# SmartDSM: A Layered Model for Development of Demand Side Management in Smart Grids

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## ABSTRACT

Growing power demand and carbon emissions is motivating utility providers to introduce smart power systems. One of the most promising technology to deliver cheaper and smarter electricity is demand side management. A DSM solution controls the devices at user premises in order to achieve overall goals of lower cost for consumer and utility. To achieve this various technologies from different domains come in to play from power electronics to sensor networks to machine learning and distributed systems design. The eventual system is a large, distributed software system over a heterogenous environment and systems. Whereas various algorithms to plan the DSM schedule have been proposed, no concerted effort has been made to propose models and architectures to develop such a complex software system. This lack of models provides for a haphazard landscape for researchers and practitioners leading to confused requirements and overlapping concerns of domains. This was observed by the authors in developing a DSM system for their lab and faculty housing. To this end in this paper we present a model to develop software systems to deliver DSM. In addition to the model, we present a road map of software engineering research to aid development of future DSM systems. This is based on our observations and insights of the developed DSM systems.

## Categories and Subject Descriptors

D.2.11 [**Software Architectures**]: Domain-specific architectures; C.2.4 [**Distributed Systems**]: Distributed applications

## General Terms

Software Engineering



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## Keywords

Smart grids, software engineering, demand side management, model driven design

## 1. INTRODUCTION

Growing power demand and carbon emissions is motivating utility providers to introduce smart grid. Smart grid is integration of computing components or information technology with the current and future electric grids [10]. That is, the future electric grids will incorporate software components to enhance its operations. From a software engineering perspective integrating software components in a very large, distributed, heterogenous system with varying system states is a daunting task. Take for instance the concept of demand side management [5]. Rahimi and Ipakchi proposed that we control the devices at user premises to achieve certain global goals [11]. This concept lead to a series of researchers exploring algorithms which can plan the devices to achieve the global goals [16][12][7]. There were various recommendations ranging from devices being smart enough to decide when they need to run based on global goals to simple systems where a smart plug is instructed to transition states based on a globally communicated information [12]. The system boundaries are usually defined as per the understanding of the author and vary greatly.

From a software engineering perspective however this task is not trivial. A device that can calculate the most optimal time to run requires sufficient hardware and software power. Pertinent question such as its maintenance, deployment, development, testing, verification and validation are so far not answered since there is no specific model over which the system is defined and built.

Experience in software engineering research and practice however has shown us that construction, deployment, testing and maintenance of large scale distributed systems is a complex task requiring specific software engineering skills and techniques. When we consider smart grids, the complexity is multiplied as the environment and the hardware both are heterogenous and distributed. Upgrading a code is much more complex when the hardware resides inside an expensive home device and security assumes more importance when devices inside a consumer's house can be controlled remotely.

Under such critical circumstances we believe that a well engineered software system is a must. However, when we started building our own DSM system we did not find any specific model which we can use to build a DSM system. To ameliorate this situation we developed a layered model to build DSM using the existing DSM algorithms and hardware and software components. The model was validated by using SmartDSM to develop a DSM system for a different set of requirements and environmental scenario.

Our experience shows that our model provide a good abstraction mechanism to develop a DSM system. Furthermore it provides crisp system boundaries for the sub-components aiding in their design, construction, verification and validation.

The paper is presented in the following way. In section 2 we ground the problem by describing the concept of DSM in smart grids and how it can help in reduce cost of energy as well as reduce its impact on the environment. In section 3 we describe the specific DSM system that we set out to build which served as the pilot study to develop the model. In section 4 we describe the model followed in section 5 by a description of its deployment in our second DSM system. In section 6 we discuss point of research and exploration in software engineering to aid development of DSM systems. This section also serves as the future work. In section 7 we conclude our work.

## 2. DEMAND SIDE MANAGEMENT IN SMART GRID

Electricity is considered the cornerstone of the human progress in the past century and is most likely to play a major role in the growth of humanity. However, the growing demand and dwindling supply of principle fuel for electricity generation - fossil fuels - has compelled the electricity generation companies to stream line and improve their systems. Like all commodities, electricity follows the usually economics supply and demand principles, more the demand higher the price. However, unlike other products the case of electricity is particular. First, electricity storage is not very profitable as the cost of storage in the best case is as much as producing it [4]. Secondly, the cost of production of electricity and its environmental impact is not linear. Various sources of electricity generation are available with variable upfront and operational expenses. Based on the average and peak needs of a system, different generation choices are made. For instance, 78% of French electricity is derived from nuclear but in Sweden where hydro-electric plants are feasible, a major contribution is from the hydro-electric projects [15]. Though both hydro-electric dams and nuclear power plants cost exorbitant amount of money, they produce electricity continually and at very cheap rate. To reduce the cost in almost all such systems the base or average load is derived from such continuous and operationally cheaper sources and at times of higher demand fossil fuel plants are used for electricity generation which cost more and are more polluting as well. These are generally called peaker plants.

