assessment and Project Appraisal, 24(3), 170-182.

Goulburn Broken Catchment Management Authority. (2012). Lake Mokoan Decommissioning Plan. Available from: http://www.gbcma.vic.gov.au/default.asp?ID=lake_mokoan [accessed 12 September 2012]

Musters, C. J. M., de Graaf, H. J., & ter Keurs, W. J. (1998). Defining socio-environmental systems for sustainable development. Ecological Economics, 26(3), 243-258.

Scholl, H. J. (2001). Agent-based and system dynamics modelling: A call for cross study and joint research. Paper presented at the System Sciences, 2001. Proceedings of the 34th Annual Hawaii International Conference on System Science.

Stave, K. A. (2002). Using system dynamics to improve public participation in environmental decisions. System Dynamics Review, 18(2), 139-167.

Taylor Cullity Lethlean, McKINNA, Sanmor, Design Flow, Prowse Qs & Arup. (2012). The Winton Wetlands and Benalla Master Plan. Benalla.

Voinov, A. (2008). Systems science andmodelling for ecological economics. San Diego: Academic Press.

An, L. (2012). Modeling human decisions in coupled human and natural systems: Review of agent-based models. Ecological Modelling, 229(0), 25-36.

Andersson, L., Olsson, J. A., Arheimer, B., & Jonsson, A. (2008). Use of participatory scenario modelling as platforms in stakeholder dialogues. Water SA, 34(4), 439-447.

Bagheri, A., & Hjorth, P. (2005). Monitoring for sustainable development: A systemic framework. International Journal of Sustainable Development, 8(4), 280-301.

Bagheri, A., & Hjorth, P. (2007a). A framework for process indicators to monitor for sustainable development: Practice to an urban water system. Environment, Development and Sustainability, 9(2), 143-161.

Bagheri, A., & Hjorth, P. (2007b). Planning for sustainable development: A paradigm shift towards a process-based approach. Sustainable Development, 15(2), 83-96.

Berman, M., Nicolson, C., Kofinas, G., Tetlichi, J., & Martin, S. (2004). Adaptation and sustainability in a small arctic community: Results of an agent-based simulation model. Arctic, 401-414.

Borshchev, A., & Filippov, A. (2004). From SD and discrete event to practical AB Modeling: reasons, techniques, tools. Proc. of the 22nd Int. SD Conf.

Buckley, R. (2004). Environmental impacts of ecotourism. Wallingford: CABI Publishing.

Cockerill, K., Passell, H., & Tidwell, V. (2006). Cooperative modeling: building bridges between science and the public. JAWRA Journal of the American Water Resources Association, 42(2), 457-471.

Coyle, G. (2000). Qualitative and quantitative modelling in system dynamics: some research questions. System Dynamics Review, 16(3), 225-244.

Elias, A., & Cavana, R. (2000). Stakeholder analysis for systems thinking and modeling. Paper presented at the 35th Annual Conference of the Operational Research Society of New Zealand, Wellington, New Zealand.

Ford, A. (2010). Modeling the Environment (2nd ed.). Washington, D.C.: Island Press.

Forrester, J. (1991). System Dynamics and the Lessons of 35 Years. In K. De Greene (Ed.), The Systemic Basis of Policy Making in the 1990s (pp. 1-35).

Gibson, R. B. (2006). Sustainability assessment: basic components of a practical approach. Impact Assessment and Project Appraisal, 24(3), 170-182.

Gibson, R. B., Hassan, S., Holtz, S., Tansey, J., & Whitelaw, G. (2005). Sustainability Assessment: Criteria and Processes. Virginia: Earthscan.

Hjorth, P., & Bagheri, A. (2006). Navigating towards sustainable development: A system dynamics approach. Futures, 38(1), 74-92.

Holmberg, J., Robert, K., & Eriksson, K. (1996). Socio-ecological principles for a sustainable society-Scientific Background and Swedish Experienc e. In R. Costanza (Ed.), Getting down to Earth: Practical Applications for Ecologica Economics (pp. 17-48). Washington, D.C.: Island Press.

Kitching, R. (1983). Systems ecology: An introduction to ecological modelling. Queensland: university of Queensland press.

Kok, K., Patel, M., Rothman, D., & Quaranta, G. (2006). Multi-scale narratives from IA perspective: part II. Participatory local scenario development. Futures, 38, 285-311.

Kok, K., Rothman, D., & Patel, M. (2006). Multi-scale narratives from IA perspective: part I. European and Mediterranean scenario development. Futures, 38, 261-284.

Lacitignola, D., Petrosillo, I., Cataldi, M., & Zurlini, G. (2007). Modelling socio-ecological tourism-based systems for sustainability. Ecological Modelling, 206, 191-204.

Lozano, R. (2008). Envisioning sustainability three-dimensionally. Journal of Cleaner Production, 16(17), 1838-1846.

Luna-Reyes, L. F., & Andersen, D. L. (2003). Collecting and analyzing qualitative data for system dynamics: methods and models. System Dynamics Review, 19(4), 271-296.

Musters, C. J. M., de Graaf, H. J., & ter Keurs, W. J. (1998). Defining socio-environmental systems for sustainable development. Ecological Economics, 26(3), 243-258.

Peet, J., & Bossel, H. (2000). An ethics-based systems approach to indicators of sustainable development. International Journal of Sustainable Development, 3(3), 221-238.

Phillis, Y., & Andriantiatsaholiniaina, L. (2001). Sustainability: an ill-defined concept and its assessment using fuzzy logic. Ecological Economics, 37(3), 435-456.

Purnomo, H., Mendoza, G. A., Prabhu, R., & Yasmi, Y. (2005). Developing multi-stakeholder forest management scenarios: a multi-agent system simulation approach applied in Indonesia. Forest Policy and Economics, 7(4), 475-491.

Robert, K.-H., Daly, H., Hawken, P., & Holmberg, J. (1997). A compass for sustainable development. International Journal of Sustainable Development & World Ecology, 4(2), 79-92.

Scholl, H. J. (2001). Agent-based and system dynamics modeling: A call for cross study and joint research. Paper presented at the System Sciences, 2001. Proceedings of the 34th Annual Hawaii International Conference on System Sciences.

Stave, K. A. (2002). Using system dynamics to improve public participation in environmental decisions. System Dynamics Review, 18(2), 139-167.

Sterman, J. (2000). Business dynamics: Systems thinking and modeling for a complex world. Boston, Massachusetts: McGraw Hill.

Voinov, A. (2008). Systems science andmodeling for ecological economics. San Diego: Academic Press.

A DEMAND RESPONSE SYSTEM FOR HIERARCHICALLY ORGANIZED AGGREGATORS IN SMART GRIDS

Sergios Soursos[(a)], Vassilis Kapsalis[(b)], George Petropoulos[(a)], Yiannis Karras[(c)] and Loukas Hadellis[(b)]

[(a)] Intracom S.A. Telecom Solutions, R&D Unit, Telco Software Business Division, 19002 Peania, Athens, Greece
[(b)] Technological Educational Institute of Patras, 26334 Patras, Greece
[(c)] inAccess S.A., 15125 Maroussi, Athens, Greece

[(a)]{souse, geopet}@intracom.com, [(b)]{kapsalis, loukas}@teipat.gr, [(c)]jkarras@inaccess.com

ABSTRACT

Current advances in Smart Grids have reshaped the business ecosystem of the energy market, allowing for the role of an aggregator to emerge. At the same time, the need to deal with power shortages and blackouts has rendered the participation of consumers to the management of energy quite necessary. Demand Response practices are becoming more popular and relative standards like the Open Automated Demand Response (OpenADR) have emerged as very promising technologies for the Smart Grid. In this context, we present an architecture that introduces the demand response functionality in an environment of multi-level hierarchically organized aggregators. We adopt and extend the OpenADR standard and provide the required functionality to support such a system. We describe the comprising components and interfaces and present the technologies used for the implementation of the system.

Keywords: demand response, automation, aggregator, multi-level hierarchy

1. INTRODUCTION

The Smart Grid concept and its supporting technologies were introduced in an attempt for society to decrease the consumption of energy resources, especially during periods of critical consumption levels and/or reduced energy production. The need for detailed monitoring of the consumption and for prediction of the future demand have led to the update of the infrastructure of the Distribution System with smart meters, comprising the Advanced Metering Infrastructure (AMI). With the placement of smart meters, the Independent System Operator (ISO) will be able to foresee demand peaks and take the appropriate measures so as to avoid overloading the Distribution System.

With the introduction of Smart Grids, Demand Side Management (DSM) has emerged as a new field of energy management that aims at controlling/shaping the demand for energy, while considering the status of the transmission and distribution networks and the available energy resources. Demand Response (DR) is a DSM approach that manages electricity demand by sending economic or incentive-based signals to the consumers who react by altering their consumption behavior based on terms of the DR program(s) they have subscribed to.

In this context, a new business role is emerging in the Smart Grids ecosystem; that of the aggregator, a business entity that acts as a mediator/broker between consumers and the Utility Operator or the ISO (Gkatzikis, Koutsopoulos and Salonidis 2013). Representing a large number of consumers provides the aggregator the bargaining power to negotiate with the ISO on prices. On the other hand, the aggregator receives DR signals from the Utility/ISO, which has to process and re-distribute them down to its customers so as to achieve the requested power cuts, considering the customers' constraints and comfort levels as well as trying to attain monetary gains for itself and its customers by minimizing also the aggregation risks that may result in penalties.

In this paper, we envision the presence of more than one aggregators per district, organized in a multi-level hierarchical structure that compete (same level) and interact (adjunct levels) with each other, so as to achieve optimal and dynamic DSM, with monetary gains both for the consumers as well as for the aggregators. It becomes obvious that an aggregator with such a rich portfolio of offered services requires an advanced system that allows for all the interactions to take place and has built-in intelligence to support the automatic handling of DR events, programs, subscriptions and constraints. Hence, in this environment, we propose an ICT system, named DAMAZO, which enables the materialization of the aforementioned concept, enabling the communication between aggregators, as well as allowing for different DR programs to be supported and different DR policies to be implemented.

The remainder of this paper is organized as follows: Section 2 overviews the existing works in the area of DR automation; Section 3 provides the core concept of the DAMAZO system, the programs and the mechanisms that it currently supports; Section 4 describes the architecture of the DAMAZO system; Section 5 provides an insight on the algorithms designed and deployed while Section 6 provides the concluding remarks and the future work.

2. RELATED WORK

The energy crisis of 2002 in California served as the driving force for the Demand Response Research Center operated by Lawrence Berkeley National Laboratory to create the first version of the Open Automated Demand Response (OpenADR v1.0) specification, which was released in April 2009 (Piette, Ghatikar, Kiliccote, Koch, Hennage, Palensky, and McParland 2009). This specification describes an open standards-based communications data model designed to promote common information exchange between the Utility/ISO and electric customers using demand response price and reliability signals. The intention of the data model is to interact with building and industrial control systems that are pre-programmed to take action based on a DR signal, enabling a demand response event to be fully automated, with no manual intervention. The DR system comprises of a single server denoted as Demand Response Automation Server (DRAS), which communicates with the corresponding DRAS clients, enabling a demand response event to be fully automated. Although, the specification promoted interoperability between Utility/ISO and electric customers, it nevertheless lacked a multi-level hierarchy between a DRAS and its corresponding clients.

The OpenADR Alliance, a mutual benefit corporation which was created to foster the development, adoption, and compliance of the OpenADR Smart Grid standard, has recently released the OpenADR 2.0a and 2.0b (draft) profile specification and schema (OpenADR 2.0a, 2012) (OpenADR 2.0b, 2013), which consist part of OASIS Energy Interoperation Specification 1.0 (OASIS EI 1.0, 2012). A feature of the new version is the adoption of a hierarchical structure between Virtual Terminal Nodes (VTNs) and Virtual End Nodes (VENs) (see Fig. 1), according to the concepts introduced in a white paper by EPRI (EPRI, 2010).

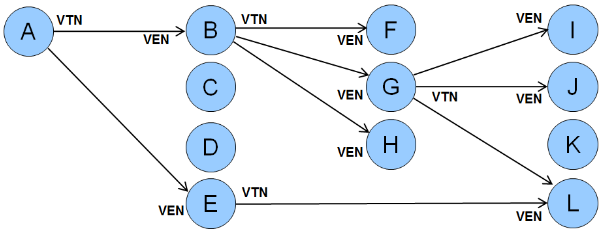


Figure 1: Example of DR interactions under OpenADR v2.0

In the above figure, certain Parties (B, E, and G) act as both VTN and VEN. This directed graph with arrows from VTN to its VENs could model a Reliability DR Event initiated by the Independent System Operator A who would invoke an operation on its second level VTNs B-E, which could be a group of aggregators. The second level VTN B, in turn invokes the same service on its VENs FGH, who may represent their customers or contracted resources. However, OpenADR 2.0 does not define how the nodes react to the information. In nodes, which support both the VTN and VEN interfaces (e.g., aggregators) there are no specifications or constraints on how messages arriving at the VEN interface is coupled or translated into any subsequent messages that may be sent from the VTN interface and vice versa.

A project dealing with the Demand Response concept is ADDRESS, a 5-year large-scale R&D project launched in 2008, that aims to deliver a comprehensive commercial and technical framework for the development of "Active Demand" (AD) in the Smart Grids of the future (Valtorta and Giovanni, 2011). "Active Demand" is the term used instead of "Demand Response" to describe the participation of consumers in the management of energy resources. The project also identifies the role of the aggregator as a key role in the energy market ecosystem. Although the work of ADDRESS is of wider scope, several objectives of ADDRESS are partly in line with our work. However, not much information about the project's proposed architecture and its implementation is provided, thus not much can be said about the compatibility of our system with the approach of ADDRESS. Furthermore, our objective for a multi-level hierarchical structure of aggregators is, as far as we know, not supported by ADDRESS.

Beywatch was a project funded by the European Commission under FP7, that aimed to design, develop and evaluate an innovative, energy-aware, flexible and user-centric solution, able to provide interactive energy monitoring for white goods, intelligent control and power demand balancing at home, block and neighbor level (Beywatch D2.1 Service Requirement specification, 2009). The BeyWatch concept included a hierarchical network architecture of interactive metering and intelligent control devices: a) the Agent at Home / Office level, b) the Supervisor at building / square / neighborhood level and c) the Service Centre at the utility level. The proposed system introduced a two layers hierarchy: micro-management and medium-management level. Under the micro-management level, all the devices in the home or a building were set under local interactive monitoring and intelligent control, in order to achieve amortization of loads and peak suppression of small-scale power consumption. The local control elements were included in a hierarchical system that coverer larger geographical regions (e.g. building blocks or neighborhood) that enabled medium-level control and coordination of the energy resources.

The SmartHouse/SmartGrid is another EU funded FP7 research project, which exploited the potential that is created when homes, offices and commercial buildings are treated as intelligently networked collaborations. The project envisioned a system, where SmartHouses are able to communicate, interact and negotiate with both customers and energy devices in the local grid, resulting into a more efficient operation of the electricity system, because consumption can be better adapted to the available energy supply, even when the proportion of variable renewable generation is high (Warmer et al., 2009). A commercial aggregator could exercise the task of jointly coordinating the energy use of the SmartHouses or commercial consumers that have a contract with him.

3. CONCEPT AND SYSTEM OFFERINGS

As already mentioned, our system follows the OpenADR v1.0 specification. In the OpenADR, the core entity expected to materialize the DR policies is the DRAS. DRAS is expected to be deployed in a three-level hierarchical topology: on the top level we have the existing system of the ISO or Utility Operator, which from now on we refer to as "Back Office"; in the middle level we have the DRAS (operated either by the Utility/ISO or by an aggregator) and in the bottom level we have the consumers.

A brief overview of the standard DR procedure is described here: initially, the interested consumers are subscribed to the DR programs they find appealing. This subscription is made at the DRAS, but the Back Office is informed as well. At some given point in time where a need for activation of a program is required (e.g. due to a critical situation at the distribution network), the Back Office issues a respective DR event to the DRAS. The DRAS, in turn, finds the consumers subscribed to the respective program and forwards the event. Consumers are informed about the event and either manually take the necessary actions (as dictated by the program) or a software agent takes the responsibility of fulfilling the expected actions.

In our work we introduce the *eDRAS (enhanced DRAS)* that implements the core functionality as specified by the standard, as well as some extensions that allow it to be used in more complex topologies and to offer more enriched functionality. Below, we highlight the offerings of the eDRAS. The innovation of our work stems from the realization of an end-to-end multi-hierarchy DR system (DAMAZO) aligned with the architecture proposed by OpenADR 2.0 (regarding to the multi-layered client-server VTN-VEV structure), introducing business and logic rules implemented in each layer for the end-to-end handling of the DR events.

3.1. Multi-level hierarchical architecture

The standard DRAS offers three types of interactions: i) with Back Office; ii) with the Smart Client (DR-aware client) and iii) with the Thin Client (non DR-aware client). For the eDRAS to support the multi-level hierarchical architecture, as shown in Figure 2, a new interface is required; that of the inter-eDRAS communication.

To support this new type of interaction between adjacent eDRASes, we re-used the interfaces specified by the standard between the DRAS and the Smart Client. Actually, for an eDRAS of level *n*, the eDRAS located at level *n+1* can be considered as a Smart Client as well. In this simple way, a multi-level topology is supported and only modifications in the logic residing inside an eDRAS are required.

3.2. Types of DR programs

Traditionally, DR supports two categories of programs which the consumers interested in participating can subscribe to: the price-based DR programs and the incentive-based DR programs. The eDRAS supports the following programs:

- Base Interruptible Programme (BIP): the participant is asked to decrease its consumption and, in case he acts accordingly, receives a compensation (in terms of discounts or credit) that is specified in the contract.
- Time-of-Use + Critical Peak Pricing (ToU+CPP): the participant is provided with a different unit price depending on the time of day, while during critical situations he receives a relative update of the price (higher price typically leads to decreased demand).
- Real Time Pricing (RTP): the participant receives updates on the price that are valid till the next update is received. Again, the consumer is expected to react to increased prices.
- Direct Load Control (DLC): the participant grants to the Utility/ISO or to the aggregator the ability to remotely control his appliances. Once such an event is received, the respective appliances are switched off/on, or their operation is shifted at a later time. Refusal to adhere to the event is penalized.

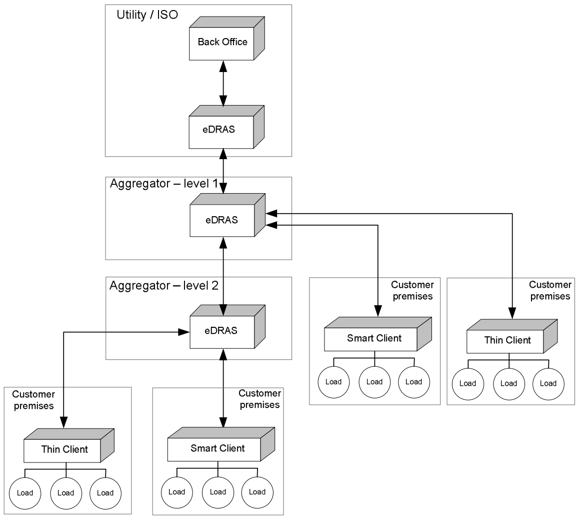


Figure 2: eDRAS' support for multi-level hierarchical architecture

The existence of multiple eDRASes introduces a complexity in handling the different programs, since an eDRAS is at the same time a client for the upper level eDRAS. And one cannot expect that each eDRAS operator (i.e., aggregator) offers exact the same programs to its clients. Assume that an *n* level eDRAS is subscribed (as a client) to a BIP program that requests a decrease of 10 kW between 10 am and 11 am. At the same time this eDRAS has issued a BIP program to its *n+1* level clients that requests a decrease of 2 kW between 10 am and 11 am. In case of a BIP event from the *n-1* level eDRAS, the *n* level eDRAS has to map the upper level BIP program to its own BIP program (straightforward in this case: issue at least 5 BIP events to its *n+1* level clients in order to meet the requirement from the upper level).

