Integrated Energy Efficient Data Centre Management for Green Cloud Computing

The FP7 GENiC Project Experience

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Abstract: Energy consumed by computation and cooling represents the greatest percentage of the average energy consumed in a data centre. As these two aspects are not always coordinated, energy consumption is not optimised. Data centres lack an integrated system that jointly optimises and controls all the operations in order to reduce energy consumption and increase the usage of renewable sources. GENiC is addressing this through a novel scalable, integrate energy management and control platform for data centre wide optimisation. We have implemented a prototype of the platform together with workload and thermal management algorithms. We evaluate the algorithms in a simulation based model of a real data centre. Results show significant energy savings potential, in some cases up to 40%, by integrating workload and thermal management.

1 INTRODUCTION

Data centres have become a critical part of modern life with the huge penetration of software as a service, mobile cloud applications, digital media streaming, and the expected growth in the Internet of Everything all relying on data centres. However, data centres are also a significant primary energy user and now consume 1.3% of worldwide electricity. With the increasing move towards cloud computing and storage as well as everything as a service type computing, energy consumption is expected to grow to 8% by 2020 (Greenpeace, 2011; Gao, 2012). While data centres of large cloud service providers have been consuming many megawatts of power with corresponding annual electricity bills in the order of tens of millions of dollars, e.g. Google with over 260MW and $67M and Microsoft with over 150MW and $36M in 2010 (Qurush, 2010), the large cloud service providers are also investing heavily in energy efficiency and green data centres, e.g. Google and Microsoft have invested over $900M in energy reduction measures since 2010. However, smaller operators and independent data centres have not yet been able to deploy many of the energy efficiency technologies that are available. This is due to lack of integrated technology solutions and uncertainty about costs and the use of renewable energy solutions.

On average, computing consumes 60% of total energy in data centres while cooling consumes 35% (Uptime Institute, 2011). New technologies have the potential to lead to a 40% reduction of energy consumption, but computation and cooling typically operate without joint coordination or optimisation. While server energy management can reduce energy use at CPU, rack, and overall data centre level, dynamic computation scheduling is not integrated with cooling. Data centre cooling typically operates at constant cold air temperature to protect the hottest server racks while local fans distribute the temperature across racks. However, these local server controls are typically not integrated with room

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cooling systems, which means that it is not possible to optimise chillers, air fans and server fans as a whole system.

The integration of renewable energy sources (RES) has received limited interest from the data centre community due to lack of interoperability of generation, storage and heat recovery and current installation and maintenance costs versus payback (Deng, 2014). By and large, data centre operators, who want to be green and use renewable energy buy electricity that has been given a green label by their respective supplier without often being able to fully verify this. The intermittency of renewable energy generation is also a critical factor in an environment with very strict service level agreements and essentially 100% uptime requirements. The adoption of new technologies related to computing, cooling, generation, energy storage, and waste heat recovery individually requires sophisticated controls, but no single manufacturer provides a complete system so integration between control systems does not exist.

Funded by the European Commission, the GENiC project (http://www.projectgenic.eu) develops integrated cooling and computing control strategies in conjunction with innovative power management concepts that incorporate renewable electrical power supply and waste heat management. The GENiC project's aim is to address the issue mentioned above by developing an integrated management and control platform for data centre wide optimisation of energy consumption, reduction of carbon emissions and increased renewables usage through integrating monitoring and control of computation, data storage, cooling, local power generation, and waste heat recovery. The proposed platform defines interfaces and common data formats, includes control and optimisation functions and decision support. We aim to verify the energy savings potential through simulation based assessment and demonstration of reduction in energy consumption through deployment of the platform in a demonstration data centre. A further premise of GENiC is that the energy consuming equipment in data centres must be supplemented with renewable energy generation and, where possible, energy storage equipment, and operated as a complete system to achieve an optimal energy and emissions outcome. This vision is centred on the development of a hierarchical control system to operate all of the primary data centre components in an optimal and coordinated manner.

In this paper we present the overall GENiC system architecture for an integrated approach to data centre management, discuss the first prototype implementation, and present use cases and a simulation based assessment of some of the energy management algorithms. The paper is structured as follows, Section 2 presents some challenges for data centre energy management, the GENiC architecture is presented in Section 3 and the prototype implementation in Section 4. Section 5 introduces the simulation models that represent a real physical data centre and their boundary conditions. Section 6 presents the simulation flow and boundary conditions. Section 7 presents and discusses simulation results and Section 8 concludes the paper.

2 CHALLENGES IN DATA CENTRE ENERGY MANAGEMENT

Data centres have evolved into critical information technology (IT) infrastructure and much of today's IT services, both for businesses and consumers, depend on their operation. Data centres consume an increasing amount of energy and contribute significantly to CO_2 emissions. However, opportunities exist to enhance the energy and power management of data centres in conjunction with renewable energy generation and integration with their surrounding infrastructure. Work has been done on powering of data centres by renewable energy (Cioara, 2015), but this has not been fully integrated into a complete energy management system considering coordinated workload management, cooling, powering, and heat recovery management. While much work has focused on integrated energy management for data centres (Das, 2011; Jiang, 2015) there is still a lack of an overall consideration of energy usage and powering with the recovery of waste heat as part of an overall thermal management approach. In order to bring the elements of workload management, cooling, powering and heat recovery together in such a way that it will be possible to achieve a high level of renewable energy powering of data centres, a comprehensive integrated energy management system is needed. The challenges that such a system needs to address are

- Comprehensive, scalable integration of workload management with cooling approaches.
- Effective power management with a high level of renewable energy supply integration while meeting service level agreements. For example, managing service level agreements while dealing with energy price fluctuations and demand response requirements.