Given such a scenario, one of the most promising way to reduce the cost and environmental impact of electricity production is to level the electric demand, that is average to peak ratio is reduced so that no peaker plants are needed. This concept is called demand side management [5]. However, such an arrangement is very complex and hitherto was not applied to majority of loads due to their numerous number. With development in computing communication and systems Rahimi and Ipakchi presented the idea that if we can use the smart grid infrastructure then we can apply this DSM to home consumers as well which make up roughly 40% to 60% of peak load in different countries [11].

To give an illustration of how this will be of help we take the example of author's universities' electricity system. The university is provided electricity by the utility at 8 cents for first 2 MW. After that the energy costs doubles to 16 cents per unit. The university has number of gas generators which can generate electricity at 4 cents a unit but gas is not available in the three winter months. In addition diesel generators generate electricity at 14 cents per unit. The first priority of the system is to run gas generators at times when it is available. If demand surpasses the capacity of gas generators then electricity is purchased from utility. When demand surpasses the 2 MW limit then diesel generators are used. What is important to note is that cost of electricity is not linear. The cost to start a generation unit is roughly 60% of the total cost after which the cost is linearly related to demand. That is, if we require 1 KW from a 1 MW generator then cost of generation is 60% of the cost of generation of 1 MW from this unit. In fact, it is recommended that generators should be loaded to 80% of their rated power for optimal operations. Therefore when a gas generator is switched on, it is advisable to use the available energy to the fullest and reducing load at this point is detrimental. In short, For optimal costing the goal is that either we avoid starting up a generation unit and if we have it powered on then we use it to its maximum potential.

A DSM system would attempt to reduce the energy consumption so that the cost of generation is minimal. To achieve this there are three schemes observable in literature. First is where the cost of electricity generation is passed onto the device, house or neighborhood where a smart controller in the local setting decides if it can move its load to a less costly time. The second stream is where the controller attempts to reduce the load by switching off devices which are of low priority or move the load where he consumer's preferences allow the device to be moved. Third is a bit different case where the goal is to maximize renewable source utilization. That is, if a solar panel is used then the system tries to move loads to the sunlight timings to maximize the use of the available energy.

Although the algorithms provide an important aspect of a DSM system, a complete software system which can deploy these algorithm requires much more effort and engineering to deploy and use. In the next section we will first describe the pilot system that we developed followed by a description of the model we developed for deploying the DSM and show how it helped us in deploying the second system.

## 3. PILOT SYSTEM: DSM IN COMPUTING LAB

The pilot system to reduce cost of electricity through demand side management aimed at deploying DSM in computing labs in the computer science department. We applied the second strategy, that is, reduce the energy to defined threshold to reduce overall energy cost. In our labs we have laptops, PCs with uninterrupted power supply (UPS) and other devices which can be switched off for a short duration without affecting the consumers. Our hypothesis is that at times of peak consumption, if we can off-load these movable loads to later timings then we can reduce the peak load amplitude and duration. Therefore when system load is bound to cross gas generator limits we move the loads forward to reduce the net load to the threshold and use the cheapest generation system. But if we are unable to keep this level of demand then we start purchasing electricity from the utility up till 2 MW of net demand. Once we reach this point we again try to shed some load and so on.

The algorithm we used was a modified version of ColorPower proposed by Ranade and Beal [12]. The algorithm was deployed on research labs in the computer science department. The algorithm requires consumers to assign priorities to the devices. Based on the supply-demand gap, the algorithm assigns probability of load shedding to each priority level. For example, if our net supply is 2 MW and our demand is 2.1 MW with 1 MW belonging to the lowest priority level then the lowest priority devices will be switched off with the probability of 0.1. Since 1 in 10 devices will be switched of from a pool of 1 MW our net reduction will be 0.1 MW giving us the demand of 2 MW which is equal to the supply. There were various practical issues that required rethink of the algorithm details of which are published in [13].