What happens however when the *n* level eDRAS has subscribed to a BIP program but has not issued any BIP program for its clients? How the eDRAS should react upon the reception of a BIP event in this case? It becomes obvious that the mapping between different types of programs is not straightforward. To deal with this situation we have come up with the following relationships between types of programs.

Table 1: Relationships between DR programs

Received Event's Program	Compatible Program	Complementary Program
BIP	BIP, DLC	ToU+CPP
ToU+CPP	ToU+CPP, RTP	BIP
RTP	RTP, ToU+CPP	BIP
DLC	DLC	BIP

When an event is received, the eDRAS tries to resolve the request by issuing an event of the same program type (differences in the parameters with respect to amount and time are resolved). If not such a program exists, clients subscribed to compatible programs are addressed. In such a case the risk of not fulfilling the needs of the original event are expected to be low and depends on the number of clients addressed and the overlaps in time periods. In the improbable case where no compatible programs exist, then events belonging to complementary programs can be issued, but the risk of not fulfilling the original requirements increases. It is expected however, that a rational eDRAS operator will offer to his clients programs that are of the same type with the ones that he has already subscribed to, or the other way around.

3.3. Selection of clients, monitoring and statistics

A client that subscribes to a program can also submit his time constraints. For example, a client subscribed to a BIP program that runs from 10 am to 12 am, may have a one-hour constraint. This can be known a priori and expressed during the subscription or can be declared dynamically (in this case the client *opts-out* from the specific program for a given time). Such time constraints and others related to the location of the clients, the groups they belong to, etc., must be considered by the eDRAS when issuing an event.

Moreover, the eDRAS should be able to estimate, before issuing an event, whether a client can accept it, considering the active events he has already accepted, the current and average consumption levels, available shed prediction throughout the day, etc. Further criteria for selection include performance and fairness. Performance has to do with the reaction of a single client after the reception of an event; if he had managed to save some energy and how close to the target value he performed. Fairness has to do with the fact that not the same clients should be selected all times; even though they might be top ranked considering their performance. Such statistics need to be collected by the eDRAS through the appropriate monitoring mechanisms.

From the above, it becomes obvious that the selection of the appropriate clients to send an event is a complex procedure that requires lots of information so as to render the action taken successful or, at least, of low risk for failure.

4. ARCHITECTURE

Having outlined the core functionality of the eDRAS, in this section the architecture of the DAMAZO system is presented. The implementation of the eDRAS and the required interfaces has been based on the OpenADR v1.0 specification with proper extensions wherever required.

Figure 3 depicts the DAMAZO system architecture. The main entities presented are the eDRAS, the Smart Client and the Thin Client. The distinction between the Smart and the Thin Client is that the former is able to communicate with the eDRAS using the OpenADR-based messages (DR I/F) and has some intelligence of its own (Control Logic). It is usually collocated with a smart meter and is in the form of a gateway with programmable capabilities. The Thin Client on the other hand is a simple gateway that can receive commands in a specific format and has no additional processing capabilities other than operating as a simple load interface.

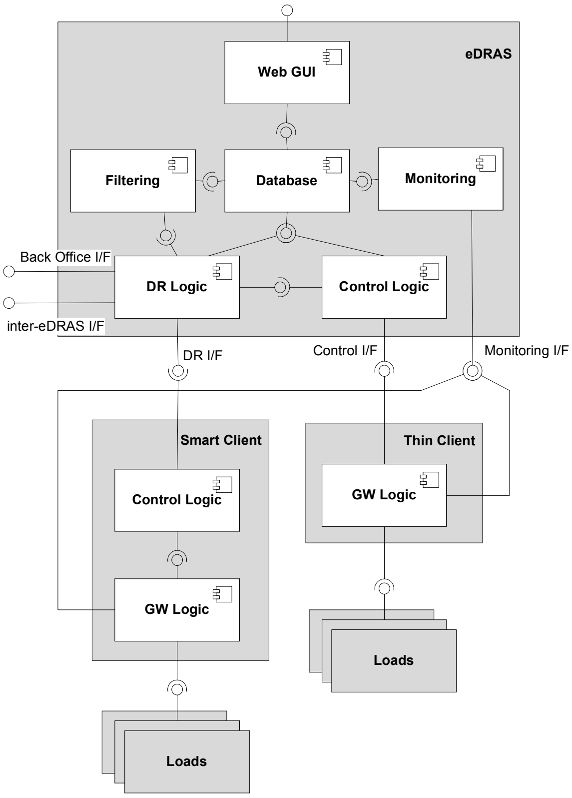


Figure 3: The DAMAZO System Architecture

The eDRAS is implemented as a Java EE application deployed in a JBoss Application Server. It consists of the following components, which are mainly implemented as Enterprise Java Beans (EJBs):

- Web GUI: Allows the eDRAS operator to create programs and register clients through the use of typical HTML pages. For each client further information for available loads and user preferences may be recorded, based on the level that the eDRAS resides. All respective information is stored at the database.
- Database: Stores all the required information received by the Web GUI component, as well as from the Monitoring, Control Logic and DR Logic components. It is implemented using the MySQL RDBMS.
- Monitoring: Collects data from the clients regarding the shed available, shed attempted (after the reception of a DR event), the current usage and the future usage. It provides a REST interface for Smart and Thin Clients to send their monitored data and saves them to the database, after performing some aggregation and normalization.
- Filtering: Implements the selection of candidate clients, given a specific DR event. It retrieves the client constraints from the database and compares them to the event requirements. Finally it provides the resulting list to the DR Logic component.
- DR Logic: Is the core component of the eDRAS. It receives a DR event from the Back Office or the upper level eDRAS, through the respective interfaces implemented using SOAP protocol. It queries the Filtering component for the list of candidate clients and then ranks them considering the criteria of performance and fairness. Then it splits the received event to the appropriate lower level DR events, running an allocation algorithm. Depending on the type of the selected clients, it either sends the resulting events to lower level eDRASes (through the inter-eDRAS interface), to Smart Clients (through the respective DR interface) or to the Control Logic interface (in the case of thin clients).
- Control Logic: it handles the details of the registered loads. Given a DR event, it decides which specific loads to either switch off or shift in time so as to achieve the requested target. Through the Control interface (implement with REST) it sends the load commands to the Thin Client.

The Smart Client is implemented as a stand-alone infrastructure on site, mainly due to the vast variety of equipment that may exist in the installation, storage needs to avoid data loss, scarce bandwidth and finally autonomous operation of field applications and logic. This infrastructure, consisting mainly of an embedded controller, undertakes the responsibilities of:

- Interfacing with all control and monitoring equipment present in the installation, in order to acquire data irrespective of the connection method and/or protocol.
- Reducing the volume of data required for transmission to eDRAS to something representative, yet less bandwidth demanding.
- Conveying events that are generated directly by the equipment upon their occurrence and generating events that are necessary yet not implemented within the equipment in the field.
- Storing all necessary parameters and events in a cyclical manner in the case of failure of the communication with the outside world.
- Implementing all necessary control loops that have to operate locally in an independent manner, providing a local autonomous implementation of intelligent DR algorithms.
- Interfacing with eDRAS using the respective standardized DR protocols.

The control and monitoring equipment as well as the loads connected are registered in the Smart Client during an initial provisioning procedure with minimal database functionality required in the field. The various components of the Smart Client have been implemented using C, C++ and Python over an embedded version of the GNU/Linux adapted for the RSC controller family. With regard to local control protocols used for communicating with the equipment, these vary depending on the technological capabilities of each component. Implemented interfaces include IEC 62056-21 over serial for local metering, Zigbee/IEC 802.15.4 for sub-metering and smart plugs control, as well as Modbus over RS-485 technologies as a common industrial and building infrastructure technology.

Finally, the Thin Client is implemented as a standalone embedded controller of lower cost that provides a subset of the functionality of the Smart client, mainly without providing local control loops and intelligent algorithms implementation or standardised communication to eDRAS. The Thin Client corresponds to installations with existing automation controllers as the only means for eDRAS to interface with the DR site, providing proprietary communication protocols and interfaces as well as custom information modelling. Actually, a Thin Client operates as a load interface, without any intelligence, other than acting as an interface between the eDRAS and the controlled loads. It is implemented as a RESTful service, running on .NET and implemented using C#. The communication between the eDRAS and any Thin Client may be based on proprietary protocols (e.g., GSM/GPRS, OPC, etc.).

5. DR AND CONTROL LOGIC

Much of the innovation introduced is included in the DR Logic and Control Logic components, as presented in the DAMAZO system architecture. They encompass all the required functionality and algorithms to achieve the promised offerings. In this section we will focus on certain mechanisms that are employed by the system.

5.1. Constraint-based Filtering

As mentioned earlier, the OpenADR standard foresees a number of stakeholders, namely the aggregator, the participant and the client. Moreover, it offers a variety of programs. Participants, clients and programs come with a set of properties accompanied by constraints mostly related to time duration and occurrence limitations. Appropriate actions are expected when a DR event of a specific program arrives at the DRAS for specific participants and clients.

DR logic is responsible to i) reject those programs, participants and clients that do not match the event properties and ii) decide and return the candidate clients and the available shed levels they can offer. The entire processing of filtering is summarized in Figure 4.

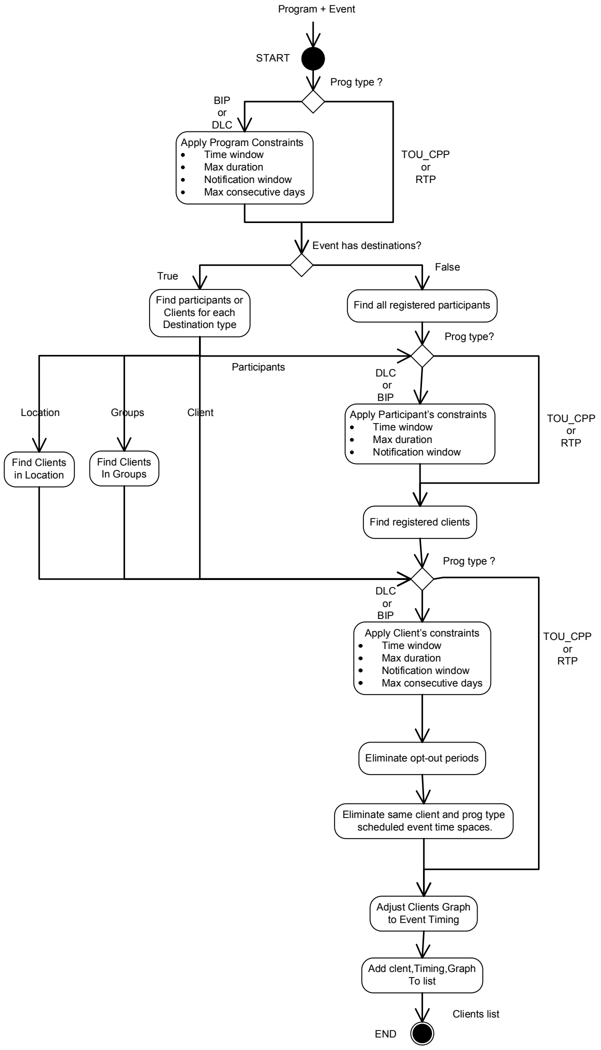


Figure 4: The filtering algorithm

The OpenADR standard specifies four types of constraints: ACCEPT (accept the event as it is), REJECT (reject the event if it does not comply with the constraint), FORCE (impose the constraint restrictions) and RESTRICT (find the intersection between the event and the constraint). Since one event can conflict with more than one constraint, we have come with the following rules to resolve the conflict between two constraints, with the goal to maximize the number of matched constraints. Note that we have also provided guidelines in the case of multiple constraints, but they are not included here due to space limitations.

Table 2: Resolution of an event's conflict with two constraints.

Constraint 1	Constraint 2	Result
ACCEPT	ACCEPT	ACCEPT
REJECT	REJECT	REJECT
ACCEPT	REJECT	REJECT
FORCE	FORCE	Choose the one with the longest duration.
RESTRICT	RESTRICT	Choose the one that provides the longest intersection.
FORCE	RESTRICT	FORCE
FORCE	REJECT	FORCE
ACCEPT	FORCE	FORCE
ACCEPT	RESTRICT	RESTRICT
RESTRICT	REJECT	RESTRICT

5.2. Ranking and Selection of Clients

DR Logic also implements the ranking and selection of the clients to be notified about the event as well as the allocation of sheds to each client, in case the event is not addressed to all clients and/or the shed offerings of the clients are more than the target of the event. As already mentioned, the ranking of the clients is based on fairness and performance criteria. Fairness is calculated according to the formula in (1):

$$F_i = 1 - \frac{TotalSuccessful\,\mathrm{Re}\,quests_i}{\max(TotalSuccessful\,\mathrm{Re}\,quests_k)} \tag{1}$$

where *TotalSuccesfulRequests* is the number of positive answers of client *i* to the allocated shed (either through feedback or opt-outs). The performance criterion is calculated as follows:

$$B_i = PositiveOp\,ts_i \cdot Avg\,(Efficiency)_i \tag{2}$$

where PositiveOpts is the percentage of positive answers from the client and Avg(Efficiency) is the average shed performed by the client in previous allocations.

$$Efficiency = \frac{CurrentShed}{ExpectedShed} \tag{3}$$

Hence, the ranking for client *i* is calculated as:

$$Rank_i = w \cdot F_i + (1 - w) \cdot B_i \tag{4}$$

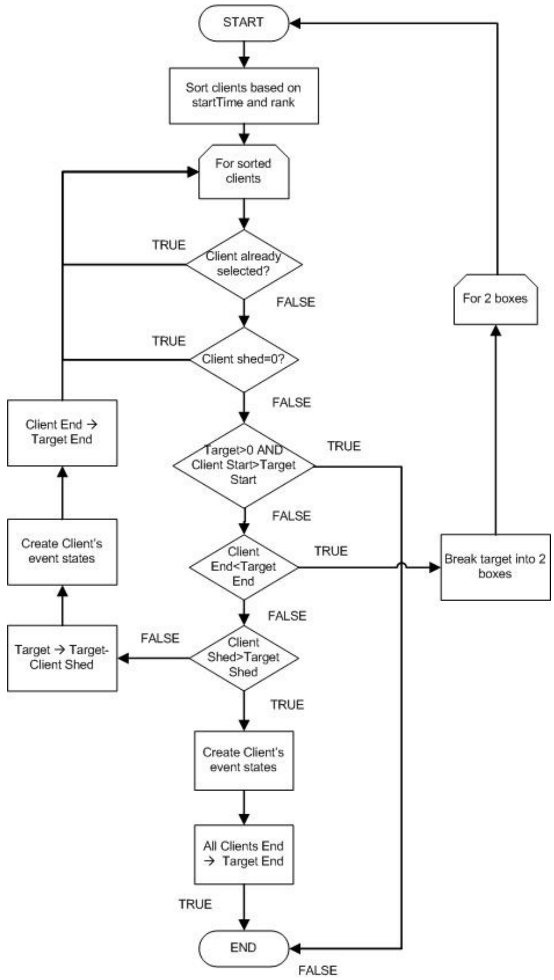


Figure 5: The selection and allocation algorithm

Once the clients are ranked, the selection and allocation algorithm comes in play. The selection considers the ranking as well as the time period in which the clients can offer the stated shed (as a result of the filtering process). The entire process of the selection is very similar to a bin packing algorithm, since we have a target shed for a given time period (TargetBox) and a number of shed offerings from the clients available in different time periods. To achieve the goal, our solution targets a slightly higher shed target. Moreover, the selection algorithm considers the feedback provided by the client on the available shed, reported periodically, as well as a reliability factor, that is defined as follows:

$$T_i = \frac{Avg\,(AvailableShed)}{Capacity\; - Avg\,(CurrentUsage)} \tag{5}$$

where Avg(AvailableShed) is the average available shed reported in the past through the feedback mechanism, Capacity is the load capacity of a client reported at the enrollment and Avg(CurrentUsage) is the average reported usage, again reported through the feedback mechanism. The resulting selection algorithm is depicted in Figure 5.

5.3. Scheduling loads

In order to manage the loads, the eDRAS employs Control Logic (CL) in collaboration with the DR Logic (DL), in the case of Thin Clients. In the case where Smart Clients are present, the functionality described below is distributed between the eDRAS and the Smart Client.

As before, DL handles a DR event and uses an algorithm which, based on static, dynamic and historical data, selects the candidate users and, for each candidate user, it selects the candidate loads that may be controlled. Specifically, the static data consists of the users' features that are stored during the configuration phase (e.g., program that the user has enrolled in, constraints related to availability for control, etc.). The dynamic data consists of the features of each specific DR event (e.g., type) and the parameter values of the DR event. Finally, the historical data consists of the number of control commands that have been issued to each user, the average responsiveness to them, opt-outs, etc. The analytic procedure followed by the DL is the following: it creates a sorted list of candidate end users that may participate in this specific event by applying a number of criteria (fairness, responsiveness, cost, etc.). For each candidate user, DL creates a sorted list of candidate loads (devices) that may participate in this event by applying the same criteria. For each load, DL calculates the amount of power (energy) that has to be curtailed during the DR event (goal), based on the currently scheduled operation for the specific load. This amount of curtailed power is sent to the CL, which tries to meet the required goal by rescheduling the load operation as will be described next. If the rescheduling by the CL succeeds, a new operation schedule is stored at the database and the algorithm proceeds to the next load. Otherwise, if the rescheduling was not successful, the current load is characterized as unavailable and the next load is checked. This procedure continues until all the loads of each candidate user have been checked. The same will be applied for each candidate user, until either the goal has been met or all the users have been checked.

Control Logic is the component that, in close cooperation with the DL, tries to meet each goal set by the DL (e.g., curtailment of 1 kW for 2 hours), by calculating a new operation schedule for each load, without violating the constraints that have been imposed by the user, regarding the preferred quality of service (e.g., comfort, finishing time). It achieves this by using static and dynamic data:

- Static data: It consists of data that stored at the database during the configuration phase, e.g., the thermodynamic model of each house, load types (interruptible, dimmable, shiftable), operational parameters of each load (e.g., consumption profile), restrictions related to the operation (minimum time of operation, etc.), etc.

- Dynamic data: It consists of the required value of curtailed power, requested by the BL and the data that change frequently, either received by sensors (e.g., current interior and exterior temperatures), Internet services (e.g., weather predictions) or by end users (e.g., comfort level, time of finishing a task), ToU or RTP prices, DR events, etc.

