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An Energy Consumption Optimization Platform For Green Data Centres

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Abstract

During the last few years, the energy sector has faced two important problems triggered by the increase of the number of Data Centres (DC), and the instability of the Smart Grids when integrating large percentages of renewable energy sources and following the electricity demand-response model. Average server utilization in DCs is often below 30% of the maximum server load and energy demand and consumption is increasing year over year, mostly due to over-dimensioning and sub-optimal allocation of DC resources. In the DOLFIN project (www.dolfin-fp7.eu), an energy Consumption Optimisation Platform (eCOP) has been designed and developed to monitor and optimize energy consumption at the single DC level.

DOLFIN eCOP is capable of providing continuous monitoring, dynamic control and adaptive optimisation of the DC infrastructure, including control of the power states of ICT and non-ICT devices (e.g. servers and HVAC, respectively). Further, eCOP implements energy benchmarking, dynamic control and adaptive optimisation of the DC infrastructure, including specific functionalities for metrics calculation and energy data collection and storage. With eCOP we can define energy policies applicable to both the ICT and non-ICT infrastructure of the DC, thus determining conditions under which specific control and optimization actions can be applied.

Accurate energy models have been implemented in the eCOP platform and are shared with the DOLFIN Synergetic Data Centres platform (SDC) for the energy-efficient allocation of demands across a network of distributed co-operating DCs. Several metrics for energy consumption are used by eCOP platform for optimization purposes including the Physical Server Energy Consumption, Average VM Energy Consumption, Average Application Energy Consumption and Application Energy Consumption. These metrics are used and processed by the various eCOP functional elements to implement optimizations.

The DOLFIN eCOP platform is currently in prototype stage and is under consolidation through validation tests in three interconnected laboratory environments, each emulating real-life DCs.

Keywords - Data Centre, energy optimization, energy policies, energy predictions.

1. Introduction

Data Centres (DC) nowadays absorb an enormous and steadily increasing amount of energy, with a significant impact on the environment and the CO_2 emissions. In 2011, DC's total energy consumption was around 271 billion kWh, enough to power up all residential households from industrialized countries such as UK or France, comparable to the total amount of energy consumed by Italy [1], approximately 7% of the US total energy consumption [2]. Just the Microsoft DC in Quincy (Washington) consumes 48MW, which is enough to power 40.000 homes [3] [4]. The consumption of dozens of MW per DC greatly affects the global economy; modern DCs may have operational costs as high as $5.6M [5] per year, while in 2010 and 2011 the USA spent approximately $35 billion in serving DC power needs.

From a systemic perspective, during the last few years the energy sector has started facing two critical challenges as to:

a) **how to support the increase of available DCs**, with the subsequent energy demand increase, further augmented by the relevant sub-optimal energy management; it is well known that the average server utilization in DCs is low, often below 30% of the maximum server load and only 10% in case of facilities that provide interactive services [6]. The operational security-driven over-dimensioning of DCs and the increased number of under-utilised servers have significantly increased the respective energy, while a huge amount of energy is also consumed for the cooling of DC servers. To lower this waste of energy, DC containment strategies (both hot and cold aisle) are widely regarded as the starting point for energy-efficiency.

b) **how to manage the instability of the Smart Grids and alleviate their difficulty to follow the electricity demand-response model**. As Europe shifts away from fossil fuels, electricity is becoming an even more important energy vector. Smart Grids lie very high on the agenda of the European energy and ICT sector; however, they have difficulty in following the electricity demand-response model.

The FP7 DOLFIN project [7] started in Q4 2012 to deal with these problems, primarily aiming at contributing towards the aggregate energy efficiency of networks of co-operating DCs and offering ancillary grid stabilization services to their containing Smart Grids. Key functions in DOLFIN are the energy monitoring and optimization at the single DC level, continuous monitoring of ICT and non-ICT infrastructure, energy benchmarking, dynamic control and adaptive optimisation of the DC infrastructure, up to control of power condition of all devices in the DC.

This paper describes the energy Consumption Optimisation Platform (eCOP) designed and implemented in DOLFIN project. eCOP implements all the logic and interfaces required by energy benchmarking, dynamic control, and adaptive optimisation functions for the DC infrastructure, including specific modules for metrics calculation and energy data collection and storage. It allows for the definition of energy policies applicable to both the ICT and non-ICT infrastructure of the DC, thus regulating conditions under which specific control and optimization actions can be applied.
The paper is organized as follows; Section 2 presents the high level DOLFIN architecture in which the eCOP functionality is initially conceived to monitor and control single DC environments. Section 3 details the internal function of the eCOP subsystem, focusing on its key modules for policy making and actuation, prediction of energy demands and optimization of DC workflows. Section 4 draws conclusions and preliminarily hints on the ongoing validation activities of the eCOP prototypes in real DC environments.