- Strategies for waste heat recovery in conjunction with the heating needs of surrounding areas.
- Design and decision support tools assisting data centre operators with data centre energy management. Effective monitoring and fault management.

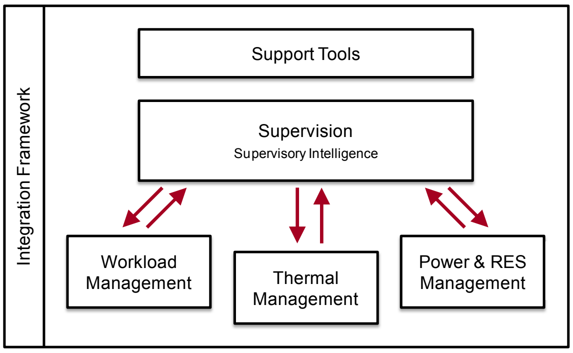

Figure 1: High level overview of the GENiC architecture (from (GENIC, 2015)).

3 GENiC ARCHITECTURE

To address the challenges outlined above, the GENiC project has developed a high level architecture for an integrated design, management and control platform (Pesch, 2015). This platform targets data centre wide optimisation of energy consumption by encapsulating monitoring and control of IT workload, data centre cooling, local power generation and waste heat recovery. In the following, a functional specification of the GENiC architecture is presented and an overview of the integration framework is provided. More detailed information can be found in (GENIC, 2015).

The GENiC system integrates workload management, thermal management and power management by using a hierarchical control concept to coordinate the management sub-systems in an optimal manner with respect to the cost of energy consumption and environmental impact, and cost policies. Figure 1 provides a high level overview of the proposed GENiC system architecture, which consists of six functional groups known as GENiC Component Groups (GCGs):

- The **Workload Management GCG** is responsible for monitoring, analyzing, predicting, allocating, and actuating IT workload within the data centre.
- The **Thermal Management GCG** is responsible for monitoring the thermal environment and cooling systems in the data centre, predicting temperature profiles and cooling demand, and optimally coordinating and actuating the cooling systems.
- The **Power & RES Management GCG** is responsible for monitoring and predicting power supply and demand, and for actuating the on-site power supply of the data centre.
- The **Supervision GCG** includes the supervisory intelligence which provides optimal IT power demand, power supply, and thermal policies to the individual sub-systems based on monitoring data, predicted systems states, and actuation feedback.
- The **Support Tools GCG** includes a number of tools that provide decision support for data centre planners, system integrators, and data centre operators.
- The **Integration Framework GCG** provides the communication infrastructure and data formats that are used for interactions between all components of the GENiC system.

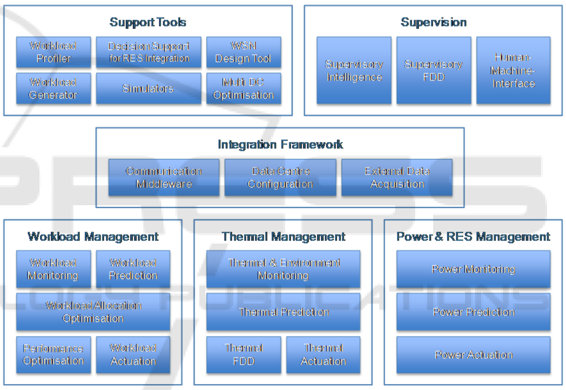

Figure 2: Components of the GENiC functional architecture (from (GENIC, 2015)).

Each GCG is composed of a number of functional components which we call GENiC Components (GCs). The individual GCs are shown in Figure 2. The core function of the GENiC system for integrated, optimised data centre management can be divided into four basic elements:

1. **Monitoring** components within the management GCGs collect data about IT workload, thermal environment, cooling systems, power demand and on-site power supply.
2. **Prediction** components within the management GCGs update their internal models and estimate future system states based on the collected monitoring data.
3. **Optimisation** components determine optimal policies based on the collected monitoring data

and calculated prediction data. These policies are provided to the management GCGs

4. **Actuation** components within the individual management GCGs implement the policies provided by the optimisation components in the data centre and at the renewable energy sources facilities.

These elements are complemented by components for external data acquisition and fault detection and diagnostics. The basic information flow for coordinating workload, thermal and power management is illustrated in Figure 3. For the simulation based assessment, the data centre and power infrastructure in the loop are replaced with their respective virtual models provided by the Simulators GC.