However, this only constitute the algorithmic aspect of the system. To develop this complete system we required series of software and hardware components and maintain them over the life cycle of the product. To measure the demand of the system we deployed meters. To control the hardware we developed our mots. However, as we noticed, the demand of electricity varied significantly and realtime data collection and decision making was not feasible. To solve this problem we modeled consumption and used limited forecasting to improve performance. To achieve this though we required update to the firmware of mots which became a project in its own. In short we stumbled across a range of software engineering problems that required our attention but no specific model was available to develop such a a system. In fact, Kazman and colleagues claim that the no models exist for smart grid system and the model has to be ad-hoc [9]. But our experience showed that this is not the case and we did see a pattern and model which we can use for our future DSM deployments. To this end in next section we describe a layered model for DSM development, deployment and research. The reason we developed a model is because we aim to develop different DSM systems for different scenarios. A model provides us with abstraction to define the general concepts in which specific domain specific technologies can be integrated with to deliver a specific solution.

# 4. PROPOSED MODEL

Our efforts to build a DSM system resulted in a software engineering chaos. To resolve this situation we build a layered model to separate the areas of concern and research, define crisp boundaries of the system for researchers and developers, and provide a method to develop future DSM systems. The system model is shown in figure 1. The layered model is composed of four components: a cyber-physical device mot, a self-aware local environment model, a device scheduler and a dispatch planner.

## 4.1 Cyber-Physical Device Mot (CPDM)

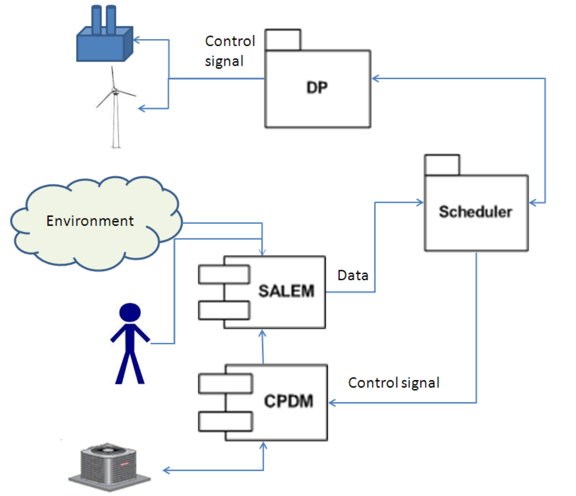


**Figure 1: SmartDSM Model. The lines show flow of data. CPDM monitors and controls consumer devices. SALEM collects data from environment, devices and measures human element to model the consumption for Scheduler. The Scheduler gathers data from SALEM and DP and schedules devices. The control signal is passed to CPDM. On the other side DP plans optimal dispatch and in some cases consult with the Scheduler for optimal planning.**

The component of the system which interacts with the consumer device is the cyber-physical device mot (CPDM). A mot is a cyber-physical device which has both monitors and actuators to control an entity. In essence it is the interface to the physical object that is being monitored and controlled in the system. The DSM system controls the devices in the consumer's premises. To implement this functionality we require cyber-physical systems which can control the hardware and communicate with the planning system. The mots available in the market vary from simply relays to device integrated systems with varying computing, monitoring and controlling power. The choice of device depends upon the needs of system and algorithms. However, from an engineering perspective it is important that a uniform interface is provided to the CPDM for access and control.

In our implementation we constructed a bridge to convert various device protocols and standards to communicate with the layers above. A good replacement is the SmartScript proposed by Adolf and colleagues [1]. The SmartScript was published after our pilot system hence was not used for our systems.

## 4.2 Self-Aware Local Environment Model (SALEM)

The self-aware local environment model (SALEM) in our view is the key to user-acceptable DSM deployment. Electric systems are very sensitive and the physics of the system demands that the supply of electricity is always more than the demand. In such critical situation, a good estimate of current state of consumption and possible future paths is of utmost importance. The device mots by their nature are restricted to the operations of devices. However, the consumption patterns are driven by human consumers as shown by Javed and colleagues [8]. SALEM provides a context to the mots data and provides a state model to predict the next states of the system.

Modeling of the environment is somewhat the most ignored module in the research community. Although pervasive computing has explored self-awareness in detail but self-awareness and its relations with energy consumption has not been explored specifically. Since this awareness may require cyber-physical sensors, the two modules have a point of integration where the two tasks can be partially achieved through a single system. However, this is not always the case.

In our pilot system we used mots with monitors to calculate the demand. However, the latency in communication protocol provided a point of failure in extreme cases and thus instead we explored load disaggregation and electricity forecast based on environmental and human elements to model the device consumption to achieve self-awareness.