The algorithm strives to optimize the energy cost of the end users under a ToU and/or RTP pricing scheme as well as during a DR (e.g., BIP) event, based on the user's preferences related to comfort levels. First, the loads are modeled based on their operational features and their control capability: dimmable (e.g., HVAC), shiftable (e.g., washing machine) and interruptible (e.g., water heater). Specifically, the HVAC system is a continuously operating (dimmable) load, which may be controlled through a thermostat which sets the desirable operating temperatures (setpoints). Based on the work presented in (Ha, Ploix, Zamai and Jacomino, 2006), the required power consumption in order to reach the desired temperature (within a time slot of specific duration, e.g. 15 min) depends on the HVAC's electrical characteristics (average power), the heat capacity and the resistance of the indoor environment and the indoor and outdoor temperatures:

$$P = \frac{T_{j+1} - e^{\left(-\frac{\Delta t}{RC}\right)} T_j}{R\left(1 - e^{\left(-\frac{\Delta t}{RC}\right)}\right)} - \frac{1}{R} T_j^{out} \tag{6}$$

where, P is the average power generated by the HVAC system during time period Δt, C is the heat capacity of the heated (cooled) indoor environment, R is the thermal resistance of the environment, T_j is the indoor temperature at time slot j, T_{j+1} is the desired indoor temperature at time slot $j+1$ (setpoint) and T_j^{out} is the outdoor temperature at time slot j. Shiftable loads (e.g., washing machine) constitute a load type, which may be shifted in time but not interrupted when started nor dimmed, since the power demands of any washing program consist of a number of continuous operational phases, each one posing specific power demands. Finally, the interruptible loads (e.g., water heater), constitute a load type, which may be interrupted but not dimmed. The control algorithm calculates a) the setpoints for the dimmable (increasable/reducible) loads (e.g. HVAC), b) the starting times for the shiftable (schedulable) loads (e.g., washing machine), and the c) starting and stop times for the interruptible loads (e.g., water heater) within a predetermined time period, taking into account both the prices per time slot (ToU/RTP) and the user's comfort preferences. The setpoints of the dimmable loads are calculated by an adequately modified Dijkstra's shortest path algorithm, while the operation schedule of both shiftable and interruptible loads comprises the time slots that maximize the objective function (energy cost and comfort). A more extensive description of the load control algorithm can be found in (Antonopoulos, Kapsalis and Hadellis, 2012). A flow chart of the scheduling operations performed by the DL and the CL is presented in Figure 6.

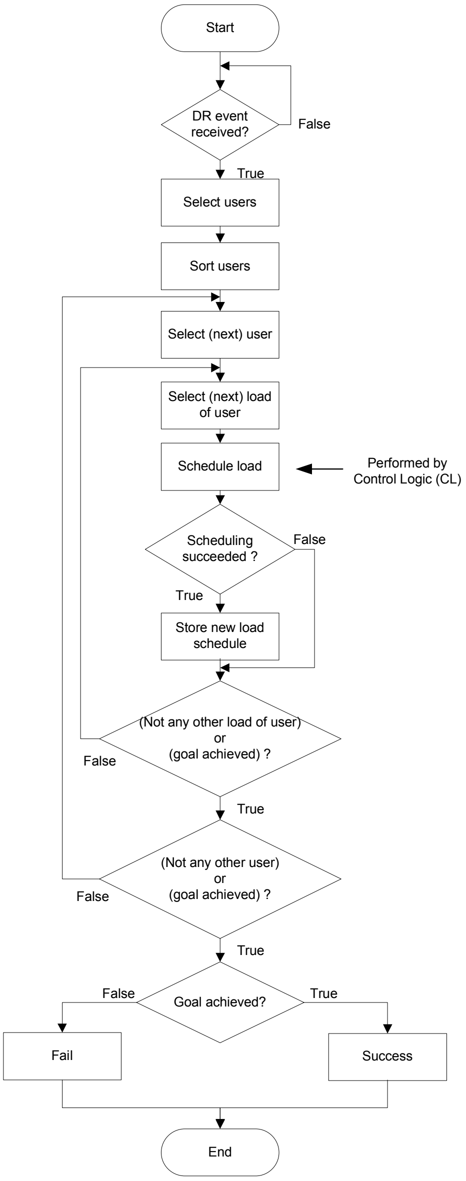


Figure 6: The load scheduling algorithm

6. CONCLUSIONS

In this paper, we have presented an end-to-end DR-based system (DAMAZO) that supports a hierarchical architecture of multiple enhanced DR Automation Servers, according to the emerging business models for the organization of aggregators in Smart Grids. We have based our implementation on the OpenADR v1.0 standard and we have also implemented certain additional functionalities to support the derived complexity of this multi-level architecture. The architectural diagram of our system is provided along with a brief description of the comprising components and the accompanying interfaces.

Future work includes the study of more complex strategies regarding the mapping of different DR programs and the more precise prediction of available shed by clients. Moreover, we will study the outcomes of relevant research projects, (e.g., ADDRESS, SmartHouse/SmartGrid, etc.) to identify similarities and differences and examine whether we can expand our implementation to support the outcomes of these projects. Finally, since the OpenADR v2.0 specification (still in draft state) also provides the communication interfaces for supporting a multi-level hierarchical organization of aggregators, we are going to update our implementation according to the new specification, while preserving the old interfaces so as to offer backward compatibility.

ACKNOWLEDGMENTS

This work has been partially supported by the Greek General Secretariat for Research and Technology (GSRT) as part of the research project "DAMAZO – Automated Demand Response Management System for the Rational Use of Electrical Energy" 09ΣΥΝ-32-613, under the "Cooperation 2009" framework.

REFERENCES

Antonopoulos Ch., Kapsalis V., Hadellis L., "Optimal Scheduling of Smart Homes' Appliances for the Minimization of Energy Cost under Dynamic Pricing", in *17th IEEE International Conference on Emerging Technologies & Factory Automation* (ETFA 2012), Krakow, Poland, September 2012.

BeyWatch, "Deliverable D2.1: Service Requirement specification", Online: http://www.beywatch.eu.

Ha LD, Ploix S., Zamai E., Jacomino M., "A Home Automation System to Improve Household Energy Control", *in 12th IFAC Symposium on Information Control Problems in Manufacturing*, 2006.

EPRI. "Concepts to Enable Advancement of Distributed Energy Resources" White Paper on DER. EPRI, Palo Alto, CA: 2010. 1020432.

Gkatzikis, L., Koutsopoulos I., and Salonidis, T. "The role of Aggregators in Smart Grid Demand Response markets", to appear, *IEEE Journal on Selected Areas in Communications*, 2013.

OpenADR Alliance, "OpenADR 2.0 Profile Specification A Profile", v1.0, 2012.

OpenADR Alliance, "OpenADR 2.0 Profile Specification B Profile", v.0.9, Final Draft, 3-18-2013.

OASIS, "Energy Interoperation Version 1.0, 2-18-2012.

Piette, M.A., G. Ghatikar, S. Kiliccote, E. Koch, D. Hennage, P. Palensky, and C. McParland. 2009. Open Automated Demand Response Communications Specification (Version 1.0). California Energy Commission, PIER Program. CEC-500-2009-063 and LBNL-1779E.

Valtorta, Giovanni, et al. "Architecture and functional specifications of distribution and transmission control systems to enable and exploit active demand." *21st International Conference on Electricity Distribution*. CIRED, Frankfurt, 2011.

Warmer C., et al., "Web services for integration of smart houses in the smart grid", in Grid-Interop Forum 2009.

ELECTRICITY MARKET AND RENEWABLE ENERGY INTEGRATION: AN AGENT-BASED CONCEPTUAL MODEL

José Carlos Sousa [a], Zafeiris Kokkinogenis [b], Rosaldo J. F. Rossetti [c], João Tomé Saraiva[d]

[a], [d] Department of Electrical and Computer Engineering, Faculty of Engineering, University of Porto, Portugal
[b], [c] Department of Informatics Engineering, Faculty of Engineering, University of Porto, Portugal
[b], [c] Artificial Intelligence and Computer Science Laboratory, Faculty of Engineering, University of Porto, Portugal
[b] Institute of Mechanical Engineering, Faculty of Engineering, University of Porto, Portugal
[d] INESC Porto and Faculty of Engineering, University of Porto, Portugal

[a] dee09003@fe.up.pt, [b] pro08017@fe.up.pt, [c] rossetti@fe.up.pt, [d] jsaraiva@fe.up.pt

ABSTRACT

The emergence of electricity markets and the opportunities consequently created have radically modified the operation planning activities of Power Systems. As direct result, there is the need for developing new methods to meet in an efficient way the requirements of generation companies, so to respond adequately to new challenges such as market competition. Agent-based models have been proposed in the literature as surrogate to equilibrium models when the problem is too complex to be addressed within a traditional equilibrium framework. Driven by this trend, this paper discusses and proposes a conceptual model following the agent paradigm that deals with the inherent complexity of electricity markets. The devised model proved to be robust enough to represent key features of our study domain and is ready to be actually developed in a computational tool to help generation companies to build their short-medium term operation decisions in a more sounded and robust way.

Keywords: Electricity market, agent-based modeling, hydro-pumping generation

1. INTRODUCTION

The optimization of power generation systems is an area that was and still remains a continuous concern for electricity companies, as well as for researchers who are dedicated to this subject (Gomes 2007). However, the emergence of electricity markets in an industry as traditional as it is the electricity sector, and the business and production opportunities created by them, have radically modified the operation planning activities of Power Systems. As a direct result there is a need to develop simulation models to forecast efficiently the operation of electricity generation companies, so that they respond in an efficient way to the new market challenges.

Since the 80th of the last century, there was a large investment in renewable energy sources worldwide. Nevertheless, these sources due to their high volatility create several problems for the management of networks and power plants, as well as for the management of electricity markets. The use of renewable energies not only allows a slow rising or even a decline of CO2 emissions, but also allows a larger independence of mankind from fossil fuels such as oil and coal.

Having in mind these ideas, the main goal of this paper is to describe an agent-based conceptual model for the Portuguese/Spain Electricity Market (MIBEL) in order to study the operational short-medium decisions of the generation companies in the day-ahead markets with more information, in a competitive environment and with a large penetration of renewable energy sources. In this scope, the modeling of hydro power plants with pumping capability is one of the main objectives of this work.

The related literature has been growing rapidly in recent years, and many different modeling approaches, such as mathematical programming, game theory, and agent-based models have been investigated and used under a liberalized market environment (Li, Shi and Qu 2001). With the recent growing of renewable energy sources, especially in Europe, electricity markets are facing more complex problems and increased risks namely due to the connection of volatile renewable sources. The intermittence of some of these renewable sources motivates the players to optimize their bidding strategies by considering new challenges (Li, Shi and Qu 2001).

This paper is organized as follows. Section 2 presents a brief description of the power system market under study, and the motivation of the proposed work. Section 3 briefly overviews some works related with the simulation of electricity markets. Section 4 discusses the proposed conceptual agent based market model and Section 5 presents the final remarks.

2. ELECTRICITY MARKET DESCRIPTION

In the following subsections the electricity market structure and organization is presented and the new paradigms are discussed.

2.1. New Structures and the Unbundling Model

To allow a suitable implementation of the electricity sector liberalization, significant modifications are needed in the traditional system. In this context, electricity shall be regarded as a product whose sellers can be chosen by buyers, within certain rules. In this new framework, companies are seen as services providers and the grids correspond to the physical locations where electricity markets are established. On the other hand, in order to ensure that the whole system operates properly, independent entities, both at a technical and at a regulatory level) are required. The electricity sector restructuring originated the unbundling of the traditional vertically integrated companies and the creation of a disaggregated structure that involves multiple actors.

Figure 1 introduces the new model of the electricity sector (Saraiva, Silva and Leão 2002).

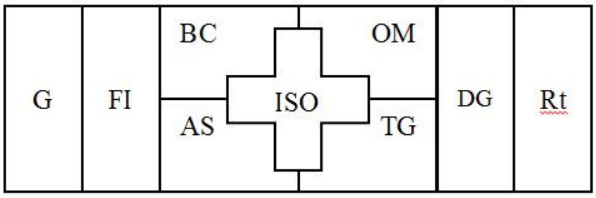


Figure 1: Desegregated Model of Electricity Sector (adapted from (Saraiva, Silva and Leão, 2002))

In this figure it is possible to identify some competitive activities: Generation (G), Financial Intermediation (FI) and Retailing (Rt). On the other hand, the Distribution Grid (DG) operates as a regulated monopoly because it is not economically feasible to duplicate distribution networks in the same geographical area. The central part of this scheme corresponds to a set of functions that were usually assigned to the transmission system. These activities include the Bilateral Contracts (BC), Organized Markets (OM), the System Operator (ISO), the Transmission Grid (TG) and the Ancillary Services (AS).

The Bilateral Contracts are characterized by the establishment of bilateral financial or physical relations between generation entities, on one side, and eligible customers or retailing agents on the other. These contracts involve several aspects as the price and energy to be supplied and consumed over a specified period of time.

Electricity markets (OM) typically correspond to a set of activities organized along time and usually starting the day before operation and continuing along the operation day. These activities are typically associated with the daily markets and the intraday markets. In case they coexist with bilateral contracts, there is what we can call a mixed model (Saraiva, Silva and Leão 2002).

Organized Markets receive bids to buy and sell electricity, typically for every hour or half hour for the next day (Day-Ahead Markets). These bids normally include power values and price (minimum amount to receive in the case of selling bids and maximum value to pay in the case of buying bids). These markets build aggregated demand and supply curves and their crossing point lead to the cleared quantity and the cleared price for each time step of the next day (Saraiva, Silva and Leão 2002). This also means that the Market Operator in charge of these day-ahead markets are responsible for obtaining a purely economic dispatch since network constraints are not yet considered until this point. There are also forward markets that include transactions of electricity blocks with subsequent delivery after day-ahead markets (futures), of physical liquidation or by differences. These markets are, in practice, derivative product markets in which the underlying asset is electricity and that can be used as a way to address the risk inherent to this short-term operation markets.

The Independent System Operator (ISO) is the entity in charge of the technical coordination functions to ensure the safe and reliable operation of the power system. For this purpose, the ISO should receive information on the economic dispatch built by the Market Operator, as well as information related to the Bilateral Contracts in terms of network nodes and powers involved. The ISO should therefore evaluate the technical feasibility of the dispatch for each time step of the next day taking considering the network constraints. If congestion occurs given the received dispatch information, the dispatch is not feasible and it is necessary to adopt a correction mechanism. If there are no limitations, the system operation is feasible from a technical point of view. In this case, the ISO sets the amounts of ancillary services and procures them given that some of them are typically mandatory while some other are contracted in specific markets. In some cases the ISO and the Transmission Grid (TG) are under the responsibility of the same entity. In this case, it takes the name of TSO (Transmission System Operator) as it happens in Portugal (REN) and in Spain (REE).

The Transmission Grid (TG) represents the entity that owns or has the concession of the assets of the transmission network and that, for economic reasons, operates in terms of a natural monopoly in the geographical area in which it is implemented. These companies, like the distribution network companies, are remunerated through network usage charges and the regulatory authorities regulate their activities.

For the safe and reliable operation of the power system it is necessary to contract several ancillary services (AS), e.g. primary, secondary and tertiary reserve and others. Ancillary Services can be mandatory or can be contracted in specific markets in which the System Operator determines the amount to be contracted and accepts bids for their provision.

This organization corresponds to the most disaggregated design with various activities associated with the generation, transmission, distribution and electricity trading. In many countries, several of these activities are grouped, as it is the case of the countries where the ISO and TG activities are merged in a TSO.

Taking into account the organization detailed above, markets can be classified according to the type of good/service that is traded and according to the temporal bases (Pereira 2004). In the context of this paper and regarding the traded goods, we can consider:

- Energy Markets: where electricity is traded between sellers and buyers, through a centralized mechanism, operating as a spot market, and/or through contracts directly established between buyers and sellers (Bilateral Contracts);
- Ancillary Services Markets: where some ancillary services are contracted, given that they are required for the secure operation of power systems with adequate standards of quality, safety and reliability. Such services include the frequency control, primary, secondary and tertiary reserves, reactive power/voltage control and black start. In some countries, some of these services are contracted by ISO's or TSO's in specific markets.

Taking into account the temporal aspects, we can consider:

- Spot market: a market that operates on a daily basis and which aims at negotiating energy for each hour or half an hour of the next day (also known as Day-Ahead Market);
- Intraday markets – these type of markets are intended to eliminate the existing imbalances between supply and demand and can be used by market agents to contract (buy or sell) electricity, typically in smaller quantities than in the day ahead market;
- Derivatives/Forward Markets: they deal with future contracts and options, which in essence are financial instruments intended to minimize the risk associated with the volatility of the price of short-term markets;

Planning markets – usually used to trade electricity blocks with longer-term delivery periods.

2.2. Power System Organization in Iberia

The power systems in Portugal and Spain went through several changes in recent years. It started with a centralized model, with vertical companies that were responsible for generation, transmission and distribution of energy. However, in the last decades there has been a change on the priorities regarding policies concerned with environmental sustainability, competitiveness and security of energy supply, especially in Europe. For this reason, and in line with the European Electricity Directives, Portugal and Spain implemented the Iberian Electricity Market (MIBEL), which is fully operational since July 2007. Nowadays, it is possible to organize the Iberian power system in five key activities, developed independently, which are:

- Generation;
- Transmission and System Operation;
- Distribution;
- Retailing;
- Organized Markets.

Generation and Retailing activities are carried out under free competition by the assignment of a license and Transmission and Distribution activities correspond to public regulated concessions, assigned by the state to specific companies. There are also two regulatory agencies for the energy sector, one in Spain and another in Portugal.

2.3. MIBEL electricity market organization

As mentioned before, markets can be classified according to the type of traded goods/services and to the temporal bases on which they operate. As for goods/services we can classify them as Energy Markets, Ancillary Service Markets and Transmission Markets. Taking into account the temporal basis, they can be also classified as Spot market, Intra Day Markets, Derivatives/Forward Markets and Planning Market. These markets can be voluntary or mandatory. The MIBEL market model is a mixed one, given that it includes a pool based market plus bilateral contracts, and it comprises two distinct geographical areas from the operation point of view, Portugal and Spain, each one under the responsibility of the respective Transmission System Operator (TSO). Figure 2 illustrates the MIBEL market model. There are also two regulatory entities, ERSE is the Portuguese regulatory agency for the energy services and CNE is its Spanish counterpart.

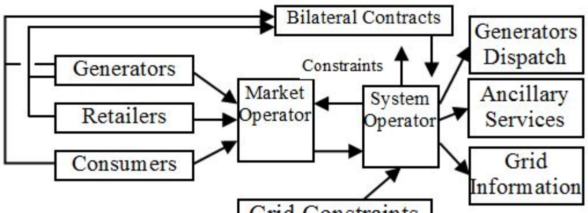


Figure 2: Mixed Model including Spot Market and Bilateral Contracts (adapted from (Li, Shi and Qu 2001))

2.4. The new paradigm and motivation

The emergence of electricity markets and the increase of renewable energy sources in an industry as traditional as it was the electricity sector, and the opportunities created by these markets have radically modified the operation planning activities of Power Systems. As a direct result, there is a need of developing new models and applications to meet in an efficient way the requirements of generation companies, so that they respond adequately to these new challenges, namely competition.

As for the electricity markets, it is necessary to understand the behavior of all its participants, and also the impacts coming from the increasing presence of renewable sources. Associated with this issue, hydro generators with pumping capability play an important role because of their storing capacity. Such generators have unique dynamic characteristics such as fast start-ups and fast response to load variations.

Due to their pumping capability, they have dual nature. They can participate in the market either as buyers, consuming electricity to pump and store water, or they can act like generators or sell electricity in the market. This propriety also gives them advantages regarding the participation in the ancillary services markets. It is in this framework that this work aims at contributing, namely modeling hydro power plants with pumping capability in the decision of bidding in energy and ancillary services markets.