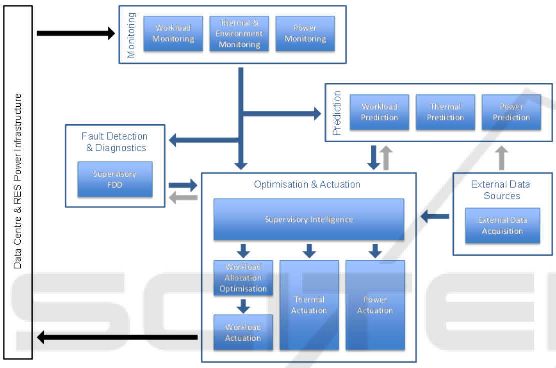

Figure 3: Information flow (simplified) within the GENiC platform for coordinating workload, thermal and power management (GENIC, 2015).

In the following, we take a closer look at the GCGs and their individual components:

Workload Management GCG: The primary objective of this GCG is to allocate virtual machines (VMs) to physical machines (PMs) such that service level objectives (SLOs) are satisfied with low operational cost. Monitoring data from the IT resources deployed within the data centre is collected by the Workload Monitoring GC. The Workload Prediction GC uses this information to provide short- and long-term predictions about the resource utilization. The allocation and migration of VMs to PMs is determined by the Workload Allocation Optimisation GC, which solves a constrained optimisation problem, taking the predicted workload as well as constraints provided by the Supervisory Intelligence GC, Thermal Prediction and Performance Optimisation GC into consideration. The Performance Optimisation GC defines colocation and anti-colocation constraints for individual VMs and modifies the individual VMs' priorities to fulfil application specific SLOs. The VM allocation plan is finally applied by the Workload Actuation GC, which provides an interface to the data centre specific virtualization platform.

Thermal Management GCG: The Thermal & Environment Monitoring GC integrates monitoring of cooling systems and wireless sensor network infrastructure for collecting temperature and other environmental data in the data centre room. The collected data is used by the Thermal Prediction GC to provide short-term and long-term predictions to support supervisory control decisions, thermal actuation and workload allocation. Long-term predictions obtained with mathematical models are used for making decisions at the supervisory level. Short-term thermal predictions based on a discrete time mathematical model are required by the Thermal Actuation GC along with real-time sensor measurements to determine optimal set points for the cooling system in order to achieve the targets set by the Supervisory Intelligence GC. These short-term thermal predictions are also necessary input to the Workload Allocation GC, as they include temperature models for the thermal contribution of IT server workload to the server inlets, and the Supervisory Intelligence GC. Furthermore, short-term predictions, combined with equipment fault information from the Thermal Fault Detection & Diagnostics (FDD) GC, are used for fault detection and diagnostics at the supervisory level.

Power & RES Management GCG: The Power Monitoring GC integrates monitoring of the RES infrastructure for local energy generation and storage and of the data centre power consumption. This data is used by the Power Prediction GC to provide long-term predictions to support supervisory control decisions and power actuation. The Power Actuation GC determines set points for the power systems based on measured data, operational conditions, restrictions and limitations and the power profiles provided by the Supervisory Intelligence GC.

Supervision GCG: The Supervisory Intelligence GC is responsible for the overall coordination of workload, thermal, power management and heat recovery. It considers power demand and supply, grid energy price, energy storage model and determines how much power should be supplied from the electricity grid, RES and energy storage to minimize energy cost/maximize RES/minimize carbon emission accordingly over a given horizon. To this end, it provides policies for the actuation components in the Workload Management, Thermal Management, and Power & RES Management GCGs based on information from monitoring and prediction components. The Supervisory Intelligence GC provides these high-level policies to the Management GCGs for the purpose of guiding these component groups towards the Supervisory Intelligence GC strategy that has been chosen as a driver for current data centre operations; the key strategies available for selection are minimization of financial cost, minimization of carbon emissions and maximization of renewables. To detect and diagnose system anomalies, the Supervisory FDD GC compares predicted values with measurement data and collects and evaluates fault information. In appropriate situations, the Supervisory FDD GC informs the Supervisory Intelligence GC when a deviation becomes substantial enough to negatively impact system operation so that mitigation action can be taken by the platform until the fault has been corrected. The Human-Machine-Interface GC provides a framework for the user interfaces that allow data centre operators to monitor and evaluate aggregated data provided by the individual GCs.

Support Tools GCG: The GENiC platform includes a number of tools to assist data centre planners, system integrators and data centre operators:

- The Workload Profiler GC consists of a set of tools to capture application profiles that can be used by data centre operators to improve application performance.
- The Decision Support for RES Integration GC is a tool for data centre planners to determine the most cost-efficient renewable energy systems to install at a data centre facility.
- The Wireless Sensor Network (WSN) Design Tool GC is a tool to capture system and application level requirements for data centre wireless monitoring infrastructure deployments.
- The Workload Generator GC provides recorded and synthetic VM resource utilization traces for the simulation-based assessment of a GENiC based system and its implemented algorithms and policies.
- The Simulators GC supports the testing of individual and groups of GCs as well as the (virtual) commissioning of a GENiC platform before its deployment in an actual data centre.
- The Multi Data Centre (DC) Optimisation GC is tool that exploits the differences in time-zones, energy tariff plans, outside temperatures, performances of geographically distributed data centres to allocate workload amongst them in order to minimise global energy cost and related metrics.