## 4.3 Scheduler

The third module is the DSM scheduler. This is the module which in most publications is considered as the DSM system. In all the cases the DSM system requires some information of the system such as demand, supply, device count etc. The scheduler constructs a schedule for device and propagates it to the devices. This propagation can be directly to the mots or can be through the self-aware environment. The model does not restrict this flow of information.

## 4.4 Dispatch Planner (DP)

The fourth module is usually not considered part of DSM in typical sense. However, it is part of the optimal scheduling of resources for delivering DSM in smart grids. Nevertheless it is possible to integrate the two modules as Arif and colleagues have shown, if decision of which generation unit to use is integrated with the decision of how much demand to curtail then the system savings can be greatly enhanced [2]. This decision of integration however, lies with the system designer and is based on various technical, financial and legal constraints.

In this section we have defined the proposed SmartDSM model. In the next section we will provide a description of how we used our model for the second DSM implementation followed by points of discussion and future work for DSM systems from a software engineering perspective.

# 5. VALIDATION: DSM IN HOME RENEWABLE INTEGRATION

## 5.1 System Description

Our second DSM system was very different from our first lab deployment from requirements perspective. The DSM system was deployed on a residential house fitted with renewable energy. In comparison to the first system, the second system had different goals, specifications and human elements. the goal in the home renewable integration is to maximize the usage of solar energy. Since the solar power is only available during the sunlight hours, it is important that we use our energy to the maximum in those timings. The system specifications and human element aspects are also different. In the computing lab the battery supplied devices can be offloaded during peak loads. The demand was concentrated in the day hours however this made the task of moving the loads harder. In contrast in our validation system the device consumption is spread throughout the day. The consumption is more erratic and the devices available for load movement are few. However, through our model we developed a system which delivered maximized utilization of renewable source as described below.

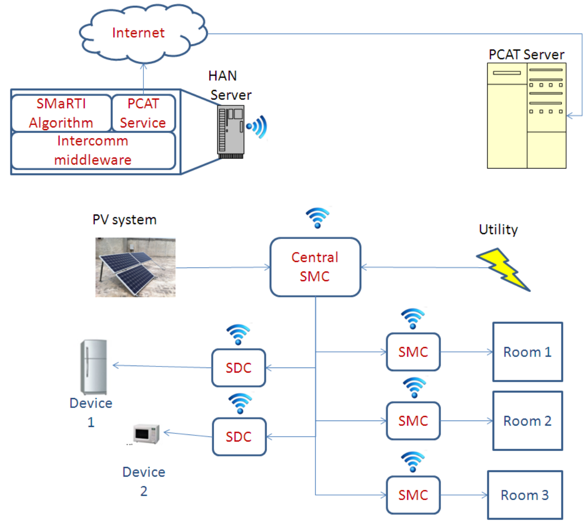


**Figure 2: System architecture of home renewable energy system. The SDC and SMC are two types of CPDM mots. SMC is able to transition between utility, solar and off states whereas SDC can only switch off or on the device. CPDMs connect to central server in the house using home area network (HAN). The server contains the code for Intercomm middleware which integrates various CPDM protocols to provide a single interface to the SALEM. SALEM in initial study was based the readings from CPDM but due to latency issue SALEM was extended with modeling features implemented through PCAT service. SMaRTI algorithm module is the scheduler and DP functionality is implemented through SMC.**

## 5.2 Model Driven Design of Home Renewable Energy System (RES)

We now discuss the design of development of home renewable energy system based on the SmartDSM model. Architecture of the system is shown in figure 2.

### *5.2.1 CPDM*

We used mots similar to the ones we used in our pilot study however in this case we used devices with better network range since the distance in the house are more than those in the lab. The controllers were connected via two different ZigBee networks to a server which collected the data and transmitted it to a web application specifically developed for data storage and visualization called PCAT [3].

### *5.2.2 SALEM*

We initially implemented SALEM using the power monitors in our CPDM. However, due to the latency and quick response requirements of this system we considered using a load disaggregation [6] and forecasting [8]. The data that was collected was passed to the PCAT. In comparison to our first system, in the validation system we plan to use a load disaggregation and forecasting algorithm to build a model of the system to predict future energy states. These states will then be used by the scheduling algorithm to build a device consumption schedule

#### 5.2.3 Scheduler

We developed a special Self-Managing Renewable Technology Integration (SMaRTI) algorithm. This development was not required as many other algorithms of this type could be used. for scheduling. However, to reduce the cost, we developed a trip mechanism to transfer the demand to utility in case the load overwhelmes the solar-based supply system as discussed next.

