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Diploma Thesis

Generator Maintenance Scheduling

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Dedicated to Nick

Abstract

The ongoing Electricity markets restructuring on a global scale, shifted much attention from centralized and in particular small isolated systems, typically found in islands. It is true that such systems, mainly run on liquid fuel Gensets, if not interconnected to some major grid may ever exhibit investment interest. As a result, many utilities constantly struggle while others due to fuel cost and the ever-increasing emission control restrictions, are near the verge to collapse. It is this necessity that actually urges for optimal managerial practices to exploit the last penny spent until-if ever, all these resource guzzling Gensets reach their retirement age. In this thesis we respect a realistic power plant feeding the tourist industry of an island. A 0/1 MILP formulation enables to accurately account for operation, maintenance and reliability status cost, providing in practical time a palette full of decision options. System demand is allocated in classes whereas the overall proposed reliability approach renders any chosen optimal schedule easily implemented in practice.

The EU's target and international commitment for 80-95% reduction in GHG by 2050, compared to 1990 emissions (Erbach, 2016), early on posed many challenges but also highlighted a lot of opportunities. The envisioned low-carbon economy heavily relies upon the reliable and efficient integration of renewable energy sources in the electricity production sector, of any country. But that is easier said than done. Major investments in critical infrastructure such as interconnection lines are absolutely necessary to boost the transition via market coupling, also enabling electricity cost convergence. In any case, the core aspect is that investments in low and zero-emission technologies are viable, if only certain technical barriers such as transmission capacity are overridden. As a result, if not for costly infrastructures to allow participation in some national or transnational market, investment interest for certain systems is limited.

This is the case for many small to medium sized isolated systems, typically found in islands. While in some cases there exists abundant renewable energy potential, absence of really costly transmission lines connecting to some main grid, do limit investment interest. It is true however that strategic planning, levies concerning renewables or both, enabled some variable capacity generators to commence operation. While the installed capacity is comparably small to any such system, it really poses additional problems to existing utilities and in many cases, rising costs. The intermittent nature of renewables, especially wind, calls for more spinning reserves if to reliably meet system demand.

But as for any system meeting rising demand annually, reliable energy production capability is in general, gradually pushed to the limits. No wonder since aging of production equipment is present and system reserves diminish. At some point, extra power stemming from newly installed Gensets compensate for the later, but that is an over simplification when cost efficiency is on the table.

Investments concerning installation of new production equipment correlate to high enough capital cost and all projects are carefully examined in great detail during planning. One such detail is the assumption that existing power production equipment shall be sufficient enough until new investments are to be realized in practice. The sufficient enough assumption takes as granted that no major failures are to arise, despite that some low impact instances are statistically anticipated that will certainly do.

What safeguards any power system against minor and major failures is above all the maintenance scheme adopted. Many cost-effective approaches do exist such as maintenance based on condition monitoring but the majority of power plants well adhere to fixed hours periodic preventive maintenance activities suggested in manufacturer's detailed manuals.

Such activities commence at some running hours with minor content and gradually escalate to major overhauls, where a Genset is not available for quite some time, typically 3 to 4 weeks. Despite the significant effect of minor maintenance instances, major overhauls are of greater importance and therefor are only taken under consideration when scheduling. It is a fact that if not delivered on time, at least premature aging due to economically irreversible wear damage is present. It follows that Generator Maintenance Scheduling (GMS) can guarantee the potential of safeguarding against Genset failures altogether with providing sufficient power to meet system demand.

On the other hand, major maintenance activities critically reserve certain amount of power for critical time. This is an issue since anticipated Genset malfunctions can lead to power shortage, compromising system reliability. As a result, GMS has to be considered in conjunction with the Unit Commitment problem assuring that at any time, sufficient power readily available will provide for system reliability, however the latter is defined or measured.

Alas, for the major part of the Energy Production Sector fuel cost is a cost leading factor. It is evident that production cost increases as long as less fuel effective Gensets keep running to meet system demand and reliability criteria. Inevitably, the Economic Dispatch problem has to be introduced in order to minimize total production cost over some period. Mukerji et. Al., (1991) put it the right way. "Generator maintenance scheduling is an integral part of overall planning …The maintenance schedule, annually updated with a 10-year horizon, is interrelated with the activities of fuel budgeting and purchasing, firm bulk power transaction planning and reliability assessment."

In our attempt, vital system operations are correlated forming a model and provided certain input parameters (system demand, maintenance duration etc.), the output of Generator Maintenance Scheduling is an optimal maintenance schedule in respect to criterions used, alongside with other valuable information.

The scope of this thesis is to provide a solid framework for that information to be sufficient and reliable enough to serve as a valuable decision aid. The holistic approach realized, offers a practical tool to enhance the performance of any utility, rendering cost savings and GHG emissions reduction, altogether. The former is greatly important, taking under consideration the scarcity of investments. The latter is mandatory as a contribution towards the global scope.

While commercial renewables do not exhibit great interest in small isolated systems, for reasons already explained, we must state that when dealing with such systems, detail plays a major role. Accurate modeling and optimality of solutions is very important for any small system incorporating any capacity of renewables. The reason is simple. While renewables serve the noble scope on the other hand may sky rocket utilities cost due to increased requirements in system reserves. And this is what makes this thesis relevant. Modeling approach presented renders major dimensionality reduction with minor accuracy loss enabling exact solutions readily available in practical time.

Generator Maintenance Scheduling (GMS) or Unit Maintenance Scheduling (UMS) is in nature a combinatorial problem. The utmost scope is to schedule preventive maintenance activities over a period of time, for each Genset belonging to a certain set, provided that an objective in the broad sense is optimized. In some cases, not that infrequent in practice, a single objective is crucial enough, especially when re-scheduling is mandatory for some reasons and many Gensets are involved.

As shall be clearly seen later, the objective function is a point of strong diversification among interested parts. In any case, a final solution conforms to the constraints of the model describing a system under consideration and provides the starting point for each Genset maintenance.

The GMS despite well studied yet is a problem difficult to solve. Usually it exhibits non linearity and real systems modeling call for many variables to be introduced, resulting in purposely loss of system detail if realistic solving time is a prerequisite. It is true however that despite the number of Gensets and time unit introduced, significant role play the computing power and the solving approach utilized.

Simplicity, ease of model understanding, ease of model modification and above all, time efficiency are calling for a deterministic approach. For example, someone could argue that load demand can be properly forecasted and that is true in some cases so it can be treated as deterministic. Maintenance duration for each Genset is another critical point. The list is endless, maintenance teams availability, special tools availability or even common tools availability (a bridge crane malfunction is not so rare) etc. exhibit a more or less level of uncertainty. It is more than evident that if uncertainty is not properly countered, it may provide management with useless or even malicious information, not serving the scope of the endeavor.

In such a case, all parameters should be carefully estimated and above all, continuously checked for consistency. This condition is sufficient for a model (in the chosen degree of detail) to be reliable enough so as to provide useful information.

No argue that GMS is a multi-objective optimization problem. A balance or a tradeoff among criterions used is inherent to the solution and the option of setting objectives as constraints (hard or soft) is intriguing. At the end, the simplifying final choice of approach is heavily influenced by the interests of the modeler. For example, in a regulated market all efforts concern minimizing costs whereas in deregulated markets the focus is on maximizing profitability and as a result, reliability is a main issue. But higher reliability for sure results in higher costs, in general.

Thesis is organized in 10 chapters. **Chapters 1 to 3** aim to provide some general knowledge to what concerns electricity production. The provided insight is absolutely necessary for the non-field expert to understand the problem at hand. Certainly, they can be skipped altogether for someone with in the power production industry.

In **chapter 4** a thorough literature review is offered, with special focus on the most important tunable parameter of any system, namely the operating reserves.

Chapter 5 is just a one page simple reference to the solution tool used. The solution tool is of great importance and as such, special attention is given.

Chapter 6 present some considerations of special importance, commonly met in practice. It is advised for someone interested in the field of optimizing power systems to acquire a solid understanding of them.

Chapter 7 introduces the basic means of Generator Maintenance Scheduling by presenting the utmost simplest instance.

Chapter 8 enhances complexity by introducing the Unit Commitment problem, an approach that best fit when system reliability is the only concern, besides the optimal scheduling itself.

Chapter 9 presents an holistic approach and the Economic Dispatch problem is introduced in addition.

Chapter 10 presents a summary and conclusions. Additionally, suggestions for future work are present for the interested.

A plethora of Appendixes provide support and evidence in order to make presented material more comprehensive.

Acknowledgements

Many people contributed for this thesis to materialize. I would like to thank them all but I feel obliged to mention some in particular.

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Chapter 1

Introduction

1.1 A Power System

Electric Energy is what makes our society keep running and blooming. Power plants constantly produce/generate broadly transmitted energy that is finally distributed to end users fulfilling their needs. An important point is that electric energy cannot be stored and as a result when produced has always to meet the demand, whatever the magnitude and variation of the later may be. In other words, in any fraction of time, generated power must equal the demand.