3. ELECTRICITY MARKET SIMULATION OVERVIEW

3.1. Simulation Methods

A large number of research works have been dedicated to model liberalized electricity power systems. From an organization point of view and according to the literature review that was carried out, electricity market modeling can be classified in four main areas (Li, Shi, and Qu 2001):

- Optimization problems, addressing a single company;
- Equilibrium Models from Game-Theory-based economics, considering a larger number of competitors;
- Agent-Based Models that simulate the behavior of the companies and the interactions between autonomous agents;
- Hybrid solutions.

Optimization models are centered in profit maximization problems for a single firm competing in the market, often considered as a price taker, while Equilibrium Models represent the market behavior taking into consideration the competition between all participants. Agent-Based Models are increasingly an alternative to equilibrium models that becomes interesting when the problem is too complex to be addressed within a traditional equilibrium framework. Agent-based computational economics (ACE) is the computational study of dynamic economic systems modeled as virtual worlds of interacting agents (Yu and Yuan 2005).

3.2. Models using ABM

Agent-Based Modeling (ABM) is a recent and evolving research paradigm, based on agents that allow developing models to represent in more realistic way electricity markets, and overcomes some disadvantages of other approaches. In ABM, each agent can build its optimal bidding strategy taking into account past experiences obtained from the direct interaction with the environment and with other agents. In practice, these agents can learn from past decisions, improving their new decisions thus adapting their strategies. In ABM, the players usually have imperfect and local information.

In (Omicini, Ricci and Viroli 2008), the authors support the idea that agents in a multi-agent system (MAS) are surrounded objects (tools or instruments) and services that affect their policy selection by shaping their surrounding environment. For this reason they propose a unifying abstraction that can be used to model and engineer the world around agents of a MAS model. Based on such conceptual foundations they discussed a MAS-based meta-model that is characterized in terms of three basic abstractions:

- Agents, to represent pro-active components of the systems, encapsulating the autonomous execution of some kind of activities inside some sort of environment;
- Artifacts, to represent passive components of the systems such as resources and media that are intentionally constructed, shared, manipulated and used by agents to support their activities, either cooperatively or competitively;
- Workspaces, as conceptual containers of agents and artifacts, useful for defining the topology for the environment and providing a way to define a notion of locality.

There are some works addressing this issue. AMES (Agent-based Modeling of Electricity Systems) is open-source software developed by an interdisciplinary group of researchers at the Iowa State University. It allows developing strategic trading behaviors within restructured wholesale power markets operating over realistically rendered AC transmission grids (Li and Tesfatsion 2009). This software can be used to simulate the day-ahead market and the real-time market and considers the AC transmission grid and the system operator activities.

EMCAS (Electricity Market Complex Adaptive Systems) is commercial software developed by the Argone National Lab and is one of the most popular ABM for the simulation of Electricity Markets. It considers the physical structure of the market and it has the capability of taking decentralized decision-making along with learning and adaptation for agents. It uses the VALORAGUA model to include the hydro generation (Thimmapuram et al. 2008). Whereas EMCAS provides a framework to simulate deregulated markets with flexible regulatory structure along with bidding strategies for supply offers and demand bids, VALORAGUA provides longer-term operation plans by optimizing hydro and thermal power plant operation for the entire year. In addition, EMCAS uses the price forecasts and weekly hydro schedules from VALORAGUA to provide intra-week hydro plant optimization for hourly supply offers.

MASCEM (Vale et al. 2011) is another approach in which the authors developed a simulation platform based on a multi-agent framework. The MASCEM multi-agent model includes agents with strategies for bid definition, acting in forward, day-ahead, and balancing markets and considering both simple and complex bids. These characteristics turn the MASCEM both a short and a medium term simulation platform. This methodology uses learning algorithms to let agents recognize changes in the environment, thus helping them to react to the dynamic environment and to adapt their bids accordingly. A similar approach is used in (Conzelmann et al. 2009; Yu and Liu 2008; Rahimiyan and Mashhadi 2010; Wang et al. 2008). These multi-agent approaches have been used for analysis of gaming, learning, and decision support to market agents.

Despite of the development of these models, the hydro generation, specially pumping hydro stations, does not have the adequate characterization taking into account the new paradigms related to the renewable energies. Even in EMCAS, that uses VALORAGUA approach to deal with hydro generation, there is not an explicit and careful simulation of the hydro power plants, because EMCAS is very dependent on VALORAGUA performance.

Accordingly, our objective is to combine the hydro generation with a more detailed modeling, especially regarding hydro with pumping, and study their impact on systems having a large penetration of renewable sources, especially wind. We will include the possibility of selling the hydro energy in the energy market or the ancillary-services market. This kind of generation also has the possibility of buying energy in the electricity market and of storing it by pumping water to upstream. This possibility will allow a better coordination between renewable and hydro power plants.

4. ELECTRICITY MARKET CONCEPTUAL MODEL

As mentioned before, this work will focus on the electricity and ancillary-services markets. The main objective is to develop an integrated Agent-Based Simulation model to help instantiating agents to prepare their bidding strategies. In this model autonomous agents will interact in a competitive environment. It is also our objective to apply the proposed simulation tool to MIBEL. In the next sections we will briefly describe the work proposed in this paper. In order to simulate electricity markets in general, and MIBEL in particular, using an agent-based platform, it is necessary to define the structure of the model and the type of agents to be used. Having in view the application to MIBEL and given that each electricity market has its own peculiarities and rules, it is important to tune this definition considering MIBEL arrangements and the players that operate in this market. The propose model is shown in Figure 3.

The objective is to simulate two markets: the energy market and the ancillary services market. The main difference between them is due to the fact that on the secondary market only energy producers can participate. In the Energy Market, the inelastic consumers want to consume electricity. They represent residential, commercial or industrial consumers that cannot buy energy directly in market. They have to negotiate with the different Retailers that act as aggregators of individual demand and that then operate as market agents.

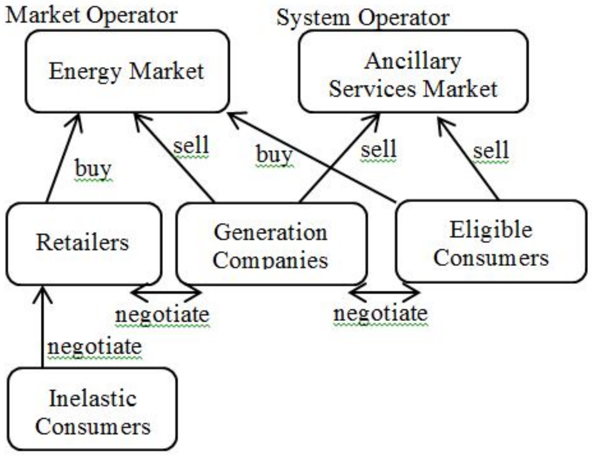


Figure 3: Structure of the Proposed Agent-based Model

Retailers are entities that buy energy in the market and negotiate with the consumers. They have to bid in the Energy Market to buy energy for the inelastic consumers. However, in the consumers group there are also consumers, typically large ones that have the possibility of buying energy directly in the Energy Market, because their demand is large these consumers will be termed as Eligible Consumers.

Generation Companies control power plants and offer their energy in the Energy Market, submitting-selling bids. They can also establish Bilateral Contracts with the Retailers or Eligible Consumers.

Regarding the Ancillary Services Market, the System Operator has the responsibility of operating the power system in a secure and reliable way. To ensure this safe operation, it contracts reserves with different time durations and activation periods. It receives offers from the Generation Companies for secondary and tertiary energy reserves and selects the least costly ones till a technical requirement is met.

As mentioned before, the main goal of this work is to develop an agent based model that also considers the hydro generation plants with pumping in the market model, accounting for a more detailed representation. This type of power plants has the possibility of buying energy and store water, which means they can be both seller and buyer. This fact gives them the possibility of getting larger profits, because they can buy at lower prices and sell at higher prices, not only on the energy market but also regarding the ancillary services provision. In fact, regarding ancillary services, the system operator typically contract upward and downward reserve energy and this type of hydro stations can provide energy in both ways.

Using traditional concepts of object-oriented development we can represent the following agent structure that groups similar agents into suitable classes of objects. Figure 4 presents the proposed model.

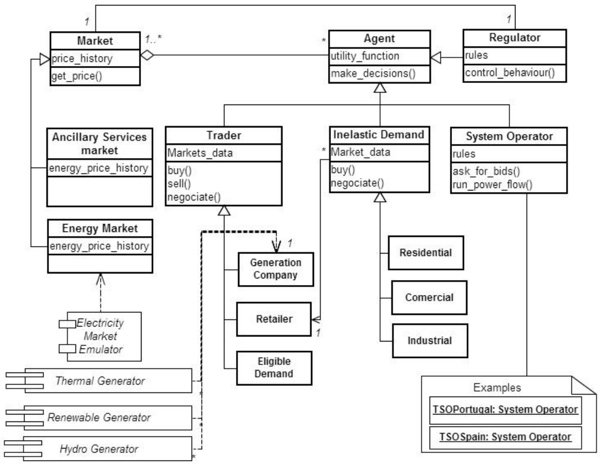


Figure 4: UML Conceptual Agent Model Diagram

This model uses 6 types of agents and 2 artifacts are defined as follows:

- Inelastic Demand Agent – it corresponds to the individual clients that can be residential, commercial or industrial consumers; they cannot buy energy in the market and have to negotiate with the Retailers Agents;
- Eligible Demand Agent – it corresponds to large consumers that can directly participate in markets. It can be either large factories or hydro pumping power stations. They can establish bilateral contracts with Generation Companies;
- Retailer Agent – it corresponds to an aggregator entity that has a portfolio of contracts with individual clients, that is, with Inelastic Demand Agents. This agent can buy electricity in the market or establish bilateral contracts with Generation Companies;
- Physical Generator Artifact – it is related to individual power plants and their characteristics; it will be an artifact agent because it does not take any decision and it has a passive role in the market with no goal or autonomous activity. It will be used by Generation Company Agents;

Generation Company Agent – it corresponds to the utilities that own a portfolio of generation assets, comprising different generation technologies, each one characterized by its generation operation and maintenance costs; These agents will have to decide whether they use their resources (hydro, gas, coal, wind) in the day-ahead market, in the ancillary services markets, or store some resources to be used in the future, when possible. It can also establish bilateral contracts with retailers. In some cases it is possible to adopt other utility functions, as for instance to increase the market share of the respective generation company. The formulation presented below shows, in a simple approach, the general problem faced by these agents:

$$\max \; X_{ct}\alpha_t + Y_{ct}\beta_t + Z_{ct}\,\varphi_t$$

$$\begin{aligned} s.t. \quad & X_{ct} + Y_{ct} + Z_{ct} \leq R_{ct} \\ & X_{c\,min} \leq X_{ct} \leq X_{c\,max} \\ & Y_{c\,min} \leq Y_{ct} \leq Y_{c\,max} \\ & Z_{c\,min} \leq Z_{ct} \leq Z_{c\,max} \\ & X_{ct}, Y_{ct}, Z_{ct} \geq 0 \end{aligned}$$

In this formulation Xct is the quantity to use in day-ahead market for power plant c, for hour t; Yct is the energy quantity to use for ancillary services for power plant c, for hour t; Zct is the energy quantity to be stored for power plant c, for hour t; αt is the value of the energy market, for hour t; βt is the value of the energy ancillary services, for hour t; φt is the future value of energy, for hour t; Rct is the quantity of resource availably for power plant c, for hour t. Hydro power plants with pumping capability can also work as Eligible Demand Agents to buy and store energy;

- TSO Agent – it represents an entity that gathers the functions of an ISO with the ownership or the concession of a transmission network. It is also the ancillary services market operator and is responsible for the reserve energy agreement;
- Organized Market Artifact – it is a process that models the energy market operator as a central entity that receives selling and buying bids for each trading hour of the next day and organizes these bids to get generation/demand schedules; it is considered as an artifact because it presents neither internal goals nor any kind of autonomous activity;
- Regulatory Agent – this agent is in charge of evaluating the behavior of the agents according to market regulation.

In this work, models are introduced according to the concept of agent organizations. Organizations are centered on the perception of the AGR structure (Ferber, Gutknecht and Michel 2004): agent, group, and role.

These agents are the “main actors” of the model. They are the entities that produce, consume and trade on the markets of our models. Each agent assumes a role (i.e. sells, buys or regulates) according to the group it belongs to. The decisions that agents have to make are essentially associated with:

- The market type, energy or ancillary services;
- The player type, traders that operate in markets (such as generation companies, eligible consumers and retailers) or individual inelastic demand;
- All physical constraints, from grid and from generators.

Learning processes, such as q-learning and genetic learning, and also by decision-support models, will also support these decisions. For example, in the last case, to help taking decisions regarding the operation of hydro-pumping stations, we will use the model presented in (Sampaio, Saraiva, Sousa and Mendes 2013). Figure 5 depicts an overview of agent decisions as explained above.

This model will be implemented and tested in NetLogo (Wilensky 1999) agent-based modelling and simulation platform to rapidly prototype simple, yet realistic, "what-if" scenarios and analyze the market performance under different real set-ups. NetLogo is an open source multi-agent programmable modeling environment for simulating complex systems evolving over time. Modelers can give instructions to hundreds or thousands of "agents" all operating independently. This makes it possible to explore the connection between the micro-level behavior of individuals and the macro-level patterns that emerge from their interaction.

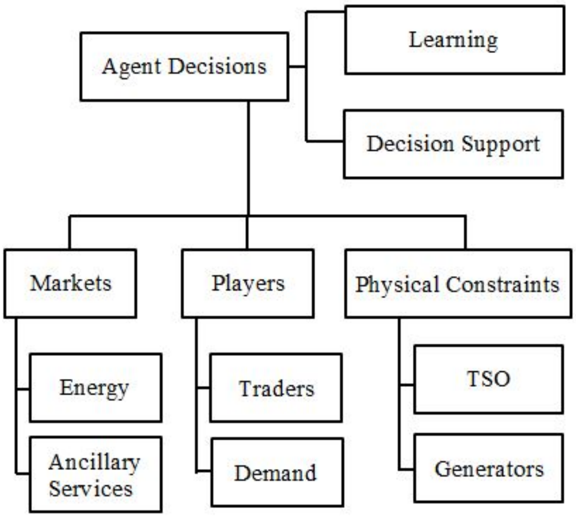


Figure 5: Agent Decision Framework

5. CONCLUSIONS

The studies on power system generation comprise a research area that was and still remains a continuous concern for electricity companies, as well as the scientific community. Electricity markets are complex frameworks that justify the development of computational models to simulate the interactions between all involved agents. In the last years, there was a large investment in renewable energy sources worldwide, and this fact brought more complexity to power systems. This paper describes an agent-based conceptual model to simulate the MIBEL electricity market and to study the behavior of involved agents, focusing on the representation of hydro power plants with pumping capability. The model is designed to be a viable tool to support planning and decision-making process in the energy market in presence of a dual nature actor that represents exactly the hydro-pumping generators.

In the near this model will be implemented using reinforcement learning algorithms, as for example q-learning (Watkins 1989) and SARSA (Rummery and Niranjan 1994), as well as communication protocols, such as Double Auction Protocols (Kant and Grosu 2005) for the negotiation among agents. The implementation design will be based on organizational concepts such as groups, roles and interactions (AGR).

ACKNOWLEDGMENTS

This project has been partially supported by FCT (Fundação para a Ciência e a Tecnologia), the Portuguese Agency for R&D, under PhD Scholarship grant SFRH/BD/67202/2009

REFERENCES

Conzelmann, G., Botterud, A., Wang, J., & Thimmapuram, P., 2009. Using multi-agent simulation to test European electricity markets. In Power & Energy Society General Meeting, IEEE, pp. 1-2.

Ferber, J., Gutknecht, O., & Michel, F., 2004. From agents to organizations: an organizational view of multi-agent systems. In Agent-Oriented Software Engineering IV , 214-230. Springer Berlin Heidelberg.

Gomes, M.H.R., 2007. New Electricity Markets and Ancillary Services Mechanisms. Thesis (PhD). University of Porto.

Kant, U., & Grosu, D., 2005. Double auction protocols for resource allocation in grids. International Conference on Information Technology: Coding and Computing (ITCC 2005), (1), 366-371.

Li, G., Shi, J. and Qu, X., 2001. Modeling methods for GenCo bidding strategy optimization in the liberalized electricity spot market–A state-of-the-art review. Energy, 36, 4686-4700.

Li, H., & Tesfatsion, L., 2009. Development of open source software for power market research: The AMES test bed. Journal of Energy Markets, 2(2), 111-128.

Omicini, A., Ricci, A., & Viroli, M., 2008. Artifacts in the A&A meta-model for multi-agent systems. Autonomous Agents and Multi-Agent Systems, 17(3), 432-456.

Pereira, I.C.G., 2004. Multi Agent System to Decision Support in Electricity Markets. Thesis (PhD). Trás-os-Montes e Alto Douro University.

Rahimiyan, M., & Mashhadi, H. R., 2010. An adaptive Q-learning algorithm developed for agent-based computational modeling of electricity market. IEEE Transactions on Systems, Man, and

Cybernetics, Part C: Applications and Reviews, 40(5), 547-556.

Rummery, G. A., & Niranjan, M., 1994. On-line Q-learning using connectionist systems. University of Cambridge, Department of Engineering.

Sampaio, G., Saraiva, J.P.T., Sousa, J.C. and Mendes, V., 2013. Optimization of the Operation of Hydro Stations in Market Environment Using Genetic Algorithms. 10th International Conference on European Electricity Market (EEM13).

Saraiva, J.T., Silva, J.P. and Leão, M.P., 2002. Electricity Markets - Regulation and Tariffs for the Use of Networks. Porto, Portugal: FEUP Edições.

Thimmapuram, P., Veselka, T.D., Koritarov, V., Vilela, S., Pereira, R. and Silva, R.F., 2008. Modeling hydro power plants in deregulated electricity markets: Integration and application of EMCAS and VALORAGUA. The 5th International Conference on European Electricity Market (EEM2008), pp. 1-6.

Vale, Z., Pinto, T., Praça, I., & Morais, H., 2011. MASCEM: electricity markets simulation with strategic agents. Intelligent Systems, IEEE, 26(2), 9-17.

Wang, J., Botterud, A., Conzelmann, G., & Koritarov, V.S., 2008. Market power analysis in the EEX electricity market: an agent-based simulation approach. In Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, IEEE, pp. 1-8

Watkins, C.J.C.H., 1989. Learning from delayed rewards. Doctoral dissertation. University of Cambridge.

Wilensky, U. ,1999. NetLogo itself: NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University. Evanston, IL. [accessed 15 July 2013].

Yu, N., & Liu, C.C., 2008. Multi-agent systems and electricity markets: state-of-the-art and the future. In Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, IEEE, pp. 1-2.

Yu, S.-k. and Yuan, J.-h., 2005. Agent-based computational economics: methodology and its application in electricity market research. The 7th International Power Engineering Conference, pp. 1-415.

AUTHORS BIOGRAPHY

José Carlos Sousa was born in Porto, Portugal in 1982. In 2005 and 2007 he got the BSc and the MSc degrees in Electrical Engineering and Renewable Energies from the Faculdade de Engenharia da Universidade do Porto, FEUP. Since 2006 he works in EDP (Energias de Portugal) and currently he is also a PhD student at FEUP. His areas of interest include optimization, electricity markets and renewable energies.