2. DOLFIN architecture

DOLFIN's primary objective is to design, develop, and validate the DC platform capable of monitoring the energy usage of the DC and react accordingly for efficient energy management.

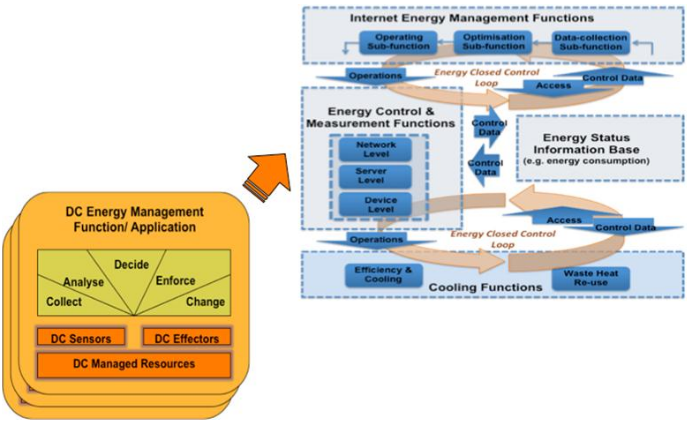

Fig. 1 From separate energy control loops to coordinated multiple DC energy control loops

The design of the DOLFIN DC framework is based on two target objectives:

- Improving capital and operational efficiencies for DC operators through the use of a common organization, automation, and operations of all energy functions across the different domains

- Migrating from an ecosystem of separate energy management functions towards a coordinated arrangement of energy management functions as represented in **Error! Reference source not found.**.

The DOLFIN system is an ecosystem of collaborative DCs, each one having its own DC customers and links with the energy network (ref. Fig. 2). Each DC may achieve further internal energy efficiency, by recycling and reusing the warm water that is used for cooling the ICT equipment for warming the DC offices (e.g. with an under floor warming system).

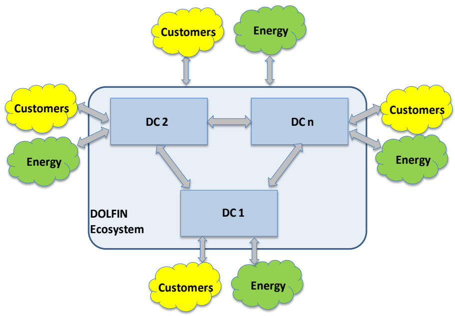

Fig. 2 DOLFIN Interworking DCs

DOLFIN is designed to be integrated within the existing DC's infrastructure through appropriate adapters. The approach used for optimizing energy consumption is hierarchical and consists of three levels:

- **Energy-conscious DC-level**: the goal here is to optimize energy consumption within the limits of a single DC, based on system virtualization and the optimal distribution of VMs. This is coupled with the dynamic adaptation of active and stand-by servers and the predictive load optimization per active server.
- **Group of Energy-conscious Synergetic DCs-level**: the goal here is to optimize the cumulative energy consumption in groups of DCs, based on optimal distribution of VMs across all of the servers that belong in the DCs' group using policy-based methods.
- **Smart City-level**: the goal is to optimize energy consumption at the Smart City level and provide stabilization of the local Smart Grid, based on distribution of VMs across the servers that are part of a group of DCs, following an electricity demand-response approach.

The DOLFIN architecture is consolidated around two specialized sub-systems, namely:

- **Energy Consumption Optimisation Platform (eCOP)**, which represents the core platform in DOLFIN as previously discussed, and is where the relevant actions are performed to manage and optimize the energy consumption at Data Centre level.
- **Energy-conscious Synergetic DCs (SDC)**, which provides a dynamic, service-effective and energy-efficient allocation of demands, across a distributed network of co-operating DCs. In addition, the SDC provides the control modules for the integration with the Smart Grid environment and that are responsible for the energy stabilisation through the interconnection with the smart grid network, responding to the demand side management directives of the latter.