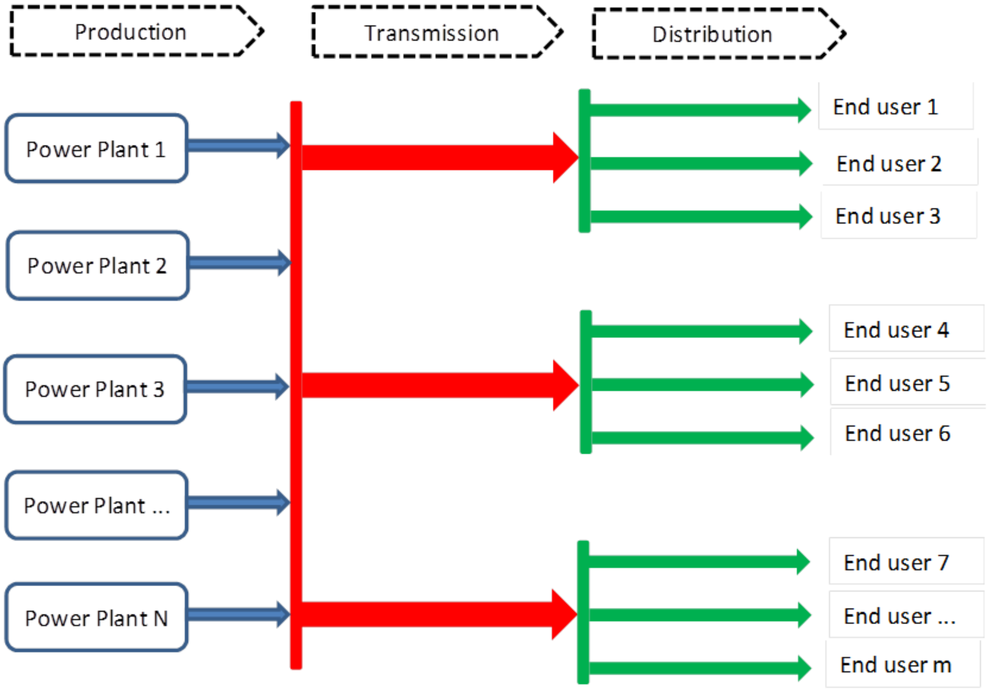


Figure 1.1: Typical system schematic

Energy produced by power plants (see Figure 1.1, above) located in suitable locations, is transmitted some hundred or thousand km away from production location. Thus, energy is transmitted with suitable technical characteristics (High voltage) in order mainly to reduce losses (cost reduction). Distribution side (Low voltage) finally feeds various end users such as houses, hospitals, pumping stations etc. In practice, several transmission lines are used (for redundancy reasons) and in some cases a single transmission line may serve just a heavy load end user.

If we think of electric energy as the final product of a process (physical or not), that process is not the same among countries around the world. Even in the same country it is possible for various processes to exist despite the fact that all processes share many common features.

Any process herein after shall be called a power system or simply system and the fact is that any system is associated with some kind of cost when it comes to the final deliverable, electric energy.

That cost may be monetary for example including fuel cost or environmental, taking under consideration GHG emissions among others. Or even a combination of. For example, co^2 emissions are charged with taxes and co^2 emission rights are traded in markets. As a result, GHG emissions constitute a real cost factor in addition to the actual impact on environment.

1.2 System regulation

The critical point is to realize that a system may be formed by many different interested parts (see Figure 1.2, παρακάτω). Generation companies, Transmission companies and Distribution Companies all participate in forming a system. But any system has to conform to certain rules so some entity has to serve as a regulator in principle. The regulator guarantees that at any point in the future, either in the short run or in the long run, demand shall be met effectively, reliably and efficiently ensuring the welfare and progress of society.

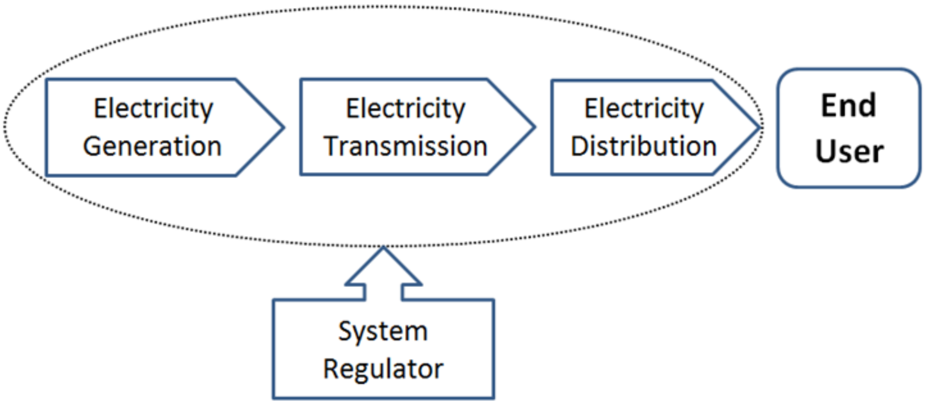


Figure 1.2:System organization

It has to be stated that in our current approach the end user is outside the boundaries of the system, as we have defined it. But the trend is that inevitably the end user will become part of the system. The integration is expected in the near future and there are many pros to it. For example, by lowering on demand end users power consumption or even the possibility of electric vehicles to discharge power to a power system offers significant flexibility to the later meeting reliability issues.

In some developed countries the regulating entity is independent (not heavily or even not at all influenced by government). In such a case the market is deregulated and anybody can participate in the system aiming for a share of the market. Bids concerning energy or various services are accepted or rejected and as a result end user cost is determined greatly by supply and demand forces.

But that is not the only case since in special cases (of great importance) or in less developed countries, all activities are controlled and carried out by the same entity (government). That was the practice until recent years and is not that surprising if we thing of the colossal investments needed (especially after WW2) in the electrical production sector. Any way in such a case we are speaking of a regulated market and the managerial practices involved, present great importance.

In both cases though, it is obvious that interested parts pay constant efforts in utilizing resources, either to maximize profit for the goods or services they offer either to offer prices as low as possible, with or without some profit. In any case, “the new competitive environment in power systems is demanding more efficient and accurate tools to support decisions for resource scheduling” (Carrion, 2006).

1.3 Perspectives

As a result, cost reduction is in any power plants daily agenda. This agenda is heavily influenced by the daily implementation of actions planned one, two or ore years in the past. Or it may even concern the real time implementation of an energy production schedule. The range of subjects in the agenda is practically big enough since many perspectives about cost reduction do exist.

When we finally arrive to the point we have to make some critical decisions, many times (as expected) we find they are conflicting to each other. In addition, a lot of factors constrain options we have regarding decisions to make. As a result, cost reduction in power systems (optimization) is challenging in nature and depends upon individual interests but if decisions are based on solid foundations, the final results are more than promising.

In our treaty we provide a general still practically useful approach for systems existing in regulated markets, since there is great interest and many worldwide small or large scale application instances still provide to common welfare. In particular, such systems are mainly found among islands but also elsewhere, as previously stated. Despite being relatively small concerning energy production, many subjects and related definitions are valid for large scale systems also.

In our treaty, we will focus on the generation side of electricity in regulated systems not only because corresponds to the leading cost factor but because it can also be safely treated apart from transmission and distribution costs and constraints (if no modifications are deployed to the later).

Without losing detail, here in after when we refer to a system we refer just to the part of Power Generation and in particular to a power station consisting of 1 or more Generating sets (Genset here in after).

Having said that, optimizing small systems may in practice be even more challenging, for certain reasons. Demand forecasting serves as an example. The smaller the system the greater the importance of accurate system demand forecasts. Another reason is that Renewable Energy sources (wind, solar etc.) have significantly great impact on small systems reliability and overall operating cost. Such a system (see Figure 1.2παρακάτω) could be treated safely for comparably small or even high Renewable Energy injection but for simplicity we will exclude any Renewable Energy injection from our treaty.

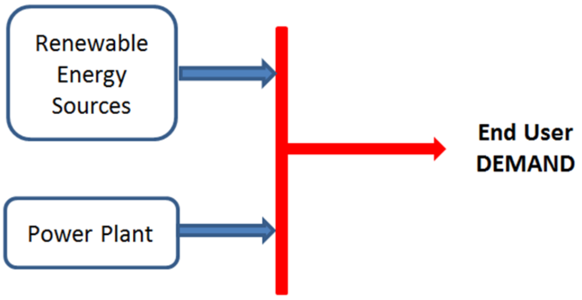


Figure 1.3:A simplified system approach

Small systems are commonly referred to as island (mode) systems.

Chapter 2

Fundamental technical concepts

The following to come gently introduce all necessary technical info and terminology concerning island mode systems. Special care was taken to adjust the text so as to correspond best to as general as possible an audience, without technical specialty on the area. We could say that the information presented here in after lie in the technical and managerial communication frontier. As a result, this chapter is full of figures for ease of understanding of underling concepts.

Potentially (and hopefully enough) it could provide some insight and fresh ideas to the ones interested in power systems optimization but luck specific technical knowledge. This chapter serves as a prelude to Chapter 3 where all necessary concepts will be finally (and gently) introduced. An imaginary but extremely close to a real system test case will serve for that cause.

2.1 Generating set

A Generating Set is the equipment producing electric power (electric energy) to meet electric demand (energy demand). Simply put, a Genset transforms the energy content of the fuel burnt to useful electric energy. In small regulated systems the commonly used fuels are liquid fuels such as Heavy Fuel Oil and Diesel Oil.

The commonly used measurement unit for electric power is the Mw:

1Mw = 1.000Kw

The measurement unit for energy is the Mwh:

1Mwh = 1.000Kwh

The formula used to derive energy from power is simple enough:

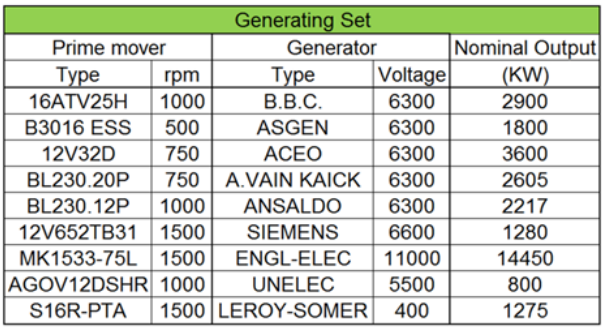
Power (Mw) x Time (Hours) =Mwh.