Zafeiris Kokkinogenis received his degree in Computer Engineering from the Faculty of Engineering of University of Pavia, Italy. At the present time he is enrolled in the Doctoral program in Informatics Engineering at the Faculty of Engineering of University of Porto. Generally speaking the areas of his interest include agent-based modeling and multi-agent systems.

Rosaldo Rossetti joined University of Porto in 2006, where he is an Assistant Professor with the Department of Informatics Engineering, and a Research Fellow with the Artificial Intelligence and Computer Science Lab. Dr. Rossetti received the B.Eng.(Hons) degree in Civil Engineering from UFC, in 2005, and both the M.Sc. and the Ph.D. degrees in Computer Science from UFRGS, Brazil, in 1998 and in 2002, respectively. He carried out most of his doctoral research as a full-time Ph.D. research student at Leeds University's Institute for Transport Studies, Leeds, U.K. His areas of interest generally include complex systems analysis, systems optimization, computer simulation, Artificial Intelligence, and multi-agent systems. Dr. Rossetti is an active member of IEEE, ACM, APPIA, and AISTI.

João Tomé Saraiva was born in Porto, Portugal in 1962. In 1987, 1993 and 2002 he got his MSc, PhD, and Agregado degrees in Electrical and Computer Engineering from the Faculdade de Engenharia da Universidade do Porto, FEUP, where he is currently Professor. In 1985 he joined INESC Porto – a private research institute – where he was head researcher or collaborated in several projects namely in the scope of consultancy contracts with the Portuguese Electricity Regulatory Agency.

A REVIEW OF CONTROL STRATEGIES FOR ANALYZING AND DESIGNING MANAGING WIND GENERATORS

Vaia K. Gkountroumani [(a)], **Peter P. Groumpos** [(b)]

[(a)] Department of Electrical and Computer Engineering, University of Patras
[(b)] Department of Electrical and Computer Engineering, University of Patras

[(a)]v.gountroumani@ece.upatras.gr, [(b)]groumpos@ece.upatras.gr

ABSTRACT

Wind energy is currently a fast-growing interdisciplinary field that encompasses many different branches of engineering and science. Modeling and controlling wind energy systems is a difficult and challenging problem. The basic structure of wind turbines and some wind control system methods are briefly reviewed. The need for using advanced theories from fuzzy and intelligent systems in studying wind energy systems is identified and justified. Fuzzy Cognitive Maps are used to model wind energy systems. Simulation studies are performed and obtained results are discussed. Many open problems in the areas of modeling and controlling wind energy systems are outlined.

Keywords: modeling, control, energy systems, wind generators, fuzzy cognitive maps

1. INTRODUCTION

The purpose of modern wind energy conversion systems (WECS) is to extract the aerodynamic power from the wind and convert it to electric power. Today the most wide spread version of WECS is the horizontal axis wind turbine (HAWT) with a 3 blade upwind rotor (Hau 2010; Tong 2010). Before the introduction of variable speed generators, the rotor speed on the HAWT was kept constant. This constraint limited the efficiency of the wind power capture. New wind turbines are able to operate more efficient over a wider range of wind speeds, which has lead to more sophisticated control strategies with the added degrees of freedom. Modern wind turbines are controlled by the pitch of the rotor blades, the electromagnetic torque of the generator and by the yaw of the nacelle. Traditionally wind turbines are placed on land or on solid foundations if placed in the water. This limits their deployment to locations of relatively shallow water because the construction costs of an underwater monopole are too expensive or technically impossible. Modeling and controlling such systems is extremely difficult but absolutely needed.

In this paper an overview of existing advanced modeling and control theories in analyzing and studying wind generators is presented. In Greece lately many wind farms have been installed on mountains. Wind energy production attracts interest as it encompasses many different branches of engineering and science. Standard and Adaptive techniques have been used for modeling and control wind generators. The strong points of these methods are reviewed, studied and presented. So, nowadays there are many methods to generate and control wind energy. However, the wind energy management is a challenging field. The need for development of wind energy will be modeled using Fuzzy Cognitive Maps. An introduction to basic theories of Fuzzy Cognitive Maps is presented. Especially the potential use of Fuzzy Cognitive Maps is investigated and future research directions are proposed.

2. WIND TURBINE THEORIES

A wind turbine (WT) consists of turbine tower, blades, rotor, generator, nacelle, shaft, drive or coupling device, converter and control system.

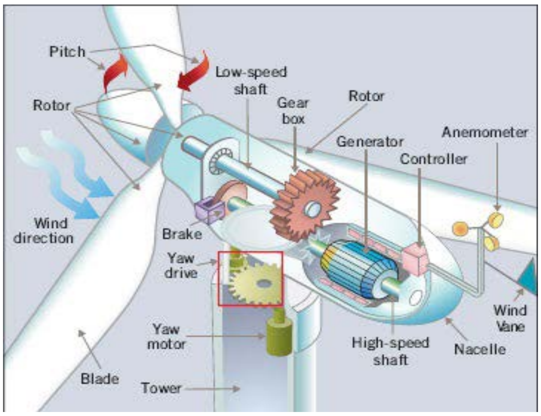


Figure 1: Wind Turbine Structure

The nacelle houses the generator, which is driven by the high-speed shaft. The high-speed shaft is in turn usually driven by a gear box, which steps up the rotational speed from the low-speed shaft. The low-speed shaft is connected to the rotor, which includes the airfoil-shaped blades. These blades capture the kinetic energy in the wind and transform it into the rotational kinetic energy of the wind turbine.

There are two main types of wind turbines: horizontal axis and vertical axis. Horizontal axis turbines, which are more common, have to point into the wind and their axis is horizontal. Because of the angle of their blades, they can collect the maximum amount of wind energy. Vertical axis turbines have axes that are vertically sticking out of the ground and blades that rotate around the axis. They don't need to point into the wind, which makes them more useful in places where the wind direction is unpredictable.

Some wind turbines are designed to operate at a constant speed, while others are built to rotate at variable speeds. The internal components of these two types of turbines are very different. In constant speed machines, the connection between the generator and grid do not allow for much variation in the blade rotation speed. Variable speed turbines use power converters that allow for a wider range in blade rotations. Power converters add to the cost of these machines, but variable speed wind turbines provide significant advantages to a wind farm and engineers continue to research ways to make these turbines more efficient.

The output power of wind turbines varies with wind speed, but is not proportional to it, as the energy that the wind contains increases with the cube of the wind speed. Variable speed wind turbines have four main regions of operation. A stopped turbine or a turbine that is just starting up is considered to be operating in Region 1 in which the wind speed is too low for the turbine to generate power. Region 2 is an operational mode in which it is desirable to capture as much power as possible from the wind and lies between the cut-in speed and rated speed. Here the generator operates at below rated power. In Region 3, in which the wind is sufficient for the turbine to reach its rated output power, the turbine must limit the captured wind power so that safe electrical and mechanical loads are not exceeded. Region 4 is the period of stronger winds, where the power in the wind is so great that it could be detrimental to the turbine, so the turbine shuts down.

3. CONTROL STRATEGIES

Above rated wind speed, the primary objective is to keep power output of the turbine and associated loads on the turbine structure within design limits. Classical techniques such as proportional, integral, and derivative (PID) control of blade pitch (Svensson and Ulen 1982) are typically used to limit power and speed on both the low-speed shaft and high-speed shaft for turbines operating in region 3. In addition, several model-based classical/optimal control design techniques have been used to design controllers to regulate generator speed in high wind speed conditions (Stol and Ballas 2001; Vihriala 2002). Below rated wind speed, the focus is on maximizing power capture. The loads on structure are, generally, small. In this region of operation (region 2), generator torque control (Fingersh and Carlin 1998) is usually used. In (Stol and Ballas 2002) disturbance accommodating control is used to limit power and speed in region 3. The reduction of mechanical loads on the tower and blades is another area of turbine control research (Wright and Balas 2004).

Furthermore, there are many aspects of wind turbine performance that can be improved with more advanced control development. Researchers have developed methods for using adaptive control to compensate for unknown or time-varying parameters in regions 2 and 3 (Bhowmik, Spée and Enslin 1999; Freeman and Balas 1999; Song, Dhinakaran and Bao 2000). A few researchers have also begun to investigate the addition of feedforward control to improve the disturbance rejection performance when the incoming wind profile deviates from that expected (Hand, Wright, Fingersh and Harris 2006). Most of these feedforward controllers use estimates of the disturbance or wind deviation. For instance, lidar sensors can provide quantities representing the wind speed and direction and various wind turbulence and shear parameters (Hand, Wright, Fingersh and Harris 2006). Advanced wind turbine controllers are discussed in (Laks, Pao and Wright 2009).

Other researchers have developed techniques in order to qualify output power and guarantee operation of the wind turbine. Their studies focus on: vector control, optimization control, power smoothing control and voltage control. Vector control is widely applied in the control of induction machines and several types of this control type are discussed in (Cárdenas and Pena 2004; Chowdhury and Chellapilla 2006). Optimization control of wind turbine includes several objectives, such as maximum power output, maximum power efficiency, minimum control input, minimum loss, etc. References (Mihet-Popa, Blaabjerg and Boldea 2004; Munteanu, Cutululis, Bratcu and Ceanga 2005) discuss optimization control methods for maximizing power extraction using algorithms, robust controllers, etc. Power fluctuation is one drawback of wind power which can influence power quality. In (Cárdenas, Peña, Asher and Clare 2004; Senjyu, Sakamoto, Urasaki, Funabashi, Fujita and Sekine 2006) control strategies pointing to power smoothing are presented. Voltage control of wind turbine or wind farm is not indispensable for itself, but also plays a great role in voltage stability of grid. In (Tapia, Tapia and Ostolaza 2004; Hatziargyriou, Karakatsanis and Lorentzou 2005) the issue of voltage control is discussed.

Modeling and control nonlinear complex systems, with new system theories, have always been fruitful challenges. Many approaches have been developed. Some of them had good success in applying them to wind energy while some others had some “problems”. However, a question as to how much wind energy should be produced on a given geographical region has not yet found a realistic and acceptable solution. Although FCMs have been used for wind modeling there still is the question of optimal and cost effective generation.

4. INTRODUCTION TO FUZZY COGNITIVE MAPS

Fuzzy cognitive map (FCM) is a soft computing technique, which is capable of dealing with complex systems. FCM is a promising modeling method for describing particular domains showing the concepts (variables) and the relationships between them (weights) while it encompasses advantageous features. FCM model represents the whole system by a signed directed graph with feedbacks, which indicate cause and effect among the concepts. It models a system as a collection of concepts and causal links between them. The concepts are represented by nodes in this graph and each concept represents a particular characteristic of the system. In the FCM model cause and effect relationships among these concepts is indicated by interconnected weighted links which have either positive or negative signs and different weights. Each link gets a weight Wij according to the strength of the causal relationship between the concepts Ci and Cj.

Some experts understand potential influences and interactions between concepts. So, the expert's knowledge is transformed into a dynamic weighted graph. Experts describe the existing relationship between the concepts as a degree of influence using a linguistic variable, such as "low", "medium", "high", etc. More specifically, the causal interrelationships among concepts are declared using the variable influence which is interpreted as a linguistic variable taking values in the universe of discourse [-1, 1]. A detailed description of the development of FCM model is given in (Stylios and Groumpos 2004).

The value of each concept at every simulation step is calculated by applying the following calculation rule (Groumpos and Stylios 2000):

$$A_i^t = f\Big(\sum_{\substack{j=1 \\ j \neq i}}^{N} A_j^{t-1} \cdot W_{ji} + A_i^{t-1}\Big) \qquad (1)$$

where A_i^{t-1} is the value of the concept Ci at iteration step t-1 and A_i^t is the value of the concept Ci at iteration step t.

Usually the f function is:

$$f(x) = \frac{1}{1+e^{-\lambda x}} \qquad (2)$$

which is the unipolar sigmoid function, where λ>0 determines the steepness of the continuous function f(x).

5. THE CONSTRUCTION OF A WIND GENERATOR SYSTEM USING FCM THEORIES

In this section a Fuzzy Cognitive Map will be constructed for a simple wind generator system. An expert proposed us a system with four inputs (C1, C2, C3, C4) and one output which is the development of wind energy (C5). So, the concepts are:

- C1: Energy demand
- C2: Fossil fuel reserves
- C3: Wind technologies / equipment / cost
- C4: Energy cost (from conventional sources)
- C5: Development of wind energy

Concepts stand in the interval [0, 1]. The closer to the 1 the value of the output concept is getting, the higher the need wind energy production is. An expert gave his opinion about the interaction between the concepts and informed us about how much "energy demand" (concept 1), "fossil fuel reserves" (concept 2), "wind technologies / equipment / cost" (concept 3) and "energy cost (from conventional sources only)" (concept 4) influence the production of wind energy (output: concept 5). So the weights between concepts are:

Table 1: Weights between Concepts

Weights					
	C1	C2	C3	C4	C5
C1	0	-0.25	0	+0.6	+0.3
C2	0	0	0	-0.55	-0.3
C3	0	0	0	0	-0.3
C4	0	0	+0.25	0	+0.3
C5	0	0	-0.15	-0.15	0

The weight matrix is presented below:

Table 2: Weight matrix

$$W=\begin{bmatrix} 0 & -0.25 & 0 & +0.6 & +0.3 \\ 0 & 0 & 0 & -0.55 & -0.3 \\ 0 & 0 & 0 & 0 & -0.3 \\ 0 & 0 & +0.25 & 0 & +0.3 \\ 0 & 0 & -0.15 & -0.15 & 0 \end{bmatrix}$$

The initial Fuzzy Cognitive Map with the first values of concepts will be as follows:

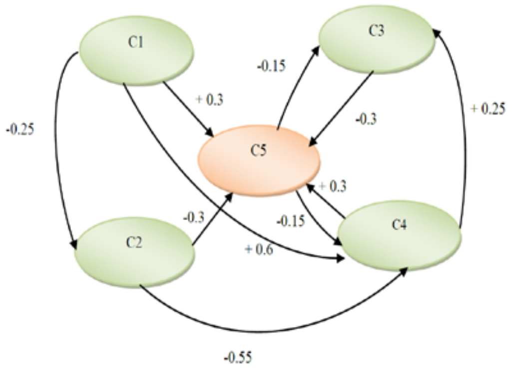


Figure 2: The FCM Model

The model shown in Figure 2 will be used in the next section in order to predict the wind energy production.

6. SIMULATION, RESULTS AND DISCUSSION

Three different scenarios will be simulated in order to decide how much wind energy production is necessary. As it was mentioned above the values of the concepts are between [0, 1].

1st Scenario: Suppose that the expert decided as initial values of the inputs the following which correspond to a situation where the need for wind energy production is low:

Table 3: Initial Values of Inputs (1st scenario)

Initial values		
C1	0.25/1	Very low
C2	0.5/1	Medium
C3	0.75/1	High
C4	0.4/1	Medium

The FCM simulation for the 1st scenario has the following results:

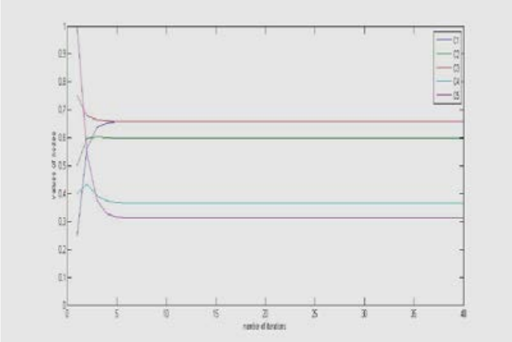


Figure 3: Subsequent Values of Concepts

where the output value is C5=0.3129. This value, according to our expert, is satisfactory enough if we take into account that the development of wind energy production should be low when the inputs (C1, C2, C3, C4) have these initial values.

2nd scenario: Suppose that the expert decided as initial values of the inputs the following which correspond to a situation where the need for wind energy production is medium:

Table 4: Initial Values of Inputs (2nd scenario)

Initial values		
C1	0.5/1	Medium
C2	0.45/1	Medium
C3	0.6/1	High
C4	0.55/1	Medium

The FCM simulation for the 2nd scenario has the following results:

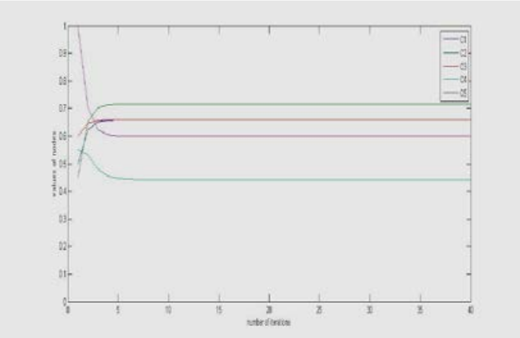


Figure 4: Subsequent Values of Concepts

where the output value is C5=0.5994. This value, according to our expert, is satisfactory enough if we take into account that the development of wind energy production should be medium when the inputs (C1, C2, C3, C4) have these initial values.

3rd scenario: Suppose that the expert decided as initial values of the inputs the following which correspond to a situation where the need for wind energy production is high:

Table 5: Initial Values of Inputs (3rd scenario)

Initial values		
C1	0.75/1	High
C2	0.25/1	Very low
C3	0.35/1	Low
C4	0.65/1	High

The FCM simulation for the 3rd scenario has the following results:

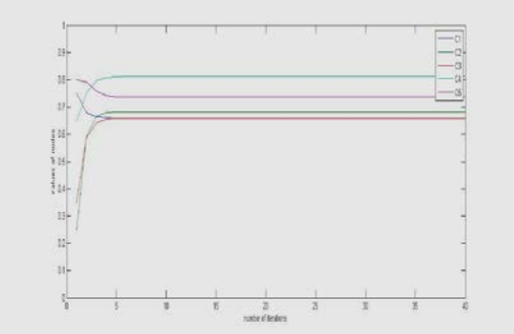


Figure 5: Subsequent Values of Concepts

where the output value is C5=0.7358. This value, according to our expert, is satisfactory enough if we take into account that the development of wind energy production should be high when the inputs (C1, C2, C3, C4) have these initial values.

7. CONCLUSIONS AND FUTURE RESEARCH

In this paper, we first reviewed the basic structure of wind turbines and then describe wind turbine control systems and control loops. We have seen that the generator torque and blade pitch control systems are very important in wind energy system design. Significant performance improvements are achievable with more advanced systems and control research. The new method of Fuzzy Cognitive Maps for modeling and controlling nonlinear systems is used for first time to model wind energy conversion systems. The proposed model is very simple in which only one expert is used. However the simulation studies show that the use of FCMs does provide a new promising methodology approach in modeling and controlling wind energy systems.

Some interesting challenging research topics include: 1) the validation of the proposed model 2) include additional concepts in modeling wind energy conversion systems especially for different geographical regions 3) use more than the one expert 4) conduct simulation studies using real data for various applications and 5) use learning algorithms to train the experts.

8. REFERENCES

Bhowmik, S., Spée, R., Enslin, J. 1999. Performance optimization for doubly-fed wind power generation systems. *IEEE Trans. Ind. Applicat.* vol. 35:949–958.

Cárdenas, R., Pena, R., 2004. Sensorless vector control of induction machines for variable-speed wind energy applications. *IEEE Trans. Energy Conversion* vol. 19:196-205.