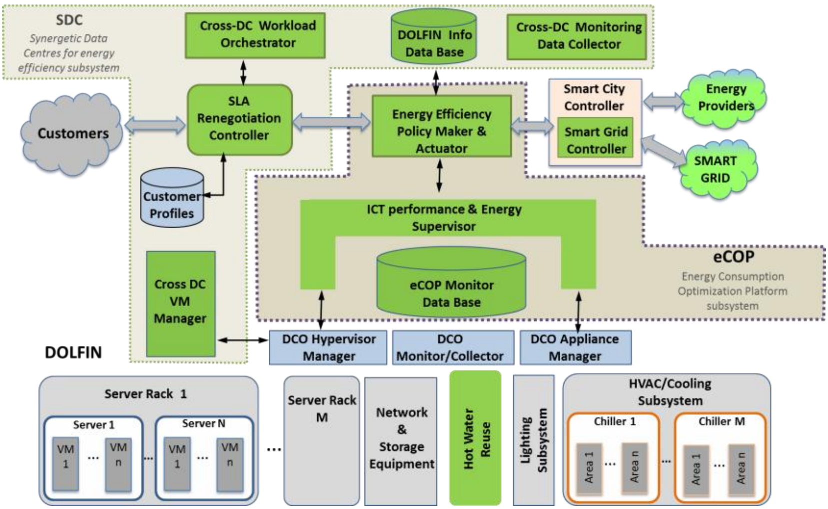

Fig. 3 High level architecture of the DOLFIN eCOP and SDC subsystems

The detailed high level architecture [8] identifying the main functionalities and modules of the eCOP and SDC is depicted in Fig. 3 and shows the functional split of the various components of eCOP and SDC.
The energy Consumption Optimisation Platform (eCOP) supports the definition of energy policies applicable to both the ICT and HVAC infrastructure to regulate conditions under which specific control and optimization actions can be applied.
The energy-conscious Synergetic Data Centres interfaces with the Smart Grids through integrating the openADR protocol [9] and working towards responding to the Grids’ load shifting and peak loads trimming needs.

3. Energy consumption optimisation platform for green DCs

The eCOP platform [10] is the core set of functional modules in the DOLFIN architecture that grants a DOLFIN-enabled DC with advanced monitoring, self-evaluation and self-optimisation capabilities. The four pillars of eCOP functionality are summarized as follows:

- Interfaces legacy/heterogeneous DC sub-systems (including cloud management platforms and building management systems) by means of specific adapters to collect all necessary information for the optimization process.
- Offers an engine able to process raw data and calculate appropriate metrics and KPIs that will be used throughout the whole the optimization process. This engine resides in the ICT Performance and Energy Supervisor module.
- Implements mechanisms to store raw data, measures and calculated metrics into the eCOP DB, and provides also efficient and abstracted interfaces to support DB operations.
- Sets the Energy Efficiency Policy Maker & Actuator module into action to perform the optimization lying in the core of the DOLFIN project scope. The module activation is based on pre-defined criteria and aggregated information from other modules (e.g. ICT Performance and Energy Supervisor, Smart Grid Controller, Cross-DC orchestrator, etc.).

The eCOP interfaces to legacy control and orchestration modules of the DC (DCO) grouped in three types of functions:

- **DCO Hypervisor Manager**, which is responsible for managing new ICT hardware and VMs configuration;
- **DCO Appliance Manager**, which acts on the non-ICT DC infrastructure (e.g. HVAC);
- **DCO Monitor/Collector**, which interfaces with both the ICT and the non-ICT DC infrastructure to collect all operational and energy related information to be stored in the eCOP.

Three main components implement the eCOP functional perspective;

1. The **ICT Performance and Energy Supervisor module** has the responsibility to interact with underlying legacy DC subsystems and collect relevant information to evaluate metrics and KPIs. The module implements mechanisms to efficiently retrieve the data from various sub-systems and distribute such information to appropriate consumers. Moreover, the ICT Performance and Energy Supervisor undertakes data analysis and representation, useful to other eCOP module for their optimization activities.
2. The **Energy Efficiency Policy Maker and Actuator** implements the intelligence needed for the derivation and application of DC

optimization policies. It is responsible for the application of the energy optimization procedures based on particular predefined criteria and conditioned by the inputs (requests) provided by other DOLFIN components, for example requests from the Smart Grids environment, from federated DCs, etc.