Example: a Genset running on 2Mwh output for 3 hours produces 6Mwh.

The main components of a Genset are, see Figure 2-1 below, the generator (the blue box in the foreground) that actually produces energy and the prime mover that rotates the generator.

Figure 2-1: Stationary Genset under maintenance

These parts are coupled together forming a Generating Set, with different upon request technical characteristics (see Figure 2-2 below).



Generating Set				
Prime mover		Generator		Nominal Output
Type	rpm	Type	Voltage	(KW)
16ATV25H	1000	B.B.C.	6300	2900
B3016 ESS	500	ASGEN	6300	1800
12V32D	750	ACEO	6300	3600
BL230.20P	750	A.VAIN KAICK	6300	2605
BL230.12P	1000	ANSALDO	6300	2217
12V652TB31	1500	SIEMENS	6600	1280
MK1533-75L	1500	ENGL-ELEC	11000	14450
AGOV12DSHR	1000	UNELEC	5500	800
S16R-PTA	1500	LEROY-SOMER	400	1275

Figure 2-2: Generating Set examples

During operation, well trained personnel (shifts) guarantee the reliable and safe operation by making routine physical checks and appropriate technical adjustments (see Figure 2-1 below). Supervising the operation of a Genset requires skillful personnel that has to take critical decisions many times in a fraction of second. In an emergency situation such as a malfunction, response time is extremely critical. Upon the severity of each instance, operation of a Genset might have to be seized (emergency stop) even in the fear of a blackout. The big picture is what really counts so personnel and production equipment health has to be constantly safeguarded.

Figure 2-3: Genset Local control room

2.1.1 Genset Power Output

Nominal Power or capacity of a Genset is the maximum Power it can deliver under certain conditions (ambient temperature, humidity, altitude) . A Genset can run up to nominal power or might run at a lower power, upon will or for other causes. Running power here in after shall be called Power Output or simply Output.

The difference between Nominal Power and Output is called Spinning Reserve (see Figure 2-4, below). It’s better for someone to think of it as a potential and it is important to grasp the idea through an example.

Suppose, just one Genset is running on Nominal Power to meet a stable magnitude demand. Suddenly, a sudden rise in demand appears but as Genset run on Nominal Output, no extra available power is present. As a result, the Genset cannot sustain operation and safety devices will trip it. To meet the problem, the chosen Genset should ideally have a higher Nominal power, so as for a spinning reserve to exist in order to meet fluctuations of demand.

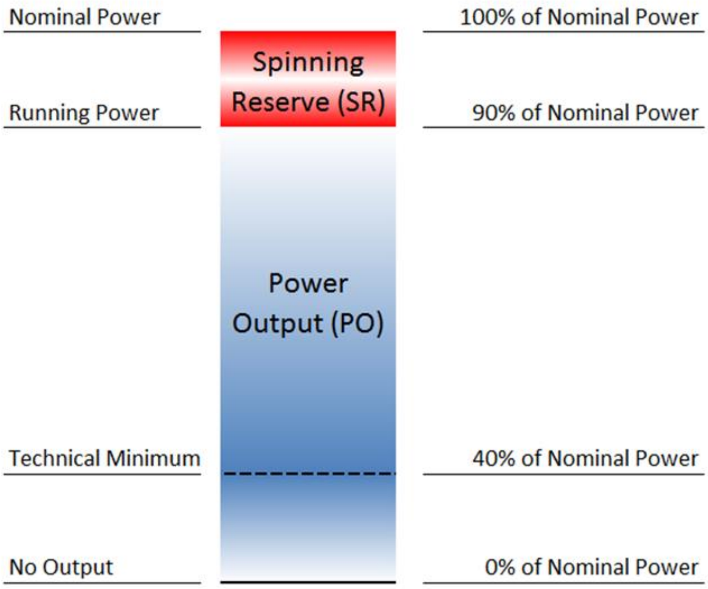


Figure 2-4: Generating Set power definitions

Also, a common technical operating constraint is that due to technical reasons, a Genset must not run bellow some output, for prolonged time. That point is called technical minimum and differs among various Gensets. In practice, it’s not advised to run a Genset bellow 40-45% of Nominal Output.

2.1.2 Fuel consumption

During operation, a Genset consumes various resources in general such as fuel, lubricants and other consumables such as air filter cartridges, at a theoretically pre-defined rate.

No argue that the most important of all resources is the fuel, since it’s the most expensive among all. But all Gensets don’t exhibit the same fuel burning efficiency. In addition, even any Genset itself doesn’t exhibit the same fuel burning efficiency over the entire range of its output. This overall efficiency is termed Specific fuel oil consumption (sfo) and represents the quantity of fuel utilized to produce 1 Kwh (See Figure 2-5 below). Typically, sfo units is measured in gr/Kwh.

At this point in order to avoid confusion we state that the term Specific fuel oil consumption refers to the fuel burning efficiency of a Genset, regardless the type of fuel it operates on (Heavy fuel oil or Diesel oil). Probably it would be best practice to use the term specific fuel consumption instead. But it is something like a convention used in practice since most of Gensets around the world operate on Heavy fuel oil.

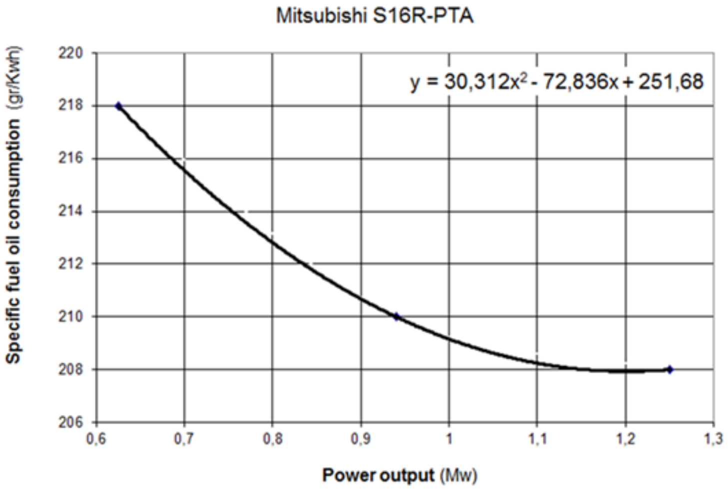


Figure 2-5: Specific fuel oil consumption example

In determining the sfo of any Genset a point of extreme interest is whether energy is measured at generator or transformer terminals (countering transformer efficiency) but we won’t delve in more technicalities.

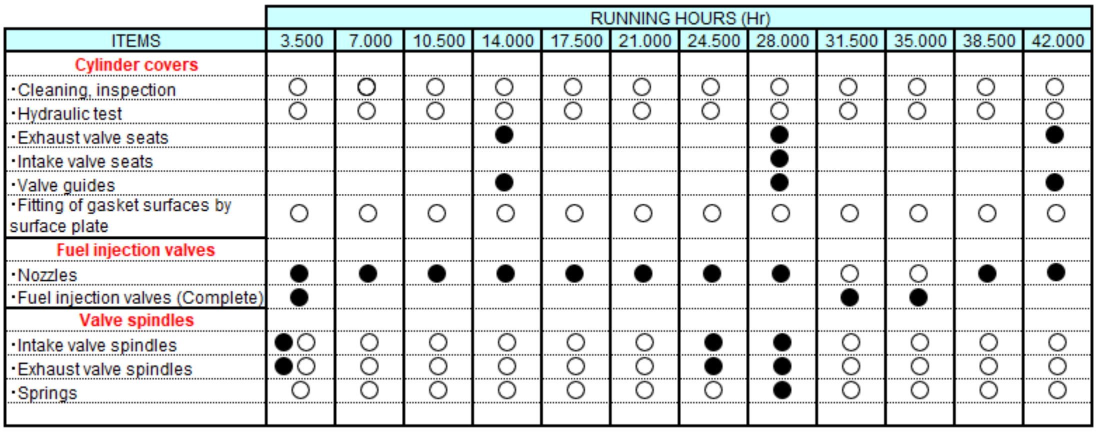
The important part to keep in mind is that the overall fuel burning efficiency can be described by a quadratic function. As we can see from Figure 2-5 above, the higher the output, the higher the efficiency. Alas, this is not always true for really aged but still in operating condition Gensets designed in past decades. The corresponding prime movers were naval engines used to exhibit best efficiency in less output than Nominal Power.

Generally, different Gensets exhibit different sfo curves but it must be stated that even among identical Gensets, differences may do exist mainly due to maintenance reasons as shall be explained after.

Its common sense that in order to reduce fuel cost, a running Genset should realize an output as high as possible. But that is not possible in many cases since a Genset has to provide an output smaller than Nominal Power for reliability issues (spinning reserve). And here lies part of the problem this thesis is dealing about.

2.1.3 Maintenance

As a Genset is operating and producing energy, simultaneously it accumulates running hours. After certain running hours of operation, a Genset must be stopped for maintenance regardless it is a simple inspection, a short period maintenance or major overhaul. All necessary information about maintenance activities to be commenced at certain time intervals is clearly stated in the operation and maintenance manual of any Genset (see Figure 2-6, below).