Cárdenas, R., Peña, R., Asher, G., Clare, J., 2004. Power Smoothing in Wind Generation Systems Using a Sensorless Vector Controlled Induction Machine Driving a Flywheel. *IEEE Trans. Energy Conversion* vol. 19:206-216.

Chowdhury, H. B., Chellapilla, S., 2006. Double-fed induction generator control for variable speed wind power generation. *Electric Power Systems Research* vol. 76:786–800.

Fingersh, L., Carlin, P., 1998. Results from the NREL variable-speed test bed. *in Proc. 17th ASME Wind Energy Symp.*, pp .233–237. January 12-15, Reno, NV.

Freeman, J., Balas, M., 1999. An investigation of variable speed horizontal axis wind turbines using direct model-reference adaptive control. *in Proc. 18th ASME Wind Energy Symp.*, pp. 66–76. January 11-14, Reno, NV.

Groumpos, P.P., Stylios, D.C., 2000. Modeling supervisory control systems using fuzzy cognitive maps. *Chaos Solit Fract.*, 11(3), 329–336.

Hand, M. M., Wright, D. A., Fingersh, J. L., Harris, M., 2006. Advanced wind turbine controllers attenuate loads when upwind velocity measurements are inputs. *in Proc. 25th AIAA/ASME Wind Energy Symp.*, Reno, NV.

Hatziargyriou, D. N., Karakatsanis, S. T., Lorentzou, I.M., 2005. Voltage control settings to increase wind power based on probabilistic load flow. *Electrical Power and Energy Systems* vol. 27:656–661.

Hau, E., 2010. *Wind Turbines: Fundamentals, Technologies, Application, Economics.* Berlin, New York : Springer.

Laks, H. J., Pao, Y.L., Wright, A., 2009. Control of wind turbines: Past, present, and future. *in Proc. American Control Conf.* June 2009, St. Louis, MO.

Mihet-Popa, L., Blaabjerg, F., Boldea, I., 2004. Wind Turbine Generator Modeling and Simulation Where Rotational Speed is the Controlled Variable. *IEEE Trans. Industry applications* vol. 40:3-10.

Munteanu, I., Cutululis, A. N., Bratcu, I. A., Ceanga, E., 2005. Optimization of variable speed wind power systems based on a LQG approach. *Control Engineering Practice* vol. 13:903–912

Senjyu, T., Sakamoto, R., Urasaki, N., Funabashi, T., Fujita, H., Sekine, H., 2006. Output Power Leveling of Wind Turbine Generator for All Operating Regions by Pitch Angle Control. *IEEE Trans. Energy Conversion* vol. 21:467- 475.

Song, Y., Dhinakaran, B., Bao, X., 2000. Variable speed control of wind turbines using nonlinear and adaptive algorithms. *J. Wind Eng. Ind. Aerodyn.* vol. 85:293–308.

Stol, K., Ballas, M., 2001. Full-State Feedback Control of a Variable-Speed Wind Turbine: A Comparison of Periodic and Constant Gains. *Journal of Solar Energy Engineering* vol 123:319-326.

Stol, K., Ballas, M., 2002. Periodic disturbance accommodating control for speed regulation of wind turbines. *in Proc. 21st ASME Wind Energy Symp.*, pp. 310–320. January 14-17, Reno, NV.

Stylios, D. C., Groumpos, P. P., 2004. Modeling complex systems using fuzzy cognitive maps. *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans*, 34, 155–162.

Svensson, J., Ulen, E., 1982. The control system of WTS-3 instrumentation and testing. *in Proc. 4th Int. Symp. Wind Energy Systems*, pp. 195–215. September 21-24, Stockholm, Sweden.

Tapia, A., Tapia, G., Ostolaza X. J., 2004. Reactive power control of wind farms for voltage control applications. *Renewable Energy* vol. 29:377– 392.

Tong, W., 2010. *Wind Power Generation and Wind Turbine Design.* USA, Canada, Mexico:WIT Press.

Vihriala, H., 2002. Control of variable speed wind turbines. Thesis (PhD). Tampere University of Technology.

Wright, A., Balas, M., 2004. Design of controls to attenuate loads in the Controls Advanced Research Turbine. *J. Solar Energy Eng.* vol. 126:1083–1091.

A NEW GENERIC MODEL FOR GREENHOUSES USING FUZZY COGNITIVE MAPS

Vasiliki K. Bouga [(a)], Peter P. Groumpos[(b)]

[(a)] University of Patras, Department of Electrical and Computer Engineering, Patras 26500
[(b)] University of Patras, Department of Electrical and Computer Engineering, Patras 26500

[(a)]v.k.bouga@ece.upatras.gr , [(b)]groumpos@ece.upatras.gr

ABSTRACT

Greenhouses are protected cultivation areas which are designed to control their micro-climate in order to obtain higher crop quality and increase the economic benefit of the producer. During the last two decades, a large effort was devoted to develop adequate greenhouse climate and crop models in order to simulate, control and manage the whole procedure. As the complexity and uncertainty of such systems increases, system theoretical methods become more crucial. One new theoretical approach in modeling dynamic complex systems is Fuzzy Cognitive Maps. FCMs are a symbolic representation for the description and modeling of a system. This paper is using for first time Fuzzy Cognitive Maps to model greenhouse environment so as to control all these parameters that affect the whole production in quality and quantity too. A generic model is developed and it can be modified depending on the application. Simulation studies, expected results and future research directions are presented.

Keywords: greenhouses, photosynthesis, intelligent systems, fuzzy cognitive maps

1. INTRODUCTION

Greenhouses provide a suitable environment for the intensive production of various crops. They are designed to control the micro-climate of the greenhouse in order to obtain higher crop quality and increase the economic benefit of the producer even when the environmental conditions do not favor the growth of some plants. Many different parameters of the climate inside a greenhouse have to be controlled, the most important of which are, generally, the temperature and the composition of the air.

During the last two decades, a significant effort was devoted to develop adequate greenhouse climate and crop models in order to simulate, control and manage the whole procedure. The scientists have focused on the optimal designing of greenhouses and on the better possible control of their environment, too. They have tried to model the conditions of the greenhouse environment so as they are very close to the real world and in this way they have the opportunity to best simulate it and make better future decisions.

Today's complex systems of any interdisciplinary nature can hardly be analyzed and/or modeled without comprehensive usage of system theoretic approach. The complexity and uncertainty of the nature of modern systems, make systems analysis harder and it is needed to use existing information and expert knowledge so as to control modeling simulation. As the complexity of systems increases, system theoretical methods become more crucial. One new theoretical approach in modeling dynamic complex systems is Fuzzy Cognitive Maps.

FCMs are a symbolic representation for the description and modeling of a complex system. They consist of concepts, that illustrate different aspects in the behavior of the system and these concepts interact with each other showing the dynamics of the system. Experts are used to show how the concepts affect each other and the output, too. This paper is using for first time Fuzzy Cognitive Maps to model greenhouse environment so as to control all the parameters that affect the whole production in quality and quantity too. The parameters which have been taken into consideration are the light intensity, the air temperature, the relative humidity, the air concentration in CO_2 as well as the air flow and the artificial heat. The expert who has been used so as we are able to construct the FCM model, has indicated photosynthesis of the plants as the output of the system.

A generic model is developed and it can use some of the climate variables inside the greenhouse, or all of them, depending on the application. So, the number of concepts and the number of experts which can be used in the proposed new model, can be varied in order to analyze and study different greenhouse systems. Simulation studies and expected results will be presented at the conference. Future research directions will also be outlined.

In section 2 a review of the ways that scientists have used to model a greenhouse microclimate and the most important control methods to control it are presented. In section 3 an introduction to the basic theories of Fuzzy Cognitive Maps is given while in section 4 the proposed decision making support system in greenhouses is shown. Finally, in sections 5 and 6 simulations, results and some conclusions about future work are given, too.

2. MODELING GREENHOUSE MICROCLIMATE

During the last decades many scientists have given importance to the modeling of greenhouse microclimate. However, most of them have focused on optimizing the design for a specific location, or considered only a single design parameter (Baptista 2007; Bot 1983; De Halleux, Nijskens and Deltour 1991; De Zwart 1996). An effort to model greenhouse environment in order to be implemented in different greenhouse constructions and in different climate conditions was made by Fitz-Rodrı´guez (Fitz-Rodrı´guez, Kubota, Giacomelli, Tignor, Wilson and McMahon 2010) but only for educational purposes. B.H.E Vontour et al (Vanthoor, Stanghellini, Van Henten and De Visser 2011) have directed to the generalization of greenhouse modeling. By building on the work of Bot (Bot 1983), and De Zwart (De Zwart 1996), in their study a more generic greenhouse model was developed and validated for a wide range of greenhouse designs and climates. The following climates were selected to validate the model: a temperate marine climate (northwest part of The Netherlands); a Mediterranean climate, (Sicily, Italy); and a semi-arid climate (Arizona and Texas, USA). The authors managed to predict with a relatively good precision the greenhouse climate in most cases. Because of the non linearity of the environment of a greenhouse, Neural Networks have also been used in modeling its microclimate (Ferreira, Faria and Ruano 2002). Furthermore, some scientists used logic control (On-Off) while others used optimal control (Pohlheim and Heißner 1997).Some other kinds of control which have been applied in order to simulate and control the climate conditions inside a greenhouse are the adaptive control (Arvantis, Paraskevopoulos and Vernados 2000), the intelligent control (Lafont and Balmat 2002; Lafont and Balmat 2004), the non-linear control (Pasgianos, Arvanitis, Polycarpou and Sigrimis 2003), and also the robust control (Bennis, Duplaix, Enea, Haloua and Youlal 2005). The controls mentioned above had their advantages and disadvantages with respect to the kinds of the greenhouses that they could be used, their flexibility and the outgoing results. Finally, it is worth noting that many scientists have used fuzzy control so as to model and control the climate inside a greenhouse (Castaneda-Miranda, Ventura-Ramos, Peniche-Vera and Herrera-Ruiz 2006).

3. INTRODUCTION TO FUZZY COGNITIVE MAPS

Fuzzy Cognitive Maps (FCMs) have come from the combination of the ideas and methods of both fuzzy logic and Neural Networks (Kosko 1986). They have been used in modeling complex systems (Groumpos and Stylios 2000; Stylios and Groumpos 2004). FCMs consist of concept nodes and weighted arcs, which are graphically illustrated as a signed weighted graph with feedback. Signed weighed arcs, connecting the concept nodes, represent the causal relationship that exists among concepts. In general, concepts of a FCM, represent key-factors and characteristics of the modeled complex system and stand for: events, goals, inputs, outputs, states, variables and trends of the complex system been modeled. This graphic display shows clearly which concepts influences with other concepts and what this degree of influence is.

A Fuzzy Cognitive Map is a graph shows the degree of causal relationship among concepts of the map while the knowledge expressions and the causal relationships are expressed by fuzzy weights. Existing knowledge on the behavior of the system is stored in the structure of nodes and interconnections of the map. Relationships between concepts have three possible types; a) either express positive causality between two concepts (Wij > 0) b) negative causality (Wij < 0) and c) no relationship (Wij = 0). The value of Wij indicates how strongly concept Ci influences concept Cj. The sign of Wij indicates whether the relationship between concepts Ci and Cj is direct or inverse. The direction of causality indicates whether concept Ci causes concept Cj, or vice versa. These parameters have to be considered when a value is assigned to weight Wij . Concepts stand in the interval [0,1]. Causality between concepts allows degrees of causality and not the usual binary logic, so the weights of the interconnections can range in the interval [-1,1].

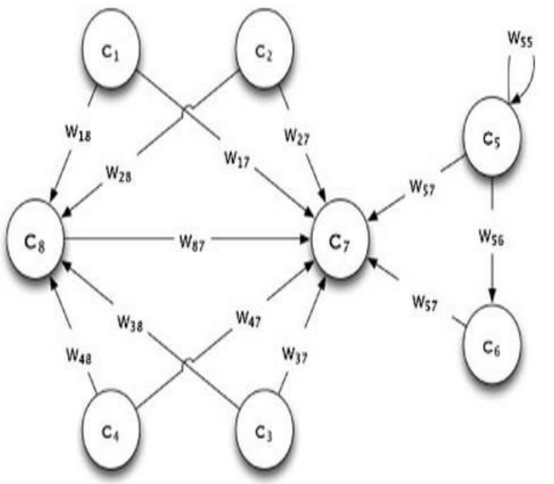


Figure 1. A Fuzzy Cognitive Map

The inclusion of the previous value of each concept in the calculation rule, results in smoother variation on the values of concepts after each recalculation of their value. The value Ai for each concept Ci is calculated by the following rule:

$$A_i^t = f\left(\sum_{\substack{j=1\\ j\neq i}}^{N} A_j^{t-1}\cdot W_{ji} + A_i^{t-1}\right) \qquad (1)$$

The value A_i^t is the value of concept Ci at time t , A_i^{t-1} is the value of concept Ci at time t −1, A_j^{t-1} is the value of concept C_j at time t −1, and the weight W_{ji} of the interconnection from concept C_j to concept Ci. The function f is a threshold function and to squash the result in the interval [0,1], two kinds of threshold functions are used in the Fuzzy Cognitive Map framework, the unipolar sigmoid function, where λ> 0 determines the steepness of the continuous function f :

$$f(x) = \frac{1}{1+e^{-\lambda x}} \qquad (2)$$

4. A DECISION MAKING SUPPORT SYSTEM IN GREENHOUSES

The method described above will be used in order to model greenhouse microclimate. The current Fuzzy Cognitive Map consists of seven concepts. Concept 7 is the decision concept (output), which will show the photosynthesis rate. Specifically these concepts are the following:

C1: Light Intensity
C2: Artificial Heat
C3: Air flow
C4: Air temperature
C5: Air humidity
C6: CO_2
C7: Photosynthesis

As it has been mentioned above, Photosynthesis rate is a very important indicator of the plant development. When the value of the output concept is getting closer to 1, the photosynthesis rate is higher. The higher the photosynthesis, the better the operation of the greenhouse.

The expert of the system has indicated the relationships between concepts and the following table was constructed:

RELATIONSHIPS BETWEEN CONCEPTS							
	C1	C2	C3	C4	C5	C6	C7
C1	0	-0.4	0	+0.5	-0.25	0	+0.7
C2	0	0	0	+0.6	0	0	0
C3	0	0	0	-0.25	-0.4	+0.3	0
C4	0	-0.55	0	0	+0.7	0	-0.3 (or +0.5)
C5	0	0	0	+0.45	+0.4	0	+0.3
C6	0	0	-0.35	0	+0.25	0	+0.65
C7	0	0	0	0	0	-0.45	0

Table 1. Values of the relationships between concepts

The following table shows the matrix of the weights between nodes:

$$W = \begin{bmatrix} 0 & -0.4 & 0 & +0.5 & -0.25 & 0 & +0.7 \\ 0 & 0 & 0 & +0.6 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.25 & -0.4 & +0.3 & 0 \\ 0 & -0.55 & 0 & 0 & +0.7 & 0 & -0.3(or+0.5) \\ 0 & 0 & 0 & +0.45 & +0.4 & 0 & +0.3 \\ 0 & 0 & -0.35 & 0 & +0.25 & 0 & +0.65 \\ 0 & 0 & 0 & 0 & 0 & -0.45 & 0 \end{bmatrix}$$

Table 2. Matrix of weights between concepts

The initial Fuzzy Cognitive Map with the first values of concepts and if we take into account the expert's knowledge of the interaction of the concepts will be as follows:

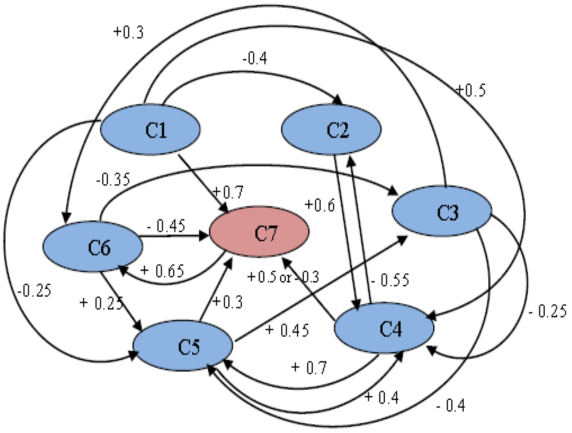


Figure 2. The initial Fuzzy Cognitive Map

5. SIMULATIONS AND RESULTS

Three different cases of the conditions that exist inside the greenhouse were simulated in order to note the rate of plant photosynthesis.

1st case:

We suppose that the climate conditions inside the greenhouse are the above:

VALUES OF NODES (1^{ST} CASE)	
C1	0.2/1 → Very Low
C2	0.3/1 → Low
C3	0.2/1 → Very Low
C4	0.4/1 → Medium
C5	0.2/1 → Very Low
C6	0.25/1 → Very Low

Table 3. Values of initial nodes for the first case

Simulating the Fuzzy Cognitive Map which has been constructed by our expert, we extracted the results below with the value of output concept to be C7=0.4.

This value, according to our expert, is satisfactory enough if we take into account that the initial values of concepts correspond to bad conditions and the low rate of photosynthesis was totally expected. For example, the expert told us that because of the low light intensity and the lack of CO_2, the photosynthesis rate would be very low and so it was.

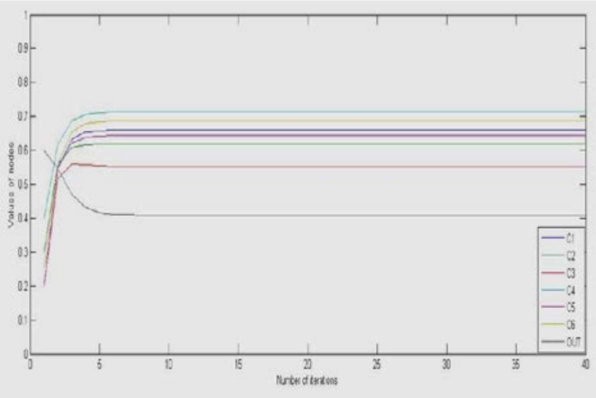


Figure 3. Subsequent values of concepts till convergence for the first case.

2nd case:

We suppose that the climate conditions inside the greenhouse are the above:

VALUES OF NODES (2nd CASE)	
C1	0.6/1 → High
C2	0.3/1 → Low
C3	0.5/1 → Medium
C4	0.6/1 → High
C5	0.45/1 → Medium
C6	0.55/1 → Medium

Table 4. Values of initial nodes for the second case

Simulating the Fuzzy Cognitive Map which has been constructed by our expert, we extracted the results below with the value of output concept to be C7=0.78.

This value, according to our expert ,is very good as it corresponds to a high rate of photosynthesis and this was expected because of the good conditions inside the greenhouse. So, all the agents that affect photosynthesis inside the greenhouse had the appropriate values to get a high rate of it.

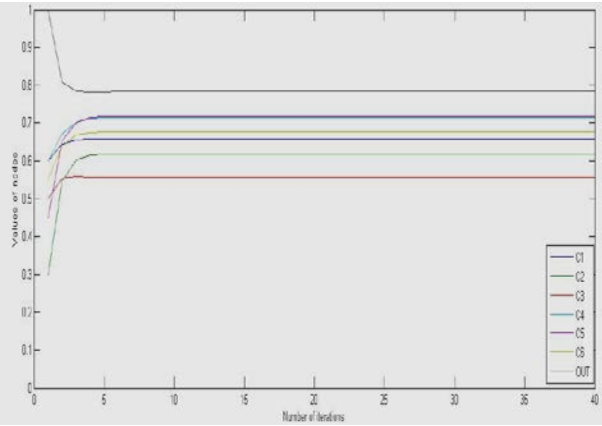


Figure 4. Subsequent values of concepts till convergence for the second case

3rd case:

We suppose that the climate conditions inside the greenhouse are the above:

VALUES OF NODES (3rd CASE)	
C1	0.45/1 → Medium
C2	0.2/1 → Low
C3	0.2/1 → Low
C4	0.55/1 → Medium
C5	0.35/1 → Low
C6	0.4/1 → Medium

Table 5. Values of initial nodes for the third case

After having simulated the conditions above, we took the results below and the value of output concept is C7=0.59.