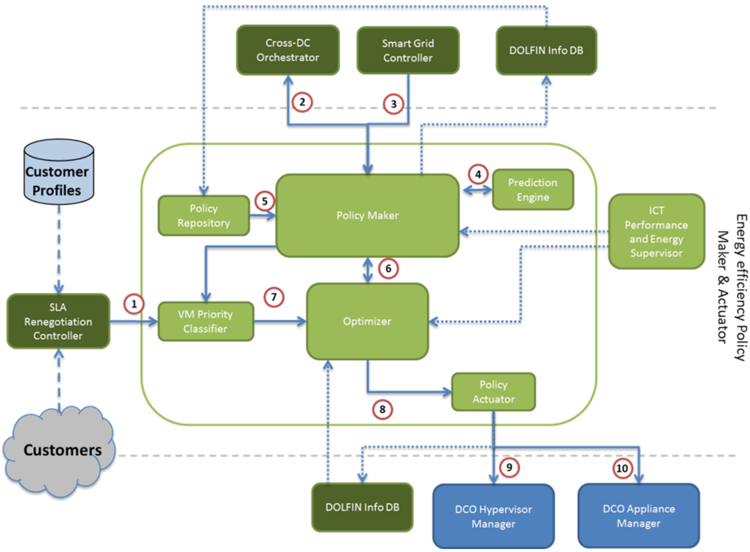

Fig. 4 The Energy Policy Maker & Actuator

3. The **eCOP Monitor Database** groups all the elements involved in the storage functionalities for measures, KPIs, DC assessment and status, etc. The eCOP Database not only implements pure database functions, but introduces specialized modules to efficiently interact with that data store and produce a time series aggregation.

All implemented components exhibit RESTful API services to expose their operational functionality and management, thus guaranteeing technology neutrality and conceptual compatibility with relevant state-of-the-art platforms and solutions such as OpenStack, whose API structuring has been largely followed by DOLFIN.

Within the ICT Performance and Energy Supervisor, the Event Process Engine (EPE) has the particular role of classifying events received from the legacy DC and executing subsequent appropriate actions, such as metrics recalculation [11] or ICT Topology Graph DB update, taking into consideration recent relevant data saved in the memory of the component, exposing basic caching capabilities; in case an external entity requests for metrics information, it can perform a quick search in its cache memory and provide a faster response.

The Energy Efficiency Policy Maker and Actuator is the core decision point of the eCOP system (Fig. 4). It is set to

- apply a set of well-known criteria and evaluation patterns to optimize the DC energy consumption (i.e. determining a set of operations to improve the DC energy efficiency);
- produce a stream of requests which can be translated into actual actions by others DOLFIN servant subsystems within a DC;
- determine corrective actions taking each action trade-offs and cost into account.

To support these roles, the Energy Policy Maker & Actuator requires interaction with external components, e.g. the Smart Grid Controller, the Cross-DC Workload Orchestrator and the SLA Renegotiation Controller, as depicted in the general workflow of the Policy Maker & Actuator is depicted in Fig. 5.

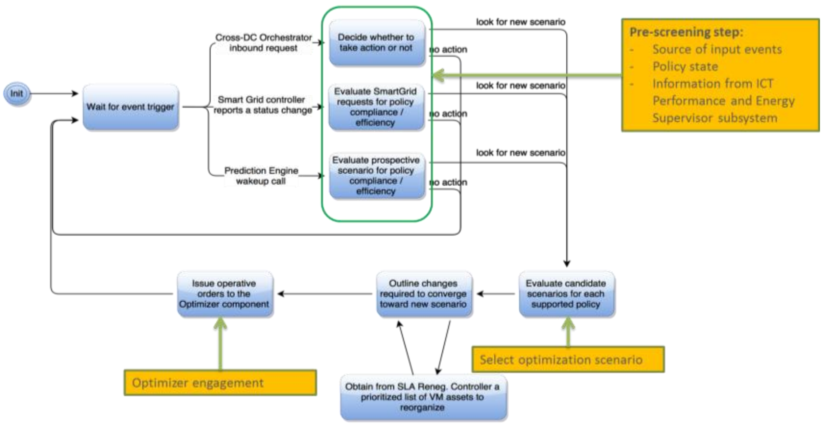

Fig. 5 The Energy Policy Maker & Actuator workflow

a. Policy Maker

The Policy Maker is responsible for scheduling the activation of the policy enforcement, on the basis of the DC status and the information provided by other modules. This module implements efficient resource management and the acceptance or rejection of incoming requests at local or synergetic DCs level. The Policy Maker implements a closed control loop following the principles of MAPE-K adaptation control loops [12] to implement both monitoring, analysis, planning and executing components, as depicted in the following picture.