Integration Framework GCG: The Communication Middleware GC provides the communication infrastructure used within the GENiC platform. The Data Centre Configuration GC uses a centralized data repository to store all information related to the data centre configuration, including information on data centre layout, cooling equipment, monitoring infrastructure, IT equipment, and virtual machines running in the data centre. Finally, the External Data Acquisition GC provides access to data that is not collected by existing components, including weather data, grid energy prices, and grid energy CO_2 indicators.

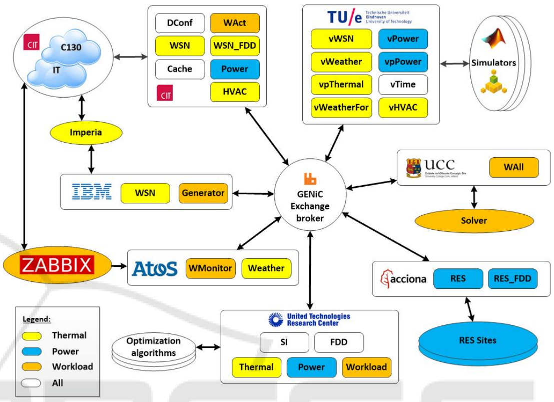

Figure 4: GENiC architecture implementation for simulation based assessment.

4 GENiC PROTOTYPE IMPLEMENTATION

Figure 4 illustrates a prototype implementation of the GENiC architecture presented in Section 3. The GENiC distributed architecture approach with clearly defined interfaces simplifies integration of a diverse set of software components from multiple manufacturers and service providers. The architecture is scalable, flexible and based on micro service architecture principles.

A central element of the implementation of the GENiC prototype is the use of the RabbitMQ (RabbitMQ, 2015) messaging system for the GENiC exchange broker. RabbitMQ provides a range of client implementations in a wide range of programming languages, which avoids compromising the integrity of the overall platform. The individual components are implemented as individual services that communicate via the RabbitMQ message broker. A generic client architecture has been developed to allow each component provider to expose their components in a distributed manner in the GENiC platform. The platform will be implemented in a real world demo site, a data centre on the campus of Cork Institute of Technology in Ireland (C130 DC), which has also been modelled in the Simulators GC (see below). We also use two renewable energy micro-grids that provide data real-time data via the GENiC platform on renewable energy generation capacity for the simulation models.

In order to enable holistic optimisation of the data centre energy consumption, the GENiC platform implementation contains a monitoring systems to guarantee that the information needed to optimise workloads and thermal distribution is collected. The monitoring components collect data with respect to IT workload (generated by both physical and virtual resources), thermal environment, cooling systems, power demand and power supply (including renewables). The correct monitoring of each management group within the platform is essential to properly operate the data centre.

5 SIMULATION MODEL - VIRTUAL C130 DATA CENTRE

GENiC has developed a Simulators GC, which is part of the Support Tools GCG. The simulator component includes energy models that emulate the performance of a data centre and its systems, supporting the development and testing of GENiC components (GC) as well as the commissioning of the overall GENiC platform, prior to its physical deployment in a real data centre. The Simulators GC consists of the following energy, space and system models as shown in Figure 5:

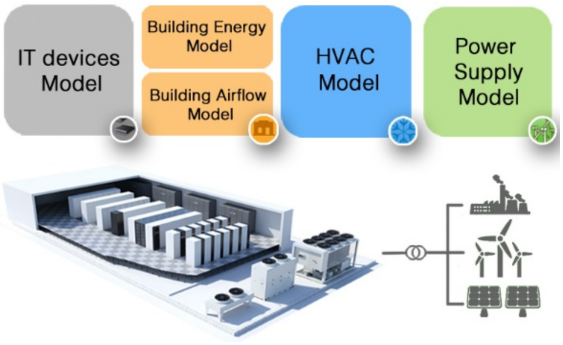

Figure 5: Types of energy models in the Simulator GC.

Demand Side - Data centre space (Building Energy Model + Building Airflow Model), IT devices model, and Heating, ventilation and air conditioning (HVAC) systems model

Supply Side - Power supply

The Simulator implements a virtual data centre model used for this study that is based on the actual GENiC demonstration site, the C130 data centre- at CIT. The data centre room is cooled by one main computer room air conditioning unit (CRAC) and one backup air conditioning unit (AC) as illustrated in the floor plan depicted in Figure 6.

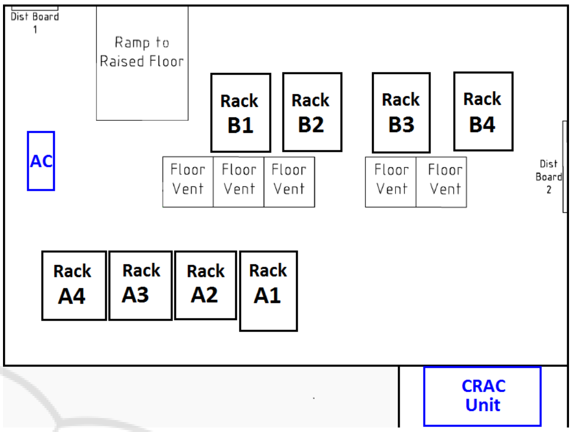

Figure 6: Floor plan of the data centre room used for the simulation based assessment.