The value of the output concept, according to our expert is reasonable because in this case the conditions inside the greenhouse are neither good nor bad and the rate of photosynthesis was expected to be medium:

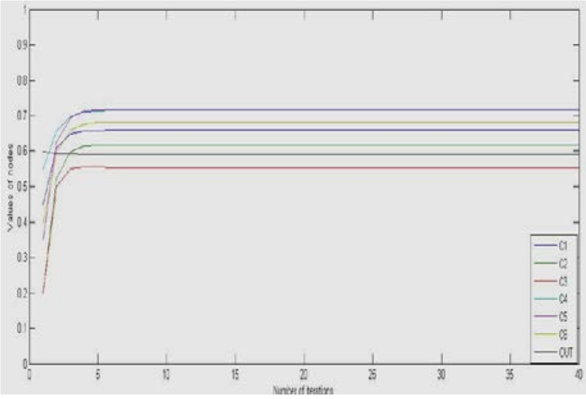


Figure 5. Subsequent values of concepts till convergence for the third case

As it was mentioned in the paragraph 3 the values of all the concepts, including the output concept, are changing and their values are calculated by the rule (equation (1)). After some calculations the values of the concepts do not change anymore and we have the equilibrium point.

6. CONCLUSIONS

In this paper, advanced techniques have been used in greenhouse modeling and the results show that these techniques had satisfactory results. For first time, Fuzzy Cognitive maps which were used to predict the photosynthesis rate of the plants inside a greenhouse gave us simple models while the simulations were understandable, flexible and easy to use. A new way for studying and analyzing the good operation of a greenhouse was presented, too.

In order to be more accurate in the future, we need to use more experts who will give us a better approach of the greenhouse microclimate model and who will probably propose new concepts which have to be inserted in the Fuzzy Cognitive Map. Moreover it is needed to use learning algorithms in order to study the process of the greenhouse microclimate and to extract

more accurate results. In this way the possibility to control better the different technical control parts will be given and we will have the chance to achieve the better possible climate conditions inside a greenhouse.
All these challenging problems will be the subject of our future research work.

REFERENCES

Arvantis, K.G., Paraskevopoulos P.N, Vernados A.A ,2000. Multirate adaptative temperature control of greenhouses. *Computer Electronics Agriculture*, 26, 303-320.

Baptista, F. J.,2007. *Modelling the climate in unheated tomato greenhouses and predicting Botrytis cinerea infection*. Thesis (PhD). E ´vora University.

Bennis, N., Duplaix J., Enea G., Haloua M. and Youlal H., 2005. An advanced control of greenhouse climate. *Proceedings of the 33rd International Symposium Actual Tasks on Agricultural Engineering*, pp. 265-277. Feb. 21-25, Croatia.

Bot, G.P.A., 1983. *Greenhouse climate: from physical processes to a dynamic model*. Thesis (PhD). Wageningen University.

Castaneda-Miranda, R., Ventura-Ramos E.Jr., Peniche-Vera R.R and Herrera-Ruiz, G, 2006. Fuzzy greenhouse climate control system based on a field programmable gate array. *Biosystem Engineering*, 94: 165-177

De Halleux, D., Nijskens, J., & Deltour, J., 1991. Adjustment and validation of a greenhouse climate dynamic model. *Bulletin des Recherches Agronomiques de Gembloux*. 26(4), 429-453.

De Zwart, H. F.,1996. *Analyzing energy-saving options in greenhouse cultivation using a simulation model.* Thesis (PhD). Wageningen University.

Ferreira P.M., Faria E.A., Ruano A.E., 2002. Neural network models in greenhouse air temperature prediction. *Neurocomputing*, Vol 43: 51–75.

Fitz-Rodrı´guez, E., Kubota, C., Giacomelli, G. A., Tignor, M. E., Wilson, S. B., & McMahon, M., 2010. Dynamic modeling and simulation of greenhouse environments under several scenarios: a web-based application. *Computers and Electronics in Agriculture*. 70(1), 105-116.

Groumpos P.P, Stylios C.D., 2000. Modeling supervisory control systems using fuzzy cognitive maps. *Chaos Solit Fract*. 11(3), 329–336

Kosko B., 1986. Fuzzy Cognitive Maps, *Int. Journal of Man-Machine Studies*, Vol. 24: 65-75.

Lafont, F. and Balmat J.F., 2002. Optimized fuzzy control of a greenhouse. *Fuzzy Sets Syst*ems, 128: 47-59.

Lafont, F. and Balmat J.F., 2004. Fuzzy logic to the identification and the command of the multidimensional systems. Int. *J. Comput. Cognition*, Vol 2: 21-47.

Pasgianos, G. D., Arvanitis, K. G., Polycarpou, P. and Sigrimis, N. 2003. A nonlinear feedback technique for greenhouse environmental control. *Computers and Electronics in Agriculture*, 40: 153 – 177.

Pohlheim, H. and Heißner, A., 1997. Optimal Control of Greenhouse Climate using a Short Time Greenhouse Climate Model and Evolutionary Algorithms. *IFAC/ISHS Workshop on "Mathematical and Control Applications in Agriculture and Horticulture"* Hannover, 113-118.

Stylios C.D, Groumpos P.P., 2004. Modeling complex systems using fuzzy cognitive maps. *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans*, 34, 155–162.

Vanthoor B.H.E, Stanghellini C., Van Henten E.J., De Visser P.H.B. 2011. A methodology for model-based greenhouse design Part 1, *Biosystems Engineering*, Vol 110: 363–377.

QUANTITATIVE SIMULATION OF COMPREHENSIVE SUSTAINABILITY MODELS AS GAME BASED EXPERIENCE FOR EDUCATION IN DECISION MAKING

Agostino G.Bruzzone[1], Marina Massei[1], Simonluca Poggi[2], Margherita Dallorto[2], Giulio Franzinetti[3], Andrea Barbarino[4]

[1] DIME University of Genoa, Italy
Email {agostino, massei}@itim.unige.it – Url www.itim.unige.it

[2] Simulation Team
Email {simonluca.poggi, margherita.dallorto}@simulationteam.com – Url www.simulationteam.com

[3] LioTech Ltd, United Kingdom
Email giulio.franzinetti@liotech.eu – Url www.liotech.co.uk

[4] DENERG Energy Department, Turin Polytechnic, Italy
Email andrea.barbarino@polito.it – Url www.polito.it/dipartimenti/denerg

ABSTRACT

Sustainability knowledge and skills are highly regarded competencies by many companies and organizations. Sustainability can be seen as an additional requirement that business/system must satisfy. The main contribution of this paper is to propose a quantitative method for modeling and integrating sustainability issues in the analysis of business alternatives in building a coal power plant in a port area.

The authors have developed a sustainability model implemented in a simulator which has been used as a tool in a role play game experience; the paper describe the simulator as well as its experimentation within the Genoa University MIPET Master Program for addressing innovation in Industrial Plant Engineering and Technologies.

Keywords: Sustainability, Power Plant Projects, Economic and Environmental Impact Model, Play-Based Experience, Multi-Party Negotiation, Simulation in Negotiation Education.

1. INTRODUCTION

According to the Brundtland Report, a "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1]. Guaranteeing a sustainable development of our society is one of the emerging problems that humans have to face. This challenge requires a multidisciplinary approach in which researchers, professionals and politicians with different backgrounds, and often belonging to different group of interests, combine their efforts.

Addressing sustainability is becoming a crucial capability in companies or governmental organization. There is a need to define competencies that are useful to train future professionals in this area and to develop a strong community of practice. Individuals leading sustainability in organizations or firms must be able to measure the impact of sustainable initiatives, properly master the dynamics of offsets and compensations between the interests of the various stakeholders.

Universities are embedding sustainability into existing engineering courses since the demand of related professionals and experts is expected to rise in the near future. In the framework of the well-established Master level course in Industrial Plants (MIPET) held by University of Genova it has been decided to complete the sustainability notions with practical activities by mean of a simulated environment.

Focus of the paper is to describe the sustainability model behind the simulator MOSES (MOdelling Sustainable Environment through Simulation, Lio Tech Ltd) which has been used as a tool in a game based experience during a MIPET class. The simulator has been used by competitive groups of students to assess in a quantitative way the sustainability of a virtual scenario of port area housing a power plant, a military base and industrial facilities close to a populated area. In particular, during the game based experience, the simulators allowed to quickly evaluate different scenario configurations and to quantitatively assess mitigation measures of the impacts. A section will be devoted to the description of the game based experience and the simulation of negotiation process of tradeoffs between stakeholders.

2. A SUSTAINABILITY MODEL

Sustainability: a SoS approach

It is important to notice that sustainability is studied and managed over many levels of time and space and in many contexts of environmental, social and economic frames of reference. For example it is possible to examine sustainable development of the whole globe, a country or a region. As the scale becomes smaller, it is more difficult to address sustainable development [2]: the above mentioned area which has been modeled in MOSES, for instance, cannot be examined without taking into consideration the interactions with the region and the country it belongs, for instance the national regulations and policies.

Because of the nature of its impacts, sustainability interfaces with economics through the social and environmental consequences. Modeling sustainability implies the ability to model sustainability economics which involves ecological economics where social aspects (cultural, health-related) and monetary/financial aspects are integrated [3][4][5][6][7]; these context are obviously very good examples of complex systems [8][9][35][36]

Some sustainability models available in literature consider as inputs a homogeneous set of quantities drawn from a single aspect of sustainability, such as environmental system or the social one [2]; indeed there examples were multiple aspects were considered combining for instance environmental and economics impacts with operational issues [23]. MOSES is moving forward to embed a comprehensive approach able to qualify each scenario with several indexes (outputs) at a time using a scalable architecture [29] [34].

The authors reckon that a valuable approach to model sustainability combines necessarily the human and the ecological system. The human system consists of the economy related to such aspects as health, work, economy, education and policies while the ecological system consists of air, land and water [2] [28]. This is a system of systems (SoS) approach, as shown in Figure 1.

Among the indicators, belonging to different systems as in Figure 2, MOSES is able to calculate classical sustainability scalars, like the carbon footprint, which allows eventually comparisons with other models. The concept of ecological footprint, introduced in [24] and developed in [25], is a valuable indicator of ecological sustainability of a system or an activity. Taking into account resources that a population/activity exploits and the main wastes generated, it is possible to convert them into a corresponding land size needed for the assimilation of the above mentioned quantities. In MOSES simulator, as suggested in literature [26], [27], the carbon footprint (also referred in this paper as [CFP]) has been modeled considering the assimilation of the equivalent CO_2.

The indicators/variables that have been taken into consideration for this model are listed in Table 1.

Our model assumes that an established port area is subject to some development proposals, with concurrent actions to be performed on its main activities. In order to set the simulation in a realistic environment the model has been tailored on a city populated by about 95K inhabitants, facing the Tyrrhenian sea, and with one commercial and military port, hosting the arsenal of a Navy. The urban area extends over 52 km^2 and includes a power plant, equipped with 2 combined cycle gas turbines and a coal-fired unit, for a total output power of about 1.3 GWe.

Table 1: List of all the modeled variables in MOSES simulator and their system aggregation.

Variables	Units	**System of Systems**					
		Human System			**Environment System**		
		Economic System	**Resource Consumption System**	**Health System**	**Land System**	**Air System**	**Water System**
[POWER PLANT]	MW	X	X				
[PLANT AREA]	m^2				X		
[BASE AREA]	m^2				X		
[INDUSTRY AREA]	m^2				X		
[TOWN AREA]	m^2	X		X	X		
[GRASS AREA]	m^2			X	X	X	
[FREE AREA]	m^2			X	X	X	
[SURFACE]	m^2	X		X	X	X	
[PLANT CO_2 EMISSION]	Mkg/y		X	X		X	
[PLANT WORKERS]	people	X					
[BASE WORKERS]	people	X					
[INDUSTRY WORKERS]	people	X					
[TOURISM WORKERS]	people	X					
[OTHER WORKERS]	people	X					
[UNEMPLOYED]	people	X					
[TOT WORKERS]	people	X					
[SALARY]	€	X					
[POPULATION]	people	X		X	X		
[COAST QUALITY]	#			X			X
[GREEN AREAS]	m^2			X	X	X	
[CFP]	m^2			X		X	
[QUALITY AIR]	#			X		X	
[PLANT SALARY]	€	X					
[BASE SALARY]	€	X					
[INDUSTRY SALARY]	€	X					
[TOURISM SALARY]	€	X					
[OTHER SALARY]	€	X					
[UNEMP SALARY]	€	X					
[DISEASES]	€	X		X	X	X	X
[DEATHS]	#/y			X	X	X	X
[PLANT PROFITS]	€	X					
[HAPPINESS]	#	X		X	X	X	X

Environmental impact, and thus sustainability issues, for a plant so close to the residential areas are a major concern for both the electrical utility and the population, due to the emissions and the possible degradation of air quality.

The military base, on the other hand, is less impacting from the environmental point of view, but extends of a big share of the available territory. Both realities have a strong impact on the occupation of the inhabitants and on the local economic framework.

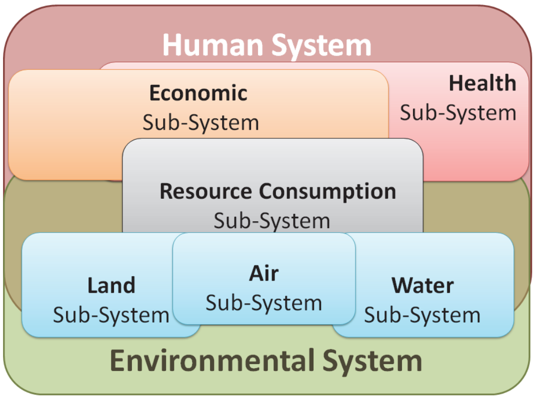


Figure 1: SoS Architecture

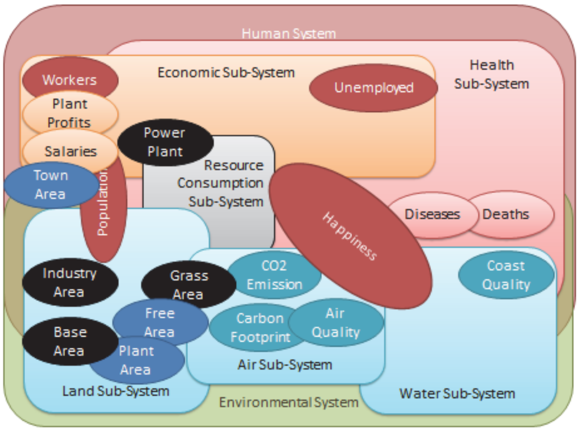
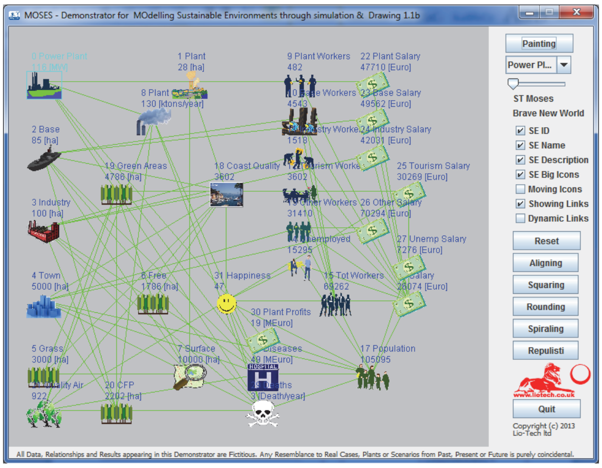


Figure 2: SoS Architecture with MOSES variables grouping



☑ SE ID
☑ SE Name
☑ SE Description
☑ SE Big Icons
☐ Moving Icons
☑ Showing Links
☐ Dynamic Links

All Data, Relationships and Results appearing in this Demonstrator are Fictitious. Any Resemblance to Real Cases, Plants or Scenarios from Past, Present or Future is purely coincidental.

Figure 3: MOSES main interface showing variables and functional dependencies (green links)

Model variables: dependency nodes and links

Even in the context of a simple model, due to the complexity of the phenomena involved in this real-world description the modeling requires two orders of discretionary choices:

- The state variables,
- The functional dependencies liking them.

The choice of the variables should be done according to the following principles [11] :

- Pertinence principles: indicators should be pertinent to the studied object;
- Representative principle: the indicator system should be representative of the economic development, resource consumption and environmental pollution;
- Availability principle: the data for the indicators should be available from statistics;
- Comparative principle: the selected indicators should be comparative in temporal, spatial and data source aspects.

The functional links constituting the mathematical skeleton of the model derive from literature and the field experience of the authors and are shown in Figure 3. Generally highly non-linear, they often represent the effect of the other state variables with exponential laws modifying a hypothetical equilibrium state.

The model has been conceived with four major independent variables that are presented in Table 2. The value of these indicators is under control of the user; the overall resulting model results in a non linear complex function starting from fourth-dimensional space of input and addressing a twentyseventh-dimensional space representing the consequent output configuration.

Indicators	Direct functional dependencies
[POWER PLANT] User input. This independent variable expresses the power of the coal power plant in MW. It varies from 80 to 1000 MW.	[PLANT], [PLANT CO$_2$], [PLANT WORKERS], [PLANT SALARY], [DISEASES], [DEATHS], [PLANT PROFIT]
[BASE] User input. This independent variable is the land in m^2 occupied by the power plant.	[SURFACE], [INDUSTRY WORKERS], [COAST QUALITY], [CFP], [BASE SALARY], [DISEASES], [DEATHS].
[INDUSTRY] User input. This independent variable is the land in m^2 occupied by the industry.	[SURFACE], [INDUSTRY WORKERS], [COAST QUALITY], [CFP], [INDUSTRY SALARY], [DISEASES], [DEATHS].

[GRASS] User input This independent variable is the land in m^2 occupied by the industry.	[SURFACE], [OTHER WORKERS], [POPULATION], [COAST QUALITY], [CFP], [TOURISM SALARY], [DISEASES], [DEATHS]

Table 2: Independent variables in MOSES and their links.

The simulator is also equipped with a mapping tool which visualizes the use of the soil in terms of intended use, superimposed to a satellite picture (Figure 4). Figure 5 shows an example of such features which are of help to the user to get the quantitative overview of the area subdivision; in the future it could be interesting to introduce this approach within innovative crowdsourcing approaches using web technologies [13][14]. The total area is divided into colored areas according to the intended use of the surface: light blue for the power plant, red for the military base, black is the available surface, blue is the sea, yellow the industry and green is the maximum available green area (grass) needed to compensate the emissions of the power plant, if available.