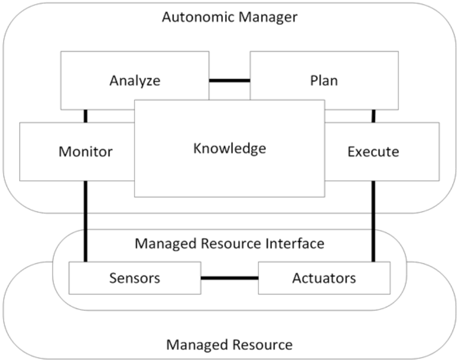

Fig. 6 MAPE-K loop for Policy Maker

b. Prediction Engine

The prediction engine has been developed to provide forecasts for all measurement types and DC infrastructure resources that are supported by the eCOP Monitor DB. Measurement types supported by the eCOP Monitor DB and, hence, by the Prediction Engine, are shown in the following table.

Table 1. Measurement types supported by the eCOP Monitor DB and the Prediction Engine

calculated	**disk.read.requests**
compute.node.cpu.frequency	disk.read.requests.rate
compute.node.cpu.percent	disk.write.bytes
cpu_util	disk.write.bytes.rate
disk.read.bytes	disk.write.requests
disk.read.bytes.rate	disk.write.requests.rate

network.incoming.bytes	**energy**
network.incoming.bytes.rate	hvac.air_volume
network.outgoing.bytes	hvac.heat_transfer
network.outgoing.bytes.rate	hvac.temperature_drop
power	memory
temperature	memory.usage

The Prediction Engine features an auto-discovery mechanism to create models of measured data, without necessitating explicit configuration. Every night, the Prediction Engine polls the eCOP DB Broker for all measurement types and resources (e.g. servers, VMs, racks etc.) and gets the relative measurements, spanning the last 30 days[1]. Then, a training model based on Support Vector Machines for Regression (SVR) is applied over the complete set of acquired data in order to get an accurate representation of their trends, after combining them to meaningful tuples of type [*resource*, *measurement_type*]; as an example, supposing that for a specific physical server there exist measurements related to energy consumption and CPU utilization only, the Prediction Engine will generate two models, one pertaining to the CPU utilization of the server and one related to its energy consumption. Following this approach, the Prediction Engine is able to provide information for a vast number of target [*resource*, *measurement_type*] forecasting tuples. Currently, the input variables for the Prediction Engine modelling procedures only comprise vectored representations of time (in the form of tuples [*Year*, *Month*, *Day of Week*, *Hour*, *Minutes*]) but will be extended to take into consideration other variables whenever appropriate (e.g. weather forecast in the case of cooling energy consumption predictions). The parameters of the SVR machines are selected after employing parameter space exploration and cross-validation, to extract the parameter values that minimize the prediction error, i.e. present the best fit for the provided input values. In any case, the kernel is statically set to Radius Basis Function (RBF).

Fig. 7 Actual power demand vs forecast by the Prediction Engine in DOLFIN eCOP.

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[1] The limited span is intended because the actual data already acquired do not span more than a year hence capturing seasonality at yearly levels is not possible. Therefore, a monthly inspection range has been selected.

Apart from SVR, DOLFIN has also considered the use of Neural Networks and various time series analysis models such as the ARMA, ARMAX and ARIMA models. The choice of SVR in favour of the rest of evaluated techniques was made because it exhibited satisfactory performance in terms of both accuracy using only limited sets of data and speed of forecasting procedures. Indicatively, the prediction of the expected power demand of a single rack for four hours in the future (starting from the time of the request) and quantized in timeframes of five (5) minutes (producing 48 prediction values in total) takes approximately 55ms (including network transfer time).