#### 5.2.4 DP

Our system specifications required a stable system where the solar-based system is limited to 3 KW of power generation. In case the supply from solar is less than the demand our system transferred some of the load to utility. This saves our system from overwhelming and tripping on its own. When the electricity demand is reduced or the supply increases to demand level, the system reverts to completely solar system. This switching in this system can be done by SMC CPDMs. From an algorithmic perspective the decision to select the source is made by DP but in this system its implementation can be achieved by controlling the CPDM thus providing a separation of concern without overwhelming the design.

### 5.3 Discussion

Our experience showed that deployment of second DSM system went much smoother than first one. This can be attributed to our experience in developing the first system. However, we maintain that through definition of this model the clutter of systems in the first deployment was handled in a much more systematic fashion. In the model based design and development the system boundary definition for components was much crisper resulting in better management of human resources and assignment of duties.

## 6. POINTS OF DISCUSSION AND FUTURE WORK

In the previous section we have defined the SmartDSM model. In this section we look in detail in the modules of this model and provide our insights into future directions of progress.

### 6.1 CPDM

Although different mots are available in the market and are being explored but there are software engineering challenges that are not being adequately addressed some of which are discussed below:

- Maintenance: Since these devices are firmware, their maintenance is a major issue. Though various techniques exist for managing the maintenance of cyber-physical systems. However, for a system which is critical and is widely distributed more research is required for maintenance aspects of these systems

- Legacy systems: DSM will control many devices in a consumers house and it is very unlikely that the devices will all conform to the new smart grid standards. Engineering for legacy systems is a strong domain in software engineering and lessons from these experiences should be applied to integration of legacy systems in smart grids.

- Inter-operability and integration of heterogenous systems: Research in smart grids is multifaceted and multi dimensional. This has resulted in a series of societies investing their time in developing new standards. Various industrial conglomerates are also developing their own standards. In such a diverse scenario a methodology for inter-operability and integration of heterogenous systems and protocol will be very beneficial.

### 6.2 SALEM

Self-awareness has been area of study of self-managing systems [14]as well as of pervasive computing [17]. However, self-awareness in a smart environment with respect to energy consumption is not very common. Within our lab we are exploring systems which can augment the self-awareness of existing systems and we propose this as a major challenge in the design and development of DSM systems.

Second, expression of self-awareness is a complex concept. What is required is a generic way to express the intent and possible future course of action of environment for the scheduling system to understand and plan upon. This may require a domain specific language for self-awareness for smart homes.

### 6.3 Scheduler and DP

Scheduling and dispatching are related fields therefore we will discuss the software engineering point of discussion together. Scheduling is the task of scheduling the devices and dispatch planning is the task of scheduling the generation unit to reduce cost and environmental impact. There are a plethora of systems proposed for DSM scheduling. In the year 2013 alone there were more than one thousand publications mentioning DSM in its text. there are two challenges in this regard to streamline DSM scheduling and dispatch planning research:

- Testing: The varied algorithms proposed use various measures and methods to compare their results. This is acceptable for research publications but to deploy control systems which impact the devices of consumers it is imperative that the system is thoroughly tested. Validation and verification of such DSM algorithms thus gains importance to verify that the promised savings will be achieved and validated that nothing will break. We require methods and techniques to test these systems comprehensively given the scope, size and criticality of the underlying system.

- Classification and Categorization according to requirements: Given the shear magnitude of the proposed systems, it is important that algorithms should be classified and categorized. We believe that categorization according to requirements of the system are the most appropriate for practitioners and researchers.

## 7. CONCLUSION

Smart grids of future are large scale software system integrated with electric grid component. At one level the system is a cyber-physical system however, for most part it is a very large, distributed, heterogenous software system of critical importance. From our experience as software engineering researcher and practitioners we know how difficult designing, building,testing, deploying, and maintaining these systems are. Therefore we need to take the leadership role and define models and architectures to development the smart grid system. This is required so that the future smart grid systems are maintainable, extendable and manageable. To this end in this paper we have presented a model to implement DSM - SmartDSM. We have used this model to build another DSM system and our observation is that it greatly aids in building, deploying and maintaining DSM systems. Furthermore, we have certain observations, insights and points of research and improvements in developing software engineering principles for DSM in particular and smart grids in general which we shared in this article.

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