5.1 IT Equipment and DC Whitespace Characteristics

To emulate the server workload in the data centre, a set of virtual machine (VM) configurations and the VMs' resource utilization traces are required. The traces used for this study have been collected from an IBM data centre production environment and reflect typical enterprise workload seen in a private cloud environment. The traces comprise resource utilization data for 2400 different VMs hosted on 132 servers. The key parameters of these servers are summarized in Table 1. The last column shows the number of servers of each specific type. Each server's dynamic power consumption is modelled as follows:

$$P_{server} = (P_{max} - P_{idle})\cdot u + P_{idle},$$

where u is the CPU utilization, P_{max} is the server's power consumption at full load (i.e. u=1.0), and P_{idle} is the server's power consumption at idle state (i.e. u=0.0 The total power consumption of all 132 servers is 24.5 kW if all of these servers operate at full load.

Table 1: Server parameters.

Type	CPU Size	CPU Speed	Mem.	Max. Power	Idle Power	# Servers
	[vcores]	[MHz]	[GB]	[W]	[W]	
S1	8	3'200	16	90	30	3
S2	8	3'200	32	95	35	8
S3	8	3'200	64	105	45	48
S4	12	2'000	64	130	70	2
S5	12	2'000	128	140	80	12
S6	12	2'000	256	160	100	23
S7	24	2'700	128	300	140	19
S8	32	2'000	128	400	270	14
S9	32	2'900	128	460	300	3

For the simulation based assessment, each server has been mapped to specific rack slot in the virtual data centre. Table 2 provides a summary of this mapping.

Table 2: Mapping of servers to racks in the virtual data centre.

Rack	Servers (top to bottom)	$\sum P_{max}$
A1	2 x S5, 6 x S3, 6 x S6, 6 x S8	4.3 kW
A2	no active equipment; patch panels only	0 kW
A3	10 x S3, 6 x S3, 3 x S6, 4 x S7, 2 x S8	4.2 kW
A4	no active equipment; patch panels only	0 kW
B1	2 x S4, 3 x S1, 8 x S3, 8 x S7, 2 x S5	4.1 kW
B2	4 x S3, 2 x S2, 4 x S5, 5 x S7, 2 x S8, 3 x S3	3.8 kW
B3	4 x S8, 4 x S6, 7 x S3, 4 x S5, 4 x S6	4.2 kW
B4	3 x S9, 6 x S6, 4 x S3, 6 x S2, 2 x S7	3.9 kW

5.2 HVAC System Characteristics

The indoor environment of the DC is maintained at 18 - 27 ˚C with a relative humidity of 30-60% as recommended by ASHRAE (ASHRAE, 2011). A CRAC unit ensures the required indoor climate. Supply air is distributed through a raised floor and goes to front side of IT devices through floor-performed tiles. Return air is drawn by the CRAC unit below the ceiling (Figure 7).

The conditions of circulating air are controlled in the CRAC unit by a direct expansion system. A condenser coil of the direct expansion system is cooled by glycol and heat is rejected to ambient in a roof-mounted drycooler. The process and devices involved are depicted in Figure 8.

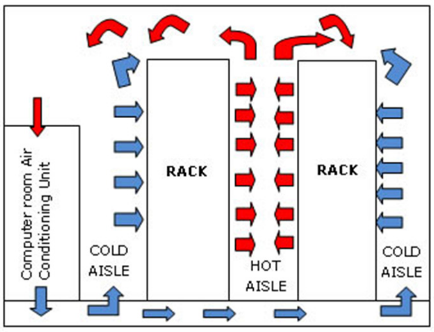

Figure 7: Schematic of hot and cold aisle arrangements without containments.

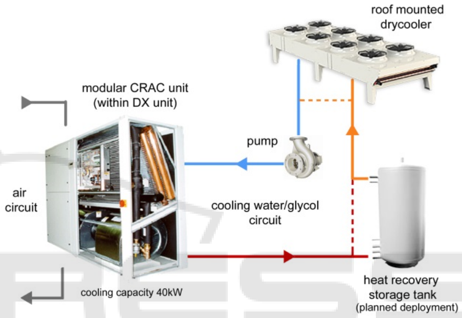

Figure 8: Main cooling system.

There is also an auxiliary floor standing air conditioning (AC) unit placed in the room, as shown in Figure 9.

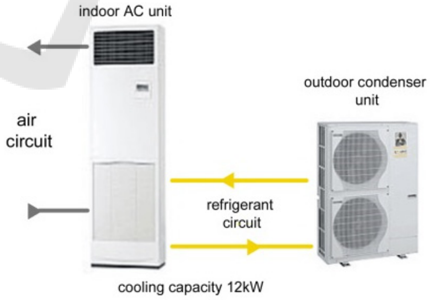

Figure 9: Auxiliary air conditioning unit.

6 SIMULATION-BASED ASSESSMENT OF ENERGY MANAGEMENT

The simulation based assessment of the GENiC energy management (EM) platform tests the interaction of short-term (S-T) actuation and long-term (L-T) decision making on a developed virtual testbed that replicates the physical processes occurring in the data centre facility. This interaction and the components involved are shown in Figure 10.