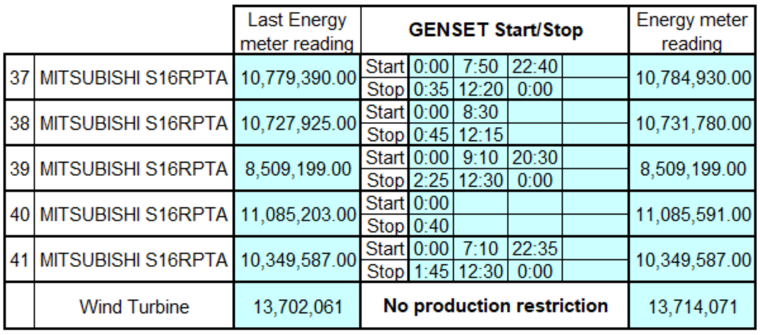
	RUNNING HOURS (Hr)											
ITEMS	3.500	7.000	10.500	14.000	17.500	21.000	24.500	28.000	31.500	35.000	38.500	42.000
Cylinder covers												
·Cleaning, inspection	○	○	○	○	○	○	○	○	○	○	○	○
·Hydraulic test	○	○	○	○	○	○	○	○	○	○	○	○
·Exhaust valve seats				●				●				●
·Intake valve seats								●				
·Valve guides				●				●				●
·Fitting of gasket surfaces by surface plate	○	○	○	○	○	○	○	○	○	○	○	○
Fuel injection valves												
·Nozzles	●	●	●	●	●	●	●	●	○	○	●	●
·Fuel injection valves (Complete)	●								●	●		
Valve spindles												
·Intake valve spindles	●○	○	○	○	○	○	●	●	○	○	○	○
·Exhaust valve spindles	●○	○	○	○	○	○	●	●	○	○	○	○
·Springs	○	○	○	○	○	○	○	●	○	○	○	○

Figure 2-6: Maintenance manual abstract

Furthermore, all spare parts needed for the successful conclusion of any maintenance operations are explicitly stated.

Generally, what concerns more the technical staff is when major preventive maintenance instances occur. Generally, as a Genset accumulates running hours its fuel burning efficiency exhibits a worsening trend and gradually, more fuel is needed to produce the same amount of energy. That’s where maintenance activities in general, restore a Genset to a previous state of higher efficiency. For sure, other reasons for maintenance activities do exist.

In practice, some Gensets realize intermittent operation (see Figure 2-7, below).



		Last Energy meter reading	GENSET Start/Stop					Energy meter reading
37	MITSUBISHI S16RPTA	10,779,390.00	Start	0:00	7:50	22:40		10,784,930.00
			Stop	0:35	12:20	0:00		
38	MITSUBISHI S16RPTA	10,727,925.00	Start	0:00	8:30			10,731,780.00
			Stop	0:45	12:15			
39	MITSUBISHI S16RPTA	8,509,199.00	Start	0:00	9:10	20:30		8,509,199.00
			Stop	2:25	12:30	0:00		
40	MITSUBISHI S16RPTA	11,085,203.00	Start	0:00				11,085,591.00
			Stop	0:40				
41	MITSUBISHI S16RPTA	10,349,587.00	Start	0:00	7:10	22:35		10,349,587.00
			Stop	1:45	12:30	0:00		
	Wind Turbine	13,702,061	**No production restriction**					13,714,071

Figure 2-7: Abstract of a power plant log

As a rule of thumb, any start / stop operation contributes to a higher wear or deterioration rate for certain parts of a Genset and if possible, this factor should be taken under consideration. We can say in general that, each start/stop operation has an equivalent of some running hours and if respective info is not provided by the manufacturer, there exists no reliable rule of thumb to be used.

2.1.4 Derating

So far, we have treated the output of a Genset in respect to its Nominal Power but as it will be shown shortly after, this approach is not valid for all cases. When the output of a Genset cannot reach its Nominal Power, it is said that the Genset is derated. In such a case, taking under consideration derating, the so-called available power is the maximum power a Genset can deliver in practice

Derating is commonly met in practice and we do not refer to power un-availability due to maintenance activities. Derating, in principle, is due to environmental conditions such as air temperature and humidity. Equipment manufacturers provide respective info indicating the maximum power a Genset can operate (or provide a power reduction factor coefficient) under various environmental conditions. A handy chart is presented in Figure 2-8, below.

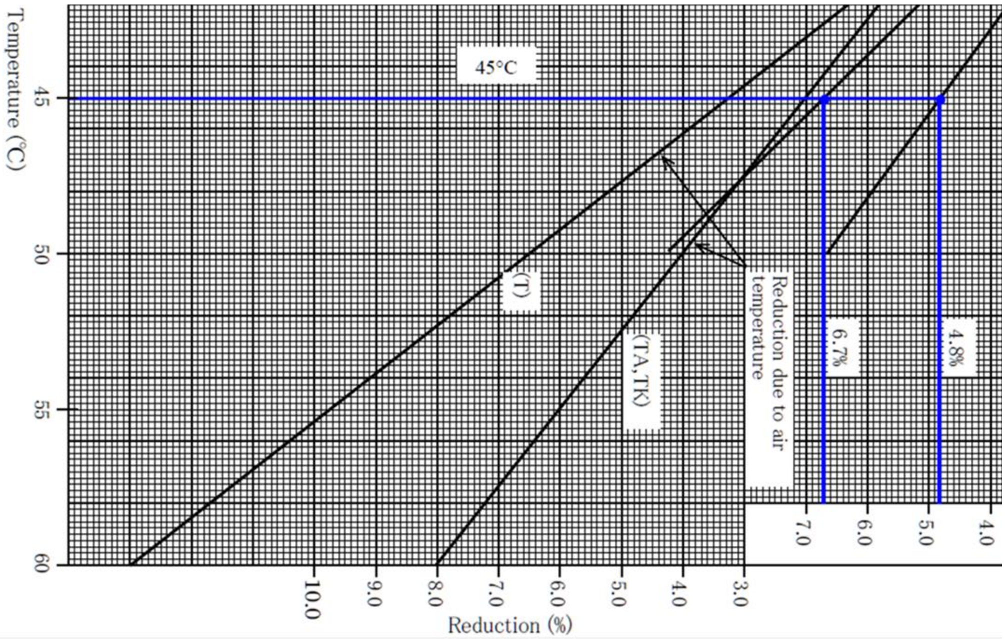


Figure 2-8: Genset air temperature derating dependence.

But other reasons, with temporal or even long-lasting effect may also contribute for a Genset derating. Figure 2-9 below, provides some examples, briefly commented since this is not a technical manual and comments are compensated for the respective audience.

Temporal reasons are mainly maintenance related. A turbocharger surging urges for turbocharger cleaning and high exhaust gas temperatures call for a fuel injection system inspection and maintenance. For severe damaged engines, (over size bearings for example) a permanent power reduction is realized, above all for safety reasons.

Genset	Nominal Power (Kw)	Available Power (Kw)	Power reduction reason
CEGIELSKI-SULZ	2.900	2.300	Over size bearings
FIAT-G.M.T.	2.480	1.800	Aged
WARTSILA	4.479	3.000	Exhust gas temperatures
FINCANTIERI	2.605	1.500	Turbocharger surging
FINCANTIERI	2.217	1.800	Aged
MTU	1.200	0	Maintenance
ROLLS-ROYCE	11.600	8.000	Aged
SACM	1.200	700	Exhust gas temperatures
MITSUBISHI	1.275	1.200	Derating
	29.956	**20.300**	

Figure 2-9: Genset derating examples

In some cases, such as for aged Gensets, power reduction cannot be determined objectively. Experience and current practice take place and suggest the maximum output beyond which, leaks, malfunctions and problems start appearing more frequently.

In any case, it should be noted that constant efforts are pointing in the direction of constantly keeping available power as possibly close to Nominal power. Otherwise, among others, capital invested in production equipment is practically lost.

Finally, in somehow extreme cases, the power output of a Genset might be even higher than Nominal Power. That is true but it is strongly recommended to be avoided. Some manufacturers offer some safe overload capability as a percentage of Nominal Power, under certain circumstances. For example, a 10% overload for 1 hour every 12 hours. Some manufacturers though disregard that option as a whole and our opinion is in the same way. The overload capability (if any) should be left out of any production scheduling calculations and simply serve really extreme cases such as transients.

2.2 Power plant

In practice, several Gensets are combined in order to meet demand, forming a power plant. These Gensets are installed in parallel inside an engine room (see Figure 2-10below) which in practice lies among the most valuable parts of any power plant.

Figure 2-10: Typical engine room arrangement

The power output of each Genset contributes to the power plants total power output. The later, through the power plants grid (see Figure 2-11, below) is feeding transmission lines.

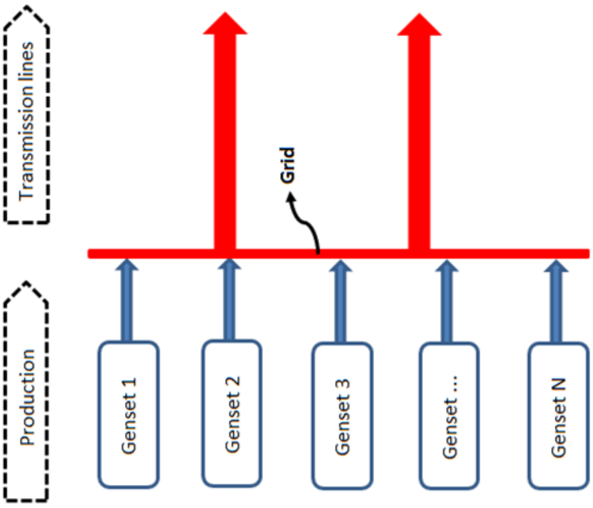


Figure 2-11: Power plant grid concept

In analogy to a single Genset, a power plant is characterized by:

- Power Plant Nominal Output: Summation of Gensets Nominal Output

-Power Plant available Output: Summation of Gensets available Power output.