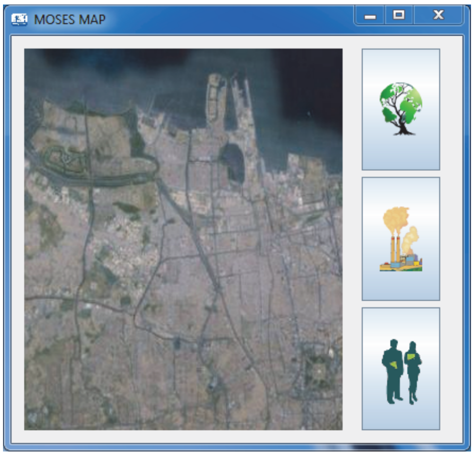


Figure 4: Satellite image of the MOSES's modeled area

3. CASE STUDY: GAME BASED EXPERIENCES ON SUSTAINABILITY

The MIPET program

The Master in Industrial Plant Engineering and Technologies (MIPET) is a one-year post-degree specialization program held by the University of Genova. This course aims at forming the new generation of top technical professionals in process engineering, industrial plant engineering, power generation and energy industry. The master program is directed by the faculty of engineering in strong cooperation with leading companies operating in several industrial sectors, setting this initiative in the international scenario.

In parallel to an intensive technical skill development program, this master also offers students a grounding in modeling and simulation for industrial processes and decision making. This course helps the students to cultivate their attitudes to critical thinking and effective management of all phases of an engineering project (offering, engineering, purchasing, construction and commissioning), also giving them an complete overview of complex activities.

Students begin their MIPET program taking the Operative Modules, followed by Thematic Modules on specific plant sectors (for example "power" and "steels are two tracks) and finally completing their knowledge on the field with an internship in one of the partner companies company, gaining at the same time a valuable experience which can be readily valorized in their curricula.

Operative modules integrated within the master program are dedicated to project works in which individual student and/or teams of student dynamically interact in a competitive/cooperative framework with experts. In particular, the operative module "R&D Projects/Innovative Technologies, Techniques and Methodologies for Industrial Plants" addresses the research and development connected to the industrial plants, in terms of competitiveness and risk analysis.

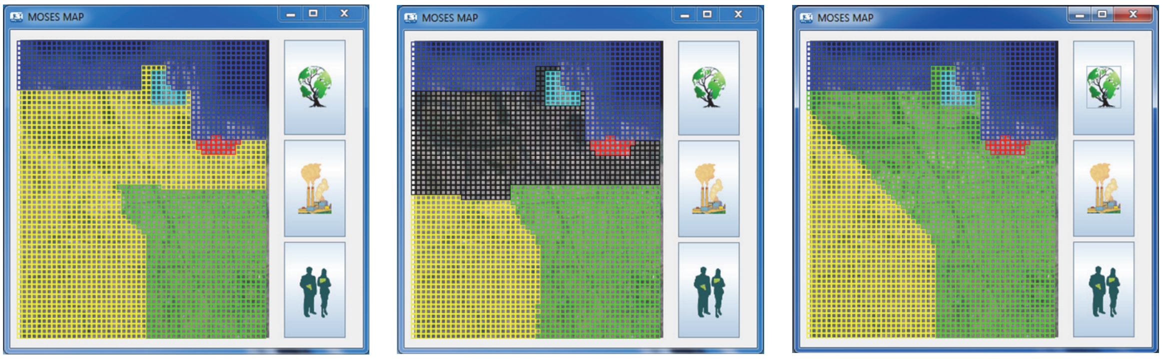


Figure 5: MOSES mapping tool in different scenario, with different inputs

This module includes a case study in which students learn and apply innovative techniques for sustainability in the industrial framework by means of simulation, using the MOSES environment. This case study requires the synergic use of notions of engineering technologies, strategies and practices to efficiently optimize energy consumption, reduce land occupation and mitigate the environmental impact [15][16]. It is organized as a game based experience, thus allowing an hands-on activity which leads to fast learning and effective assimilation by the students of the contents.

Case study on Sustainability and game based experience

In the following, the aforementioned game based experience is introduced, with particular emphasis on methodology.

The approach pursued in this paper, aligned with similar studies [17], is based on quantitatively representing the sustainability effect of a business or design alternative, in order to train engineers and professionals to understand the value of tradeoffs [18]. For this purpose, game based experiences in higher education, in particular in engineering, have proven to be successful for six major reasons [19][20] according to the teachers who have extensively used them:

1 - enhance student motivation to learn and student interest in the topic, the course, and learning in general;
2 - enhance students' concept learning, decision-making skills, and systematic analytical skills;
3 - improve future course work;
4 - trigger affective learning of the subject matter by changing students' perspectives and orientations, and increasing their empathy and appreciation of others' circumstances;
5 - enhance participants' self-awareness and self-confidence;
6 - promote better student–student and student–teacher relations.

Furthermore it is of particular interest the integration of sustainability aspects that affect professional engineering decision-making into master level courses since traditional engineering decision-making is relatively narrowly focused and tied to many contemporary environmental problems [12]. The advent of sustainable engineering requires a broader systems perspective and a more complex system tradeoffs and priority setting competencies.

The main contribution of this simulator is to show a preliminary model of integrated sustainability that can be used in the analysis of business alternatives in the early requirements analysis phase of a power plant project, sited in a specific geographical area.

Participants of the game based experience

The one day long experience took place at University of Genova and was the final assessment of the knowledge acquired through the lessons of the mentioned Operative Module focused on Innovation for Industrial Plant Engineering and Technologies during the 4th edition of MIPET Master Program [21] [38][39]; indeed use of M&S as support for training and education have a great potential and it usual a very power approach to be embedded in class experiences, team working and role play games [32][33][37] .

The experience included 15 MIPET students who worked in two groups. All participants were randomly assigned to the roles. In the experience students were supervised by professional engineers with professional background in the field. One group played the role of the governmental authority of the region, and were equipped with the MOSES environment. The second group took care of the interests of a company which aims at building and operating a coal power plant in a specific virtualized area and economic scenario. These team members were acting as the engineers who had to make the technical proposal and draft the design document including the environmental impact assessment. The latter also used MOSES simulator, obviously with a prevailing interest in a subset of output variables which was different from the one of the previous and more profit-oriented, while the former focused on social indicators. The goal of the two groups was the negotiation on the offsets and to adopt winning strategies [30][31].

The governmental authority had also to identify the requirements to license the construction of a coal power plant. These requirements needed to meet not only the interest of the local community, measure of which could be the sustainability modeled by the simulator, but they also embed the policies of norms and (i.e. emissions, water pollution, noise impact etc).

For an example of negotiation performed, it is worth noting that MOSES is able to forecast the amount of greenhouse gases emissions of a defined system or activity, considering all direct and indirect sources. Greenhouse gases emission are often expressed in terms of the amount of carbon dioxide (CO_2) with an equivalent greenhouse effect. Once the size of a carbon footprint is known, a strategy can be devised to reduce it, e.g. by technological developments, carbon capture, consumption strategies, and others. Indeed, the mitigation of carbon footprints passes through the development of alternative projects, such as reforestation or green grass areas (carbon offsetting). The quantification of these compensating measures was one of the objects of the game experience.

Procedure of the game based experience

The experience was conducted in two stages. During the first one the participants used the simulator and came up with a strategy to address the problem of sustainability according to the interest of the group they were representing. Each group had analyzed different solutions and, after an internal brainstorming process, they chose the optimal solution and related tradeoffs to be shown the other group. During a second phase the two groups had to converge to a single scenario with a negotiation process. This phase allowed to train students' sustainability-specific decision-making skills.

Negotiation: methodology and experimental analysis

Given the four input variables described in section 2, each group of students had to perform a multivariate study trying to minimize their own target function. In order to do so, the method of Analysis of variance (ANOVA) with contrast matrices seemed to the two groups the more standard and robust methodology to estimate the sensitivity of each output parameter to the different input scenarios.

Each group has selected a subset of output variables which, in their opinion, would have the highest sensitivity to their targets. The following variable grouping has been suggested by the students during the experience:

- Variables of interest for the Company: Plant, Plant Profits, Plant Workers, Plant Salary, Industry Workers, Industry Salary, Base Workers, Base Salary.
- Variable of interest for the Authority: Happiness, Coast Quality, Air Quality, Green Area, Diseases, Unemployed and Population.
- Variables that the Company considered useful for mediation with the Authority: CFP, Free, Other Workers, Other Salary, Total Workers, Salary, Surface.

After the analysis, the simulation pool has been represented by a polar graph, clearly indicating the best solution. Figure 6 shows the graph with the seven variables results of the sensitivity analysis of the Government group. Through many trials the group found the optimal scenario (red one)

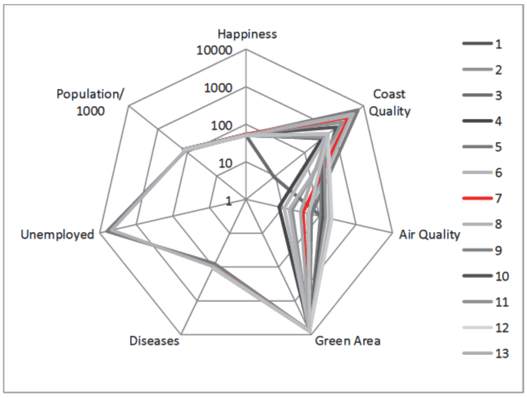


Figure 6: Polar graph of the Government group trials, with the relevant variables and the optimal scenario identification(red one)

4. CONCLUSIONS

We have presented a first attempt to treat sustainability of a port area, with a power plant, an industrial activity and a military base with the use of MOSES simulator. The simulator has been designed using the indicators and mathematical models connected to sustainability. We have faced some research challenges in order to successfully develop and test our model, such as finding the right level of detail, difficulty to incorporate quantitative data and lack of standard measures for sustainability.

Our simulator MOSES was able to quantitatively represent the sustainability of different design alternatives. MOSES allowed to properly conduct a game based experience, in which two groups of students of MIPET program, understood the tradeoffs between sustainability and other business goals and made informed decisions. The negotiation game permitted to train sustainability-specific decision-making skills. We believe this represents a first step in the contribution to the challenge of training young engineers and, to some extent, to ensure a sustainable development of our society.

We plan to continue this research line and, finally, we would like to apply our approach on new real case studies.

ACKNOWLEDGMENTS

The authors wish to sincerely thank Michele Tirinnanzi, DuPont, whose collaboration during the experience introducing case studies on sustainability has enriched the research in the sustainability field and has led to success the game based experience; special thanks to Lio Tech Ltd. for volunteering the support in the MOSES implementation and in the support to the current experimentation. The authors are glad to thank the whole MIPET Program and, in particular, the Organizers including, Genoa University Polytechnic School, ABB, Danieli Centro Combustion, Fisia Italimpianti, Paul Wurth, Prisma Impianti, Tenova, Confindustria, l'Ordine degli Ingegneri Genoa and ANIMP for their spontaneous support to the initiative. Profound gratitude is expressed to the MIPET students for their active involvement in the game based experience; indeed the authors would like to express their warmest wishes to the students' future careers.

REFERENCES

[1]. Our Common Future. Oxford, U.K.: Oxford Univ. Press, 1987 [Online]. Available: www.un-documents.net/wced-ocf.htm, UNEP (United Nations Environment Program), The World Commission on Environment and Development
[2]. Phillis, Yannis A.; Kouikoglou, Vassilis S.; Manousiouthakis, V., "A Review of Sustainability Assessment Models as System of Systems," Systems Journal, IEEE , vol.4, no.1, pp.15,25, March 2010.
[3]. Bruzzone A.G., Kerckhoffs (1996) "Simulation in Industry: 8th European Simulation Simposium", Genoa, Italy, October, Vol. I & II, ISBN 1-56555-099-4
[4]. Longo, F. (2012) "Sustainable supply chain design: An application example in Local Business Retail", Simulation 88(12), 1484-1498
[5]. Mujica, M., Piera, M.A.,(2012) "The translation of CPN into NetLogo environment for the modelling of political issues: FUPOL project", Proceedings of the 24th European Modeling and Simulation Symposium, EMSS, Wien, Austria
[6]. Zigurds Krishans, Anna Mutule, Yuri Merkuryev, Irina Oleinikova. Dynamic Management of Sustainable Development. Methods for Large Technical Systems. Springer-Verlag, London, 2011. 163 p.
[7]. Bruzzone, A.G., Longo, F., 2010. An advanced system for supporting the decision process within

large-scale retail stores. Simulation 86 (12), 742-762.

[8]. Thompson J., Bossomaier T. (2006) Agent Based Modelling of Coevolution of Trust between Client and Wealth Managers", CIMCA/IAWTIC, 131

[9]. Bruzzone, A., Bocca, E., 2012. Innovative solutions based on simulation combined with optimization techniques for maintenance service management within complex systems. International Journal of Modeling, Simulation, and Scientific Computing 3 (2), art. no. 1240004

[10]. H. Cabezas and B. Fath, "Towards a theory of sustainable systems," Fluid Phase Equilibria, vol. 194–197, pp. 3–14, 2002.

[11]. Fu-Liu Xu, Shan-Shan Zhao, Richard W. Dawson, Jun-Yi Hao, Ying Zhang, Shu Tao, "A triangle model for evaluating the sustainability status and trends of economic development", Ecological Modelling, Volume 195, Issues 3–4, 15 June 2006.

[12]. Eagan, P.; Gutafson, M.; Vieth, C., "Building a competency model for sustainability," Electronics Goes Green 2012+ (EGG), 2012, vol., no., pp.1,5, 9-12 Sept. 2012

[13]. Sanz Adán F., Emilio Jiménez Macías, E. Martínez Cámara, Mercedes Pérez de la Parte (2008) "Simulation Applications Based on Digital Terrain Models Integrated in Web3D Viewers and Graphic Engines", UKSim 590-596

[14]. Bruzzone A.G., Marques H., Cantice G., Turi M. (2012) "Innovative C2 and Simulation for Crowdsourcing as Force Multiplier", Proceedings of European Modeling and Simulation Symposium, Wien, Austria, September

[15]. De Felice F., Petrillo A. (2013) "Multicriteria Approach for Processing Modelling in Strategic Environmental Management Plannig", International Journal of Simultion and Process Modeling, Vol.8, No.1, pp.6-16

[16]. Kronberger G. K. , S. Fink, M. Kommenda, M. Affenzeller (2011) "Macro-economic Time Series Modeling and Interaction Networks", Lecture Notes in COMPUTER SCIENCE, Vol. 6625, No. 1, pp. 101-110

[17]. Cabot, J.; Easterbrook, S.; Horkoff, J.; Lessard, L.; Liaskos, S.; Mazoòn, J., "Integrating sustainability in decision-making processes: A modelling strategy," Software Engineering - Companion Volume, 2009. ICSE-Companion 2009. 31st International Conference on, vol., no., pp.207,210, 16-24 May 2009

[18]. Longo, F., Massei, M., Nicoletti, L. (2012) "An application of modeling and simulation to support industrial plants design" International Journal of Modeling, Simulation, and Scientific Computing, 3 (1), art. no. 1240001

[19]. Merkuryev Y., Galina Merkuryeva, Miquel Angel Piera, Antoni Guasch (2009) Simulation-based Case Studies in Logistics: Education and Applied Research. Springer-Verlag, London. 232 p.

[20]. Druckman, Daniel and Ebner, Noam, "Games, Claims, and New Frames: Rethinking the Use of Simulation in Negotiation Education", Negotiation Journal, 29-1, 1571-9979, pages 61-92, 2013.

[21]. DuPont Sustainability Report 12 111612

[22]. DuPont 2012 Global Reporting Initiative Report

[23]. Bruzzone Agostino G., Alberto Tremori, Marina Massei, Federico Tarone, "Modeling Green Logistics," Asia International Conference on Modelling & Simulation, pp. 543-548, 2009 Third Asia International Conference on Modelling & Simulation, 2009

[24]. W. E. Rees, "Ecological footprints and appropriated carrying capacity:What urban economics leaves out," Environ. and Urbaniz., vol. 4, pp.121–130, 1992.

[25]. M. Wackernagel and W. E. Rees, Our Ecological Footprint: Reducing Human Impact on the Earth. Philadelphia, PA: New Society Publishers, 1996.

[26]. M. L. M. Graymore, N. G. Sipe, and R. E. Rickson, "Regional sustainability: How useful are current tools of sustainability assessment at the regional scale?," Ecolog. Econom., vol. 67, pp. 362–372, 2008.

[27]. N. Fiala, "Measuring sustainability: Why the ecological footprint is bad economics and bad environmental science," Ecolog. Econom., vol. 67, pp. 519–525, 2008.

[28]. H. Sverdrup and M. G. E. Svensson, "Defining the concept of sustainability - a matter of systems thinking and applied systems analysis," in Systems Approaches and Their Application, 2004, pp. 143–164

[29]. Bruzzone A. G,, "Human Behaviour Modelling as a Challenge for Future Simulation R&D: Methodologies and Case Studies", Plenary Speech at Eurosim 2010, Prague

[30]. Tao F., L. Zhang, Z. H. Zhang, A. Y. C. Nee, (2010) "A quantum multi-agent evolutionary algorithm for selection of partners in a virtual enterprise", CIRP Annals - Manufacturing Technology, 59, 485–488

[31]. Gintis H. (2000) "Game Theory Evolving: A Problem-Centered Introduction to Modeling Strategic Behavior", Princeton University Press, ISBN 978-0-691-00943-8

[32]. Giribone P., Bruzzone A.G. (1997) "Production Games: An Improvement in the Education and Training for Engineers working in Production and Logistics", Proceedings of European Simulation Symposium, ESS'97, Passau, Germany, October 20-23

[33]. Bruzzone A.G. (1999) "Interactive Web-Based Tools for Education in Industrial Management", Proceeding of ITEC99, The Hague (NL), April 13-15

[34]. Bruzzone A.G., B.E., Bocca E., Massei M. (2007) "Evaluation of the impact of different human factor models on industrial and business processes" , ISSN 1569190X, Simulation

Modeling Practice and Theory, Volume 15, Issue 2, February 2007, Pages 199-218

[35]. Bruzzone A.G., Massei M. (2010) "Intelligent Agents for Modelling Country Reconstruction Operation", Proceedings of AfricaMS 2010, Gaborone, Botswana, September 6-8

[36]. Bruzzone A.G., Madeo F., Tarone F. (2010) "Modelling Country Reconstruction Based on Civil Military Cooperation", Proceedings of EMSS 2010, Fes, Morocco, October 13-15

[37]. Bruzzone A.G., R.Mosca, A.Naamane, C. Frydman, N.Giambiasi, G.Neumann, D.Ziems, S.Capasso, R.Signorile, S.Ghosh, A.Nisanci, P.Elfrey, B.C., B.M. (2001) "Logistics & Education In IEPAL International Cooperation", Proceedings of HMS2001, Marseille October 15-17

[38]. Bruzzone A.G. Massei M., Bocca E. (2012) "Simulation Models and Serious Games for Project Team Training in Engineering, Procurement, Construction and Commissioning", Proceedings of Africa M&S, Gaborone, Botswana, September

[39]. Bruzzone et al. (2013) “Mastering Industrial Plant Engineering and Technologies”, DIME Press, Genoa

ON-LINE REFERENCES

- www.dupont.com/corporate-functions/our-approach/sustainability.html
- www.dupont.com/corporate-functions/our-approach/sustainability/performance-reporting/sustainability-reports.html
- www.enel.it/it-IT/doc/azienda/ambiente/dichiarazioni_ambientali
- www.futurelab.org.uk/sites/default/files/Games_based_experiences_for_learning_0.pdf
- www.itim.unige.it/mipet
- www.liotech.co.uk
- www.simulationteam.com

Author's Index