As shown in **Error! Reference source not found.**, the quality of the prediction is more than satisfactory, featuring a coefficient of variation (relative standard deviation) of less than 3%.

a. Optimizer

Upon receipt of an optimization request from the Policy Maker, the Optimizer acknowledges receipt and updates its status in order to let the interested components know that an optimization plan is currently ongoing. Based on the currently active policy governing the DC operation, the Optimizer asynchronously serves the optimization request and produces an appropriate optimization plan. The latter is forwarded to the Policy Actuator in order to be executed. Simultaneously, the Optimizer changes its status to Idle and notifies the Policy Maker that the particular optimization request has been served and a relevant optimization plan has been sent to the Policy Actuator. In the current version of the Optimizer, the absolute minimization of the energy consumption of the DC is pursued, constituting the principle policy for proper DC operation (granted that SLAs are met for all customers). Particularly, the Optimizer determines the optimal VM allocation to the physical servers of the DC so that the number of servers that can be finally switched off is maximized, simultaneously maximizing the possible energy consumption merits acquired by the avoidance of their operation. The problem has been modelled as a one dimension (1D) Bin-Packing, considering RAM of the VMs as the sizable dimension and the physical servers as bins.

As time is critical for proper and timely DC adaptation and it is not possible to acquire an analytical solution to such problems in reasonable (polynomial) time (the generalized Bin-Packing problem is known to be NP-Hard), we have developed two heuristics that are able to achieve near-optimal allocations, without being too time consuming. Particularly, when the DC is under high load and an optimization request for minimizing the energy consumption is received, the Optimizer performs a simple Best Fit Decreasing (BFD) algorithm that is able to arrange the VMs in the operating servers in a near-optimal way. Particularly, in the direction of employing the BFD the DC servers are indexed based on their energy-efficiency, with energy-efficient servers being assigned a lower index. Subsequently, the VMs are placed into physical servers in order of decreasing energy efficiency index. As a result, energy-efficient servers are assigned a higher priority and for instance servers of a Green Room are reserved first, or servers of the same DC segment are reserved prior to remote DC servers in order to allow remote DC servers to hibernate, providing substantial energy savings. Next, the VMs are sorted by RAM size and are then placed in order of increasing index, first into the occupied physical servers of lower available capacity and then, in case they do not fit into the occupied servers, or in case of a tie, VMs are placed in order of increasing index into the lower indexed physical server they fit.

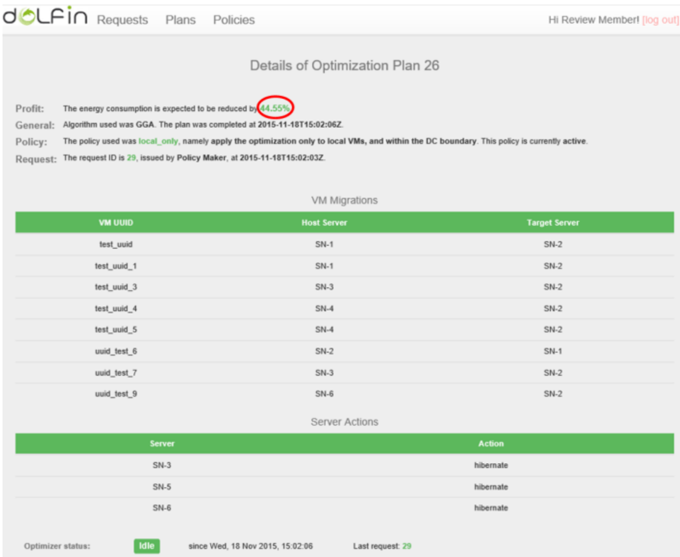

Fig. 8 Indicative Optimization Plan determined by the Optimizer. In this scenario, a virtual DC containing 6 under-utilized servers and 15 VMs has been considered for optimization.

In case of more drastic DC workload re-organization, Grouping Genetic Algorithms (GGAs) have been used, in which each gene of a chromosome corresponds to a tuple of elements corresponding to the VMs of each physical server and the latter are the building blocks evolved by the employment of the GAs. The use of GGA, initialized by BFD, for the optimal VM allocation allows for the consolidated allocation of VMs at an intra-DC level as well as an inter-DC level, whenever a VM consolidation is imposed by the Smart Grid operation.

4. Conclusions

This paper presented some key functional elements of the DOLFIN DC energy consumption optimization platform (eCOP), used to monitor and optimize energy consumption in Data Centres.

The DOLFIN project is demonstrating how the coordinated action of event processors, policy and prediction engines with optimizers allows to maximize energy efficiency through workload redistribution within the DC, also offering enhanced monitoring data to a cross-DC synergetic optimization layer. The DOLFIN eCOP platform is currently in prototype stage and under validation in three interconnected laboratory environments in Poland, Italy, and Greece, each emulating real-life DCs. Final results from this validation are experiments are expected by Q3-2016.

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