Power Plant spinning reserve during operation will be explained with the use of a simple example, helpful to grasp the underlying philosophy, see Figure 2-12, below.

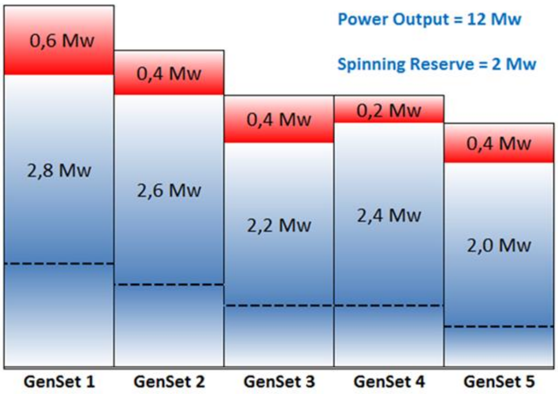


Figure 2-12: Power plant spinning reserve

Suppose five (5) Gensets of 14Mw Nominal Power in total, meet 12Mw system demand. Contribution of each Genset is different but the important point is that there exists a 2Mw spinning reserve margin allocated to all 5 Gensets. In case of a sudden extra power demand up to 2Mw, the plant can sustain its operation since we can say in a simplifying manner, each Genset will rise its Output up to Nominal Power . Bottom line is that if not for an adequate spinning reserve existing we would face power shortage and consequent problems.In general, as system demand fluctuates, we have to alter spinning reserve magnitude accordingly (see Figure 2-13, below).

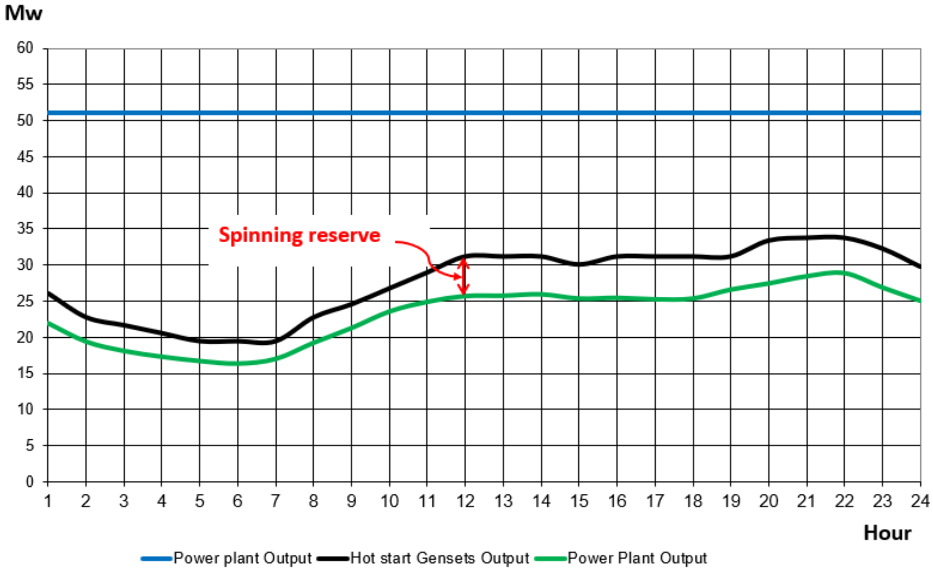


Figure 2-13:Power plant spinning reserve time line

This task is far from easy for some reasons. First of all, spinning reserve has to do with the Gensets currently running. At some point, as system demand increases, we have to synchronize an additional Genset to sustain reliable operation. But additional power comes in increments of the available reserve power. This results in certain instances where spinning reserve is much higher than needed. And that is extremely cost in-effective.

2.2.1 Load shedding and Blackouts

Some times its possible due to technical failures in general, for a power plant not to be able to meet demand, under any circumstances. For example, a massive generator malfunction, (due to inappropriate fuel) might trigger a complete blackout where no power is produced and no end user is served.

In such a case and after a black start, given the persisting malfunction and provided no power reserves exist, system demand cannot be restored and certain end user will be left unserved. That is called load shedding and is usually deployed in a periodical way. All end users at some point will not be served (for some hours maybe) until the power shortage problem is alleviated.

2.2.2 Island mode

It’s extremely important for new comers to understand the difference between an infinite power grid and an isolated power grid (island mode).

If power grids of many different power plants are interconnected, in case of Genset malfunction to some power plant, power production from an other power plant (spinning reserve) could assist real time to meet demand. If there is an abrupt rise in demand, this extra load will be, for simplicity sake, analogously distributed among all operating Gensets of all plants. Thus, the grid is said to have infinite power because it’s extremely not likely to meet power shortage and end users will continue harvesting energy.

That is not the case if a single power plant with discrete number of Gensets serves its own grid (serves the total demand of an area). In case of a Genset malfunction or a sudden rise in demand, no extra resources are present and the power plant has to resolve the situation itself. The means used are spinning reserve as already presented and non-spinning reserves. In island mode systems, reserve Gensets that can commence operation within minutes serve the non-spinning reserve requirements.

2.2.3 Power Plant specific fuel oil consumption (PPsfo)

The total quantity of fuel burnt by all generating sets per total delivered energy is depicted in Power Plant specific fuel oil consumption (PPsfo). It serves as the average fuel consumption efficiency of a power plant for a given time period (in the past). Efforts are concentrating on minimizing this quantity year by year, thus consuming less fuel. This is especially important when we face increasing power or energy demand. In our attempt for cost reduction, previous period’s PPsfo can serve as a benchmark. All generating sets as already stated are not fuel efficient the same (see Figure 2-14below).

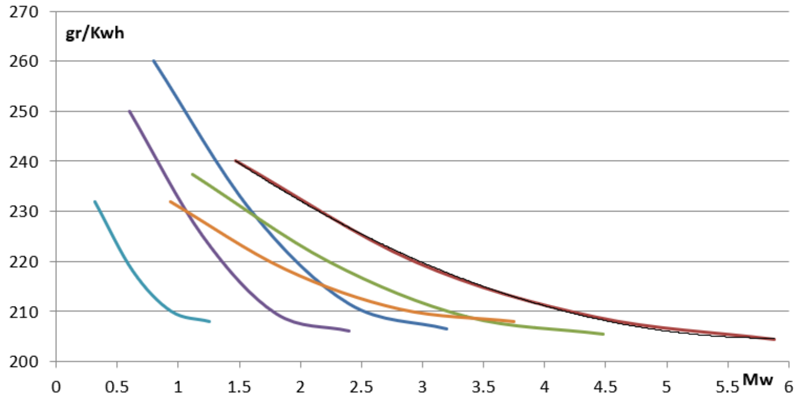


Figure 2-14: Sample Genset sfo curves

That’s a critical point and results in a different share of the overall burned fuel, depending upon output, as a percentage of Nominal Power. This % on average output is depicted in Figure 2-15, below and efforts concentrate on keeping this percentage as high as possible.

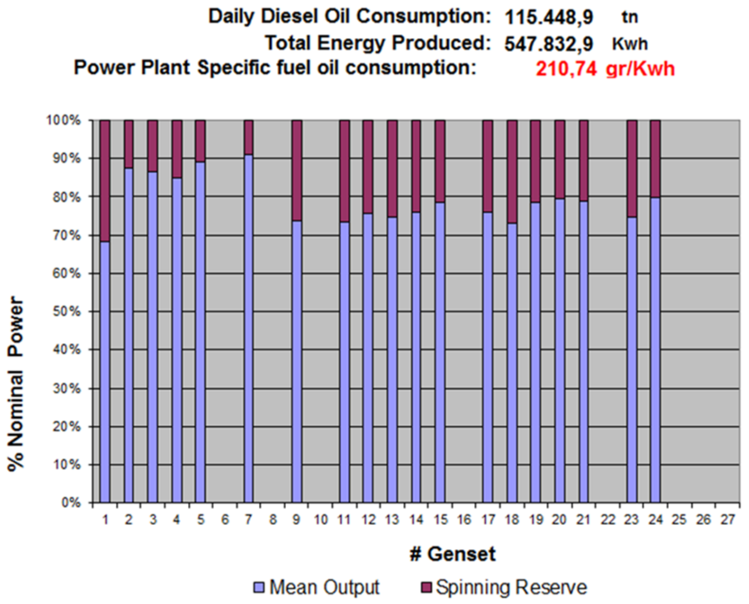
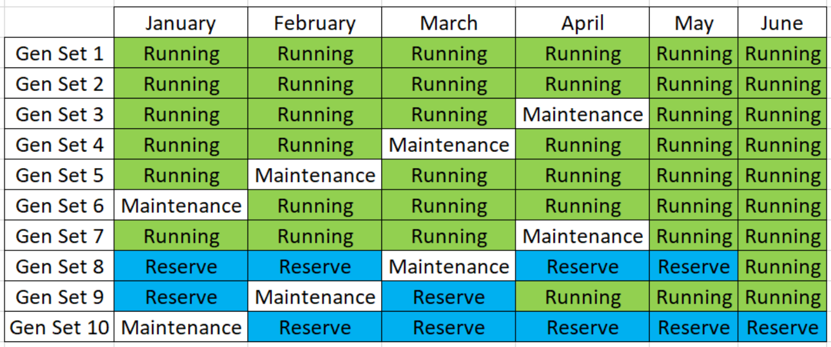


Figure 2-15: Power Plant specific fuel oil consumption

Utmost scope is to lower power plants total fuel consumption for given energy produced. In other word, lower power plants specific fuel oil consumption. Taking under consideration the number of Gensets possibly running in any given instance, that task is far from easy and optimization approaches have to be realized as will be clearly seen.