A key component in all evaluations reported in this paper (and shown in Figure 10 via the arrows between components) is the Communication Middleware GC, which provides the glue between all the different GENiC components and enables message exchange between components via the RabbitMQ broker (see above). The details which components are relevant to a particular evaluation are discussed in the following.

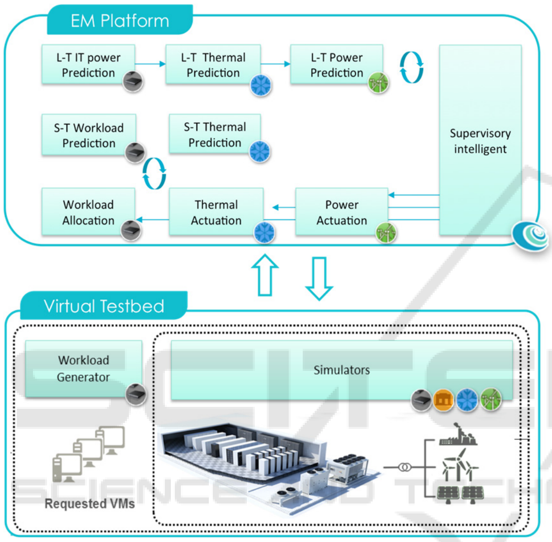

Figure 10: Schematic of interaction between EM platform GENiC components and Virtual Testbed.

6.1 Boundary Conditions for the Simulation-based Assessment

All use cases are tested based on identical boundary conditions so that the different operating strategies can be compared to each other. The following external factors are considered as boundary conditions:

- **Requested VMs** are related with the type of services and end-user behaviour.
- **Electrical Grid Info** is related with electricity market and the ratio of RES (CO_2 emission factor) in the grid.
- **Weather** conditions are specific to the DC location.
- **DC Operator Strategy** represents the baseline control strategy that establishes the reference baseline to assess the energy management saving potential.

6.2 Workload Management GCG

We test the Workload Allocation GC algorithm under the following scenarios (experiments):

- Workload Allocation – VM migration limits
- Workload Allocation – Thermal preferences

The test with VM migration limits refers to the testing of Workload Allocation GC with different values for the maximum number of VM migrations allowed per time period. The test with thermal preferences refers to the testing of Workload Allocation GC considering a static thermal server preference. This experiment represents a thermal-aware workload allocation strategy (Tang, 2007). This experiment assesses the performance of the Workload Allocation GC when it considers thermal actuation preferences. For the simulation based assessment, a static thermal preference matrix for each of the servers is developed based on Supply Heat Index (SHI) analysis (Sharma, 2002) of the C130 DC white space from the baseline inputs.

These scenarios compare against each other and against a baseline allocation strategy. This comparison is assessed based on i) the thermal behaviour in the white space (e.g. temperature distribution, hot spots), and ii) energy consumption

6.2.1 GENiC Components Involved and Testing Process

The GCs involved in this workload management evaluation are a subset of those that form the Workload Management GCG. The experiments for this evaluation follow these steps:

1. The Simulators GCs publishes the virtual time that will serve for the different GCs in the testing loop to synchronise their actions.
2. The Workload Generator GC publishes the VMs profile for the current time stamp
3. The Workload Allocation GC optimizes the allocation strategy for the given arrangement in the virtual C130 DC.
4. The Workload Allocation GC is able to consider thermal priority for each box (where each box represents one third of a rack). Static thermal priority will be used to test a thermal awareness-based workload allocation strategy.
5. The Sever Configuration component translates VM allocation to power consumption per box (1/3 of a rack).

The Simulators GC captures all the data relevant to this process for its analysis and post-processing. The focus of this use-case it to analyse the influence of workload allocation strategies in the temperature distribution of the white space as well as in the total DC energy consumption.

6.3 Thermal Management GCG

We tested the performance of the Thermal Management GCG algorithms with optimal thermal actuation. We will compare this scenario against a baseline operation strategy. This comparison will be assessed based on data centre energy consumption and white space temperature.

6.3.1 GENiC Components Involved and Testing Process

The GCs involved in this thermal management evaluation are a subset of those that form the Thermal Management GGCs. The experiments for the Thermal Management evaluation follow these steps:

1. Virtual synchronization time and current white space temperatures are published for the given timestamp.
2. The S-T thermal prediction GC predicts the thermal states of the white space for the next hour. This prediction supports the decision making process that takes place in the Thermal Actuation GC
3. Optimal temperature set points for the CRAC and AC units for the next timestamp are sent back to the HVAC systems model part of the Simulators GC

The Simulators GC captures all the data relevant to this process for its analysis and post-processing. The focus of this use-case it to analyse the influence of S-T Prediction and Thermal Actuation strategies in the temperature distribution of the white space as well as in the total DC energy consumption.

6.4 Power Management GCG

The aim of this evaluation is to test the Power Management GCG algorithms under the following scenarios (experiments) – i) Power Actuation Logic, and ii) Power Actuation Logic + SI static constraints These scenarios will be compared against each other and against the baseline operation. This comparison will be assessed based on – i) energy demand vs supply (Broken down per source)

6.4.1 Genic Components Involved and Testing Process

The GCs involved in this use-case is a subset of those that form the Power Management GGCs. The experiments for the Power Management evaluation follow these steps:

1. The Simulators GC generate the virtual time stamp and the current status of power metering in all equipment at the demand-side (DC) and at the supply-side (on-site).
2. The Power Actuation GC generates optimal set points for the electricity batteries and the ORC plant for the next time step
3. The Power Actuation GC receives a power policy (24h profile) from the Supervisory Intelligence GC. A static SI constraint was used for the testing.

The Simulators GC captures all the data relevant to this process for its analysis and post-processing. The focus of this evaluation it to analyse the Power Actuation operation strategies to satisfy the total DC demand. The power actuation real time adjustments are defined to assure the renewable energy supply contribution, balancing the lack or excess of weather dependent generation using the controllable unit characterized with “unlimited” energy (kWh) capacity which is the ORC that will never end the energy capacity if the biomass storage is continuously refilled. It has to be understood that electrical batteries are characterised by limited energy capacity (around 10 kWh) and limitations for the operation according to the definition of FSoC (fractional state of charge: between 0 and 1) upper and lower limits. As stated before, according to the difference between RES weather dependent units prediction and real production, the ORC generation is adjusted taking into account the upper and lower power available referred to the maximum and minimum generation capacity of the ORC (4kW minimum and 7 kW maximum).

7 EVALUATION RESULTS

In the following we present in the first instance evaluation results from the Workload Management GCG. The simulation-based experimental setup involved allocating workload over a 48 hour period in a data centre using real VM resource utilization traces. Each VM was initially assigned to the server indicated in the real traces. Therefore the Workload Allocator GC did not control the initial assignment and could only influence power consumption through VM migrations and server consolidation.

7.1 Workload Allocation – VM Migration Limits

We first tested the impact of the migration limit on the workload allocator (without thermal priorities for servers). The baseline is a migration limit of 0, i.e. each VM was run on the server it was initially assigned to. We then tested various migration limits (from 1 to 100) as shown in Figure 11.

We observe that, as expected, increasing the migration limit resulted in a reduction in power consumption (see Figure 11). The largest migration limit tested (100 migrations per 10 minute time period) required just a few time periods to achieve a reduction from approximately 11kW to just over 4kW. Indeed, the average hourly energy consumption of the IT equipment was 6.71kWh less with a migration limit of 100 than with the baseline.
The figure for IT power consumption (see Figure 11) further illustrates that all positive migration limits tended to this equilibrium state, with a migration limit of 10 reaching the 4kW mark in less than 9 hours and the limit of 5 requiring approximately 24 hours. Once reached, the variations in power consumption between the migration limits were minor. This means that if the workload allocator had controlled the initial assignment of VMs to servers, then a migration limit of 10 or even 5 would have been sufficient to achieve similar savings as with a limit of 100.

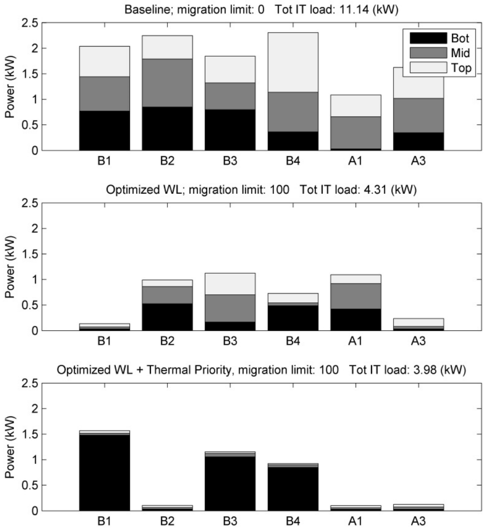
Baseline; migration limit: 0 Tot IT load: 11.14 (kW)
Optimized WL; migration limit: 100 Tot IT load: 4.31 (kW)
Optimized WL + Thermal Priority, migration limit: 100 Tot IT load: 3.98 (kW)

Figure 12: Workload distribution per third of rack.

7.2 Workload Allocation – Thermal Preferences

The following experiments were performed under identical settings to those previously discussed with the exception that each server had an associated thermal preference thereby allowing a proper ranking of servers. The thermal preference was used to rank the servers for consolidation.

In addition to the baseline described in the previous section, we tested with and without thermal preferences for migration limits of 10 and 100. The experiments showed there to be little difference in the total IT power consumption for the thermally ranked