In daily basis some Gensets must operate to meet demand and as demand increases, additional Gensets are synchronized to the grid and start producing energy. The pool of available Gensets to realize operation has to be determined in advance and among other factors by maintenance scheduling as depicted below, in a bulk monthly scheduling.

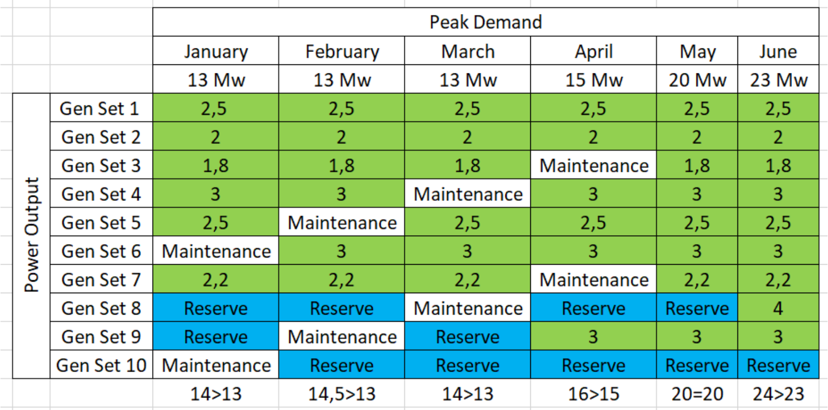


	January	February	March	April	May	June
Gen Set 1	Running	Running	Running	Running	Running	Running
Gen Set 2	Running	Running	Running	Running	Running	Running
Gen Set 3	Running	Running	Running	Maintenance	Running	Running
Gen Set 4	Running	Running	Maintenance	Running	Running	Running
Gen Set 5	Running	Maintenance	Running	Running	Running	Running
Gen Set 6	Maintenance	Running	Running	Running	Running	Running
Gen Set 7	Running	Running	Running	Maintenance	Running	Running
Gen Set 8	Reserve	Reserve	Maintenance	Reserve	Reserve	Running
Gen Set 9	Reserve	Maintenance	Reserve	Running	Running	Running
Gen Set 10	Maintenance	Reserve	Reserve	Reserve	Reserve	Reserve

Figure 2-16: A bulk monthly production schedule

The right choice of Gensets, concerning cost criteria, is challenging. The starting point should be the sfo curves but in practice they are quite a few. The problem gets even harder in case a power plant is dual fired. Heavy fuel oil is much cheaper than Diesel oil and as a result certain Gensets offer cost effectiveness.

In any case, to realize over all fuel cost savings, power output of each Genset must be well determined by some optimization process that provides an output such that presented in Figure 2-17 below.



		Peak Demand					
		January	February	March	April	May	June
		13 Mw	13 Mw	13 Mw	15 Mw	20 Mw	23 Mw
Power Output	Gen Set 1	2,5	2,5	2,5	2,5	2,5	2,5
	Gen Set 2	2	2	2	2	2	2
	Gen Set 3	1,8	1,8	1,8	Maintenance	1,8	1,8
	Gen Set 4	3	3	Maintenance	3	3	3
	Gen Set 5	2,5	Maintenance	2,5	2,5	2,5	2,5
	Gen Set 6	Maintenance	3	3	3	3	3
	Gen Set 7	2,2	2,2	2,2	Maintenance	2,2	2,2
	Gen Set 8	Reserve	Reserve	Maintenance	Reserve	Reserve	4
	Gen Set 9	Reserve	Maintenance	Reserve	3	3	3
	Gen Set 10	Maintenance	Reserve	Reserve	Reserve	Reserve	Reserve
		14>13	14,5>13	14>13	16>15	20=20	24>23

Figure 2-17: Sample of monthly economic dispatch

2.2.4 Renewable energy sources

Renewable energy sources are in the center of global attention since many years now, in order to reduce GHG effect. Among the different renewable energy sources such as hydro, biomass, geothermal, tidal and wave, wind and solar power installations attract the major portion of new investments in the field. Hydro is well established for many years now and almost all sites of great potential are already farmed.

Island mode systems do not attract that much attention in respect to investments in renewable energy sources and if so, wind power is usually preferred. Despite that, large scale applications are not evident simply because system demand is comparably small and cannot absorb all potentially produced energy. But even in this case where small amounts of renewable energy are injected in to a small grid, extreme caution is mandatory.

Despite we are pretty sure about the potential of solar energy production (duck curve) in respect to wind power things are not that clear. Energy stemming from wind power can abruptly seize and a power plant must compensate for on time. As a result, spinning reserve should be high enough countering for the intermittency of wind power. It must be noted that the magnitude of spinning reserve should be carefully chosen since it costs. In general, the higher the spinning reserve the least blackouts to happen and if that serves as a reliability criterion for someone, spinning reserve is the source of a cost driving factor. Until the energy storage problem is alleviated, island mode systems will keep experiencing comparably small amounts of renewable energy injection.

In Figure 2-19 and Figure 2-20 below we can see reservoirs of the state of the art NAERA hybrid power plant where energy storage is realized in a practical way. The power station utilizing pumping driven by wind energy, fill reservoirs with water that can be later used on demand to produce energy (hydro power).

Figure 2-18: NAERA hybrid power plant reservoir

Figure 2-19: NAERA hybrid power plant reservoir

Figure 2-20: NAERA hybrid power plant reservoir

2.2.5 Mobile Genset units

Generally, units are installed inside buildings (engine rooms). This approach obtains cost reduction in many aspects and has its pros and cons. Alternatively it is possible to utilize relatively small capacity units (running on various fuels) at a compact size and at a reasonable cost that are mobile. Everything needed for power production is within a single container.

Figure 2-21: Typical mobile Genset and the associated daily fuel tank

These units have their pros and cons we won't analyze deeply but what really concerns us is the flexibility they offer.

These mobile Genset units can be relocated really fast (see Figure 2-21 above). For example, despite necessary laborious operations we can power up an entire island like Mykonos (a grid of about 50Mw peak power), within days.

As a policy once again, some percent of installed nominal power for some island mode systems may refer to mobile units. And in case of some failure in one system it is possible for other systems to contribute in a very effective way. That is the case when the same entity regulates many island mode systems.

In another way, it is extremely handy, to be able to adjust for deviations in demand forecasts. Relocating some mobile Gensets not really needed somewhere helps matching peak system demand in many systems in an efficient way.

Some limitations do exist though due to the fact that there is some dispersion concerning fuel used among power plants, but one way or another it can be overridden. Especially when fuel cost is a major factor. And here comes the pleasant side of the story: due to the relative new technologies these units possess, they are in many cases more fuel effective than current installed units. A power plant thus, can lower its specific fuel oil consumption resulting in less money spent on fuel (in general).

Chapter 3

System under consideration

System under consideration is a fictional case study. Despite that, it incorporates many characteristics of a real highly-tourist island somewhere in the Mediterranean. In other words this system is realistic enough so it could be possibly operating somewhere around the globe (if not already).

The Genset portfolio of the corresponding power plant consists of real Gensets found around many power plants and Genset data used are real data. System demand used refer to a real systems actual year of operation. The important point though is that some scenarios presented (either met in practice or not) reveal the managerial struggle to efficiently operate any power plant through the years of constant raise in system demand. This is the single best way for showing the necessity of optimizing the maintenance of Generating sets.

So, power plant originated operation far before 1982 with installed capacity ranging within some hundred Kw. When capacity entered the Mw range, existing Gensets were found soundly placed inside an engine room and auxiliary equipment rooms (pumping station etc.) and fuel storage tanks were deployed on the surface of the power plants terrain.

As peak loads started rising, a decision was taken to build a second engine room and install extra Gensets. As loads kept rising, new technology and higher capacity Gensets were replacing existing ones while thoughts about how to reduce production cost emerged.

3.1 System demand pattern

Daily system demand curve follows a certain pattern (see Figure 3-1, below). Minimum demand appears during late hours and a first peak is present during noon. Days maximum demand (peak load) is about 20:00pm-21:00 pm both in winter and summer time. This pattern is representative for the whole year as actual data determine.

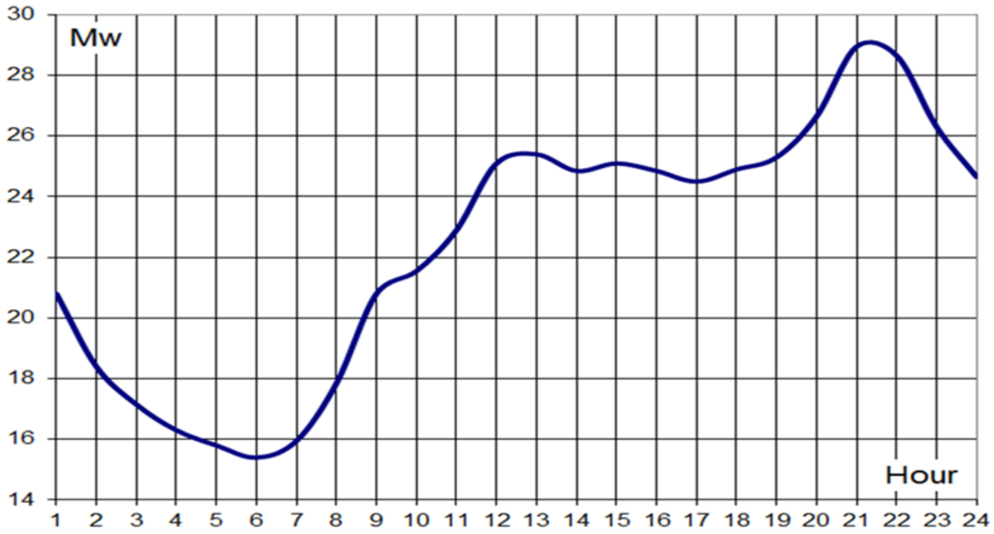


Figure 3-1: Daily system demand curve

For 8 consecutive days in summer time (see Figure 3-2 below) for example, the pattern repeats day by day. but with some shift concerning the exact time of appearance and magnitude of minimum demand and peak load.

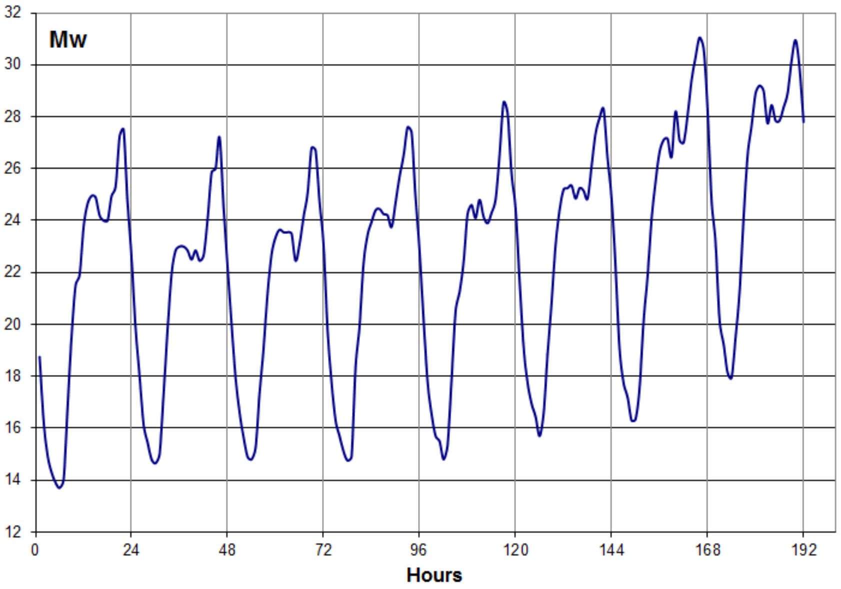


Figure 3-2: Daily demand pattern

3.2 Daily Peak load

What is more important though, is to derive the magnitude of daily system peak load which varies significantly during seasons and years of course (see Figure 3-3 below). Daily peak load forecast in conjunction to demand patterns enable preparations in advance to effectively meet end users' needs.

Our island as already stated is a very attractive tourist destination so it's crystal clear that peak value has to do with the number of visitors during summer and for sure with climate conditions.

We notice that peak loads during winter are somehow stable. No tourist activity is taking place and only island inhabitants supported by usual business activities contribute to daily system demand. This fact is extremely significant for our case as shall be seen later.

Later on, we can notice a spike during Easter. The island during this period attracts many visitors and for more than a week, power demand is high enough. Local businessmen start preparations early enough to service customers during Easter time and after the end of visit, renovations continue for the summer to come.

This is a critical point since statistically, after Easter time there is a constant rise in power demand, peaking during mid-August. No wonder because that period, islands hotel beds capacity reaches the capacity limit.

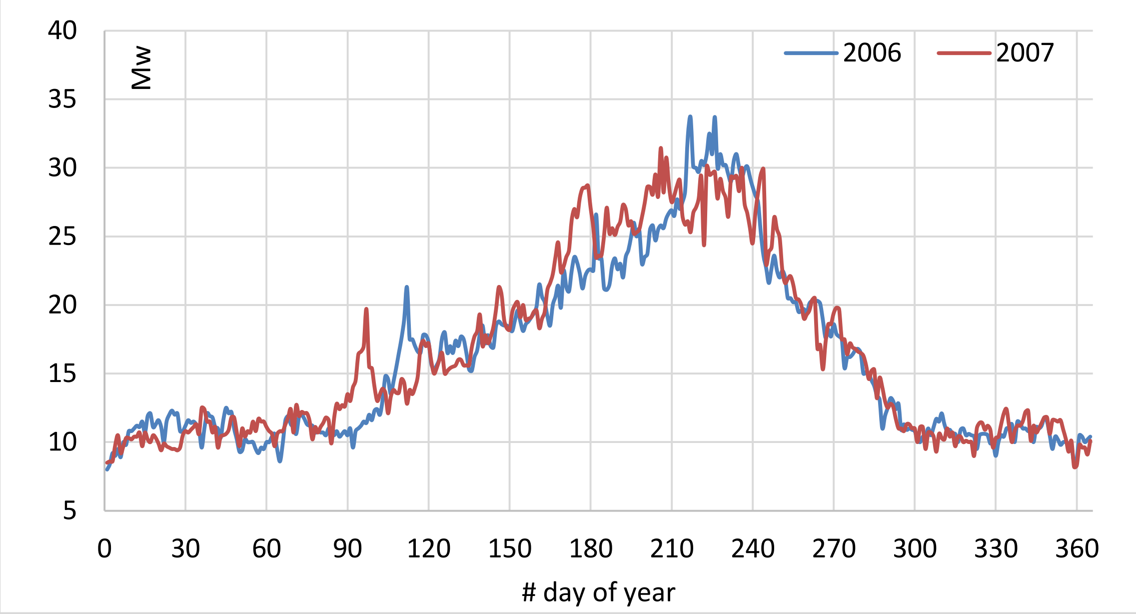


Figure 3-3: Daily peak load 2006 & 2007

And the habits are known. If during high season period there exist a hot summer, all A/C inside rooms are left working. If not, summer is cooler let's say, some of them hopefully will be turned off. In any case, statistics confirm our thoughts.

Some islands though, meet peak power demand during winter and that’s not uncommon among cases where there is not a strong tourism industry involved. That’s one of the points of interest when referring to our specific touristic island.

3.3 Annual peak load

Mainly for capacity planning reasons, it is extremely important to realize the trend with what concerns the annual peak load demand. Our system exhibited year by year, a change in peak load which is depicted in the more than informative Figure 3-4 below.

Up to 1994 the graph depicts peak demand that was met by the power plant. In other words, depicts the peak load delivered by the power station.

For 10 years and especially from 1994 up to 2004, local power plant faced some technical problems resulting in power deficits. As a result, it could not meet demand and a power station from a nearby island, utilizing grids interconnection capability, provided the extra power needed. So, from 1994 up to 2004 graph depicts a portion of the actual peak demand that was met by the power plant. The rest was met by the nearby power plant.

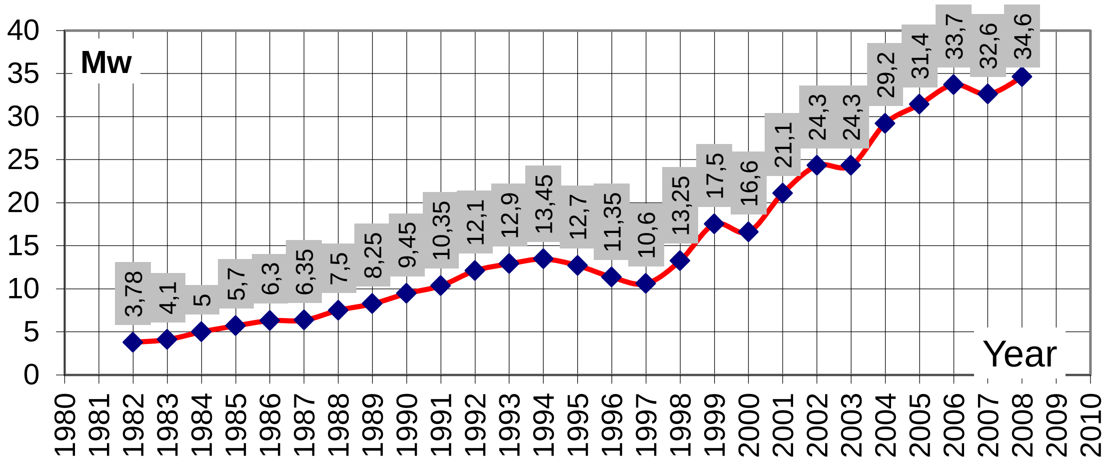


Figure 3-4: Annual Peak load

After 2004 the interconnection wasn’t used any more since local power plant managed after all to sustain full and reliable operation and the graph depicts real peak demand.

Having all that information in mind and after actual analysis we conclude that there appears an almost constant rising system demand trend, regardless any partial load contributions.

3.4 Load duration curve

It is extremely critical to know for how long system demand is above a certain magnitude. For doing so, we plot hourly maximum system demand against the whole year (8.760 hours) forming the so-called Load Duration Curve (see Figure 3-5 below that corresponds to an arbitrary year).

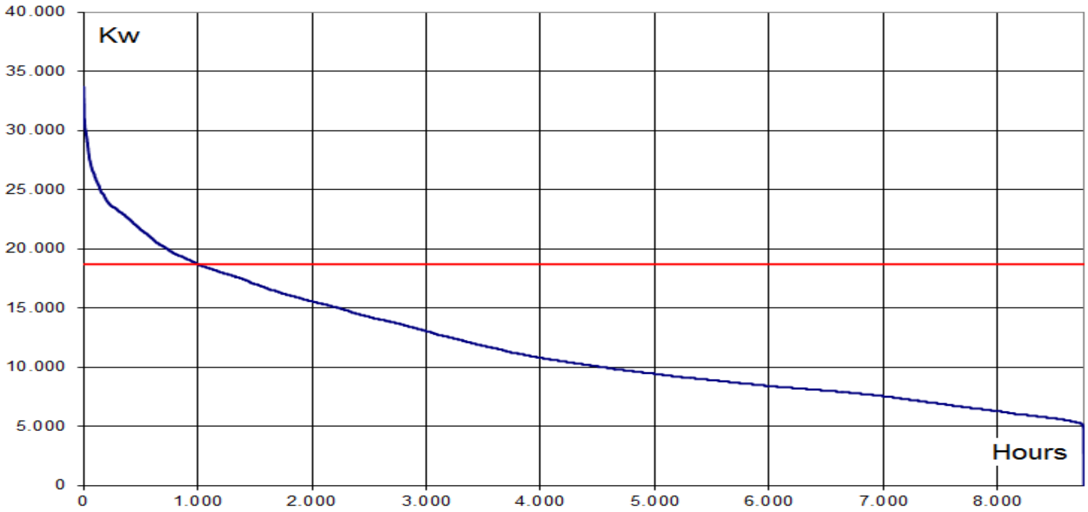


Figure 3-5: Load duration curve

The area under the curve presents the overall energy produced, with sufficient enough accuracy.

Conclusions stemming from the graph are easy. We can see for example that power demand was above 18 Mw for a thousand hours. This information is critical enough for the reasons to follow. First of all, we can realize the utilization of power plants installed capacity. Secondly, it can serve as a decision aid. As peak load of the system increases over the years, new investments in production equipment is on the table.

Suppose for example we run a power plant of 35 Mw installed capacity. From the graph we read that for 8.760-1.000=7.760 hours, demand could be met by 18 Mw production equipment (less capital invested). But for 1.000 hours we need more power. In other words we need some 17Mw more capacity, that for more than 7.760 hours is not needed. And that’s an issue.

Instead, someone could argue that with in an economic horizon, its best to rent power (rent mobile Gensets) than install new Gensets. Or a hybrid approach could be effective as well.

3.5 System and energy Demand to burnt fuel calculation

Since now we might have treated system demand and energy demand interchangeably since one correlate to the other. But there is more to it if to accurate calculate fuel burning cost through acquired statistical data.

Figure 3-6 below presents yearly peak system demand and energy demand on a daily base. This kind of graph is usually constructed for every year since it is extremely handy in many occasions for comparison reasons mainly. But there is also another aspect.

We can say that if system demand was flat for the entire year, so would be energy demand, as the product of demand to time. In other words, the area under the system demand curve (flat line in respect) represents total energy produced.

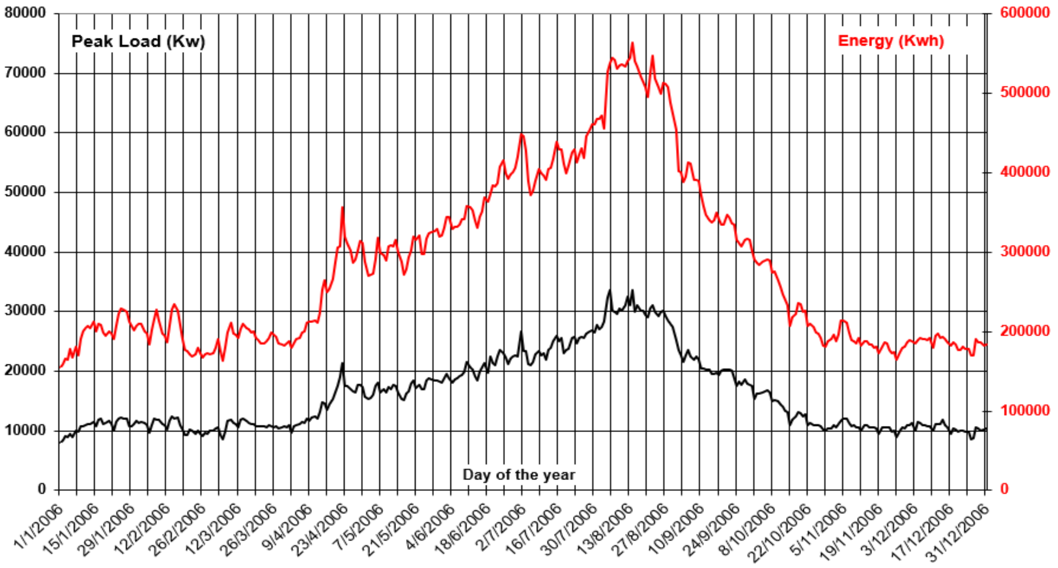


Figure 3-6: Daily peak system and energy demand for an entire year

But, the single important point is that during each day of operation, peak load appears for a certain fraction of time. The rest of the time, system demand is much less. As a result, the area under the system demand curve is not the actual energy produced.

If recordings were on an hourly base, a better (good) approximation could be realized. It is true however that the smaller the time unit used (minutes or even less) the greater the accuracy we can realize. But beyond a certain point it is somehow impractical. The excess calculations involved don't compensate for the higher accuracy.

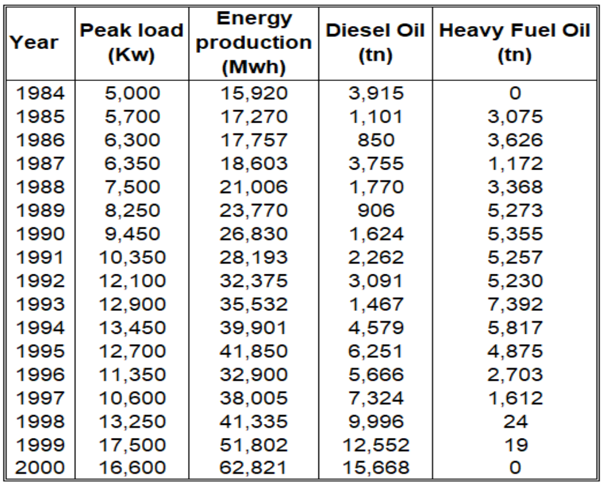
In any case, the hourly reference period suits the needs best because offers sufficient enough approximation and exhibits a good balance between accuracy and calculations involved.

This convention is of great importance when it comes to calculating (validating) individual Gensets fuel consumption.

3.6 Managerial interest aspects

For about 15 years in the past, power plant run dual fuel. Heavy fuel oil is still much cheaper so new Gensets with suitable characteristics were chosen so as to run on that cheap fuel. Savings were significant but for some reasons, the power plant ceased operation on heavy fuel oil and relied solely upon diesel oil.

Those years, tech level could not effectively or even cost effectively control emissions. That fact, for our highly touristic island was something extremely unpleasant contributing to upsetting local community and businessmen.



Year	Peak load (Kw)	Energy production (Mwh)	Diesel Oil (tn)	Heavy Fuel Oil (tn)
1984	5,000	15,920	3,915	0
1985	5,700	17,270	1,101	3,075
1986	6,300	17,757	850	3,626
1987	6,350	18,603	3,755	1,172
1988	7,500	21,006	1,770	3,368
1989	8,250	23,770	906	5,273
1990	9,450	26,830	1,624	5,355
1991	10,350	28,193	2,262	5,257
1992	12,100	32,375	3,091	5,230
1993	12,900	35,532	1,467	7,392
1994	13,450	39,901	4,579	5,817
1995	12,700	41,850	6,251	4,875
1996	11,350	32,900	5,666	2,703
1997	10,600	38,005	7,324	1,612
1998	13,250	41,335	9,996	24
1999	17,500	51,802	12,552	19
2000	16,600	62,821	15,668	0

Figure 3-7: Dual fuel operation

As a result, after some time, the verdict was final. Power plant gradually reduced dependency upon the cheap fuel and after 1997 practically no heavy fuel oil was burnt (see Figure 3-7, above).

As a result, capacity planning was out of trucks since significant changes were now present. In conjunction with the constant rising peak demand and the not suitable any more aged facilities in general, significant problems appeared. The power plant struggled to meet demand and with a great relief, installation of new Gensets commenced during 2005. In practice, a hybrid approach was chosen.

Technology could eventually face with cost effectiveness any local community arguments and the many newly introduced legislation constraints. So, new tech Gensets capable of running on heavy fuel oil assisted by mobile Gensets running on Diesel oil would meet reliably and cost effectively present and future power demand.

The new fleet of Gensets offered significant flexibility in meeting any magnitude of demand. The mobile Gensets can start and stop practically without any serious preparation and we could say without any cost. Technical minimum was not a concern any more nor the magnitude of spinning reserve, since the combinations concerning the choice of running Gensets were high enough. The change was somehow astonishing.

Figure 3-8: Genset stacks and auxiliary equipment

Figure 3-9: Power plan terrain

Some disadvantages though were evident. There was no choice other than forming a Genset farm inside power plant terrain (see below below) resulting to some issues concerning among others, exhaust gas dispersion.

Figure 3-10: Mobile Gensets farm

Since the air-cooled mobile Gensets were highly prone to derating thanks to summer temperatures and the overall layout design, available power during summer was constantly less than nominal.