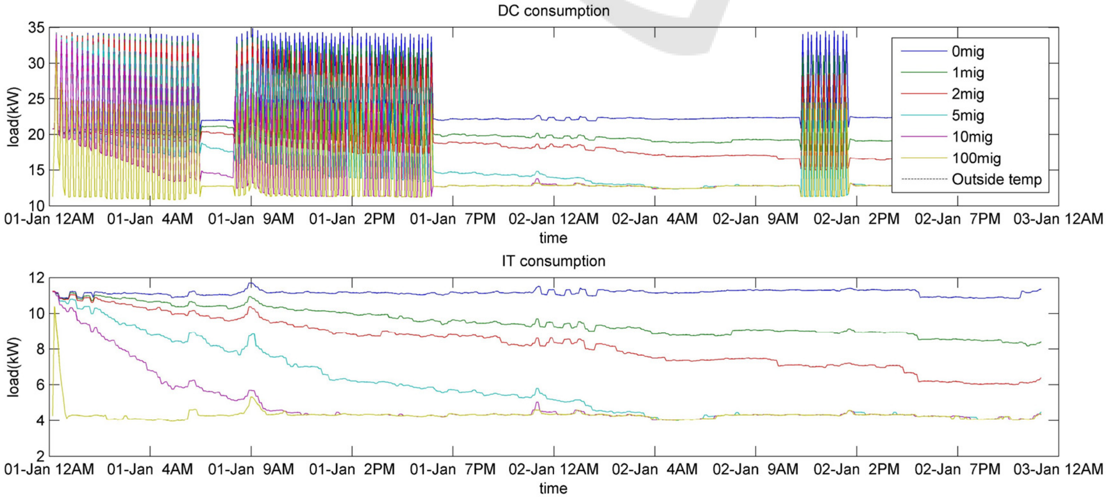
DC consumption
IT consumption

Figure 11: Power consumption with different migration limits over 48 hour horizon.

server consolidation, while HVAC energy consumption was reduced by approximately 20kWh over the 48-hour period relative to the baseline approach, and by 6.5kWh compared to the scenario with 100 migrations and no thermal preference.

The behaviour of the scenarios with thermal preference can be better understood when analysed at the third of rack level (top, middle and bottom boxes) as shown in Figure 12. We observe that the only servers used were the bottom level of three racks: B1, B3, and B4. The loads from all the other servers were migrated and the servers powered off, as can be seen from the power value for the scenario with thermal preference and limit of 100 migrations

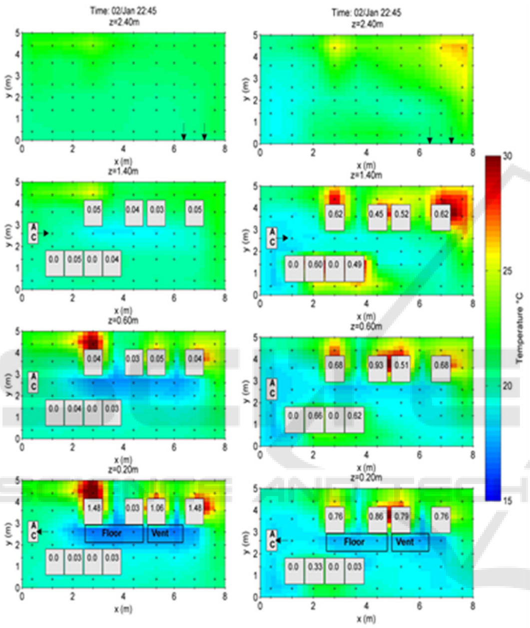

Figure 13: Temperature distribution for (a) thermal preference and (b) baseline.

Finally, Fig. 13 presents the temperature distribution of the DC for (a) the thermal preference with 100 migrations and (b) the baseline. The baseline study indicates risks of a hot spot at top layer of the last rack in row B. The supply air temperature is around 18°C, however the inlet temperature of the particular box is approximately 23°C. The rise of temperature is due to infiltration of hot air from the hot aisle to the cold aisle space. The optimized workload allocation with thermal preference scenario ensures that the airflow will use the shortest path from the cold air supply to the heat source. The cold air is taken by preferable servers in the bottom boxes. The typical cold aisle-hot aisle distribution can be observed in this case. The inlet temperature of all active servers is approximately 18°C.

8 CONCLUSIONS

In this paper we present and architecture for an integrated energy management system for data centres proposed by the FP7 GENiC project. The proposed system combines optimisation of energy consumption by encapsulating monitoring and control of IT workload, data centre cooling, local power generation and waste heat recovery. We also present initial results from a simulation based assessment of some of the energy management algorithms. The initial simulation based assessment was chosen by the project for a number of reasons. Firstly, it allows to evaluate the performance of management and control algorithms before deployment in the real data centre space. Secondly, the architecture of the platform is designed such that the system interacts with the simulated data centre in the same manner as it interacts with the components in a real data centre, allowing also the testing and commissioning of novel management and control concepts before deployment in target space. The specific algorithms developed in GENiC attempt to optimise strategies focused on Workload, Thermal and Power management in a data centre. The optimisation occurs at different time horizons, short term predictions are generated to support actuation decisions that are made within each of the mentioned Management groups, and long-term predictions supporting decision making at the supervisory level (coordinating Management groups). Here we have focused on an initial analysis of workload and thermal management techniques. The operation strategies applied by the Workload Allocation GC prove significant savings potential (of up to 40%) in terms of total energy consumption. This reduction is achieved through the optimization of the allocation strategy of Virtual Machines (VMs) while switching off unused servers. The performance of the Workload Allocation GC shows a more effective utilization of the DC with the same number of processed IT jobs. In the final year of the GENiC project we will replace the simulation environment by a real physical data centre for the evaluation and demonstration of the developed management algorithms and strategies in a real world setting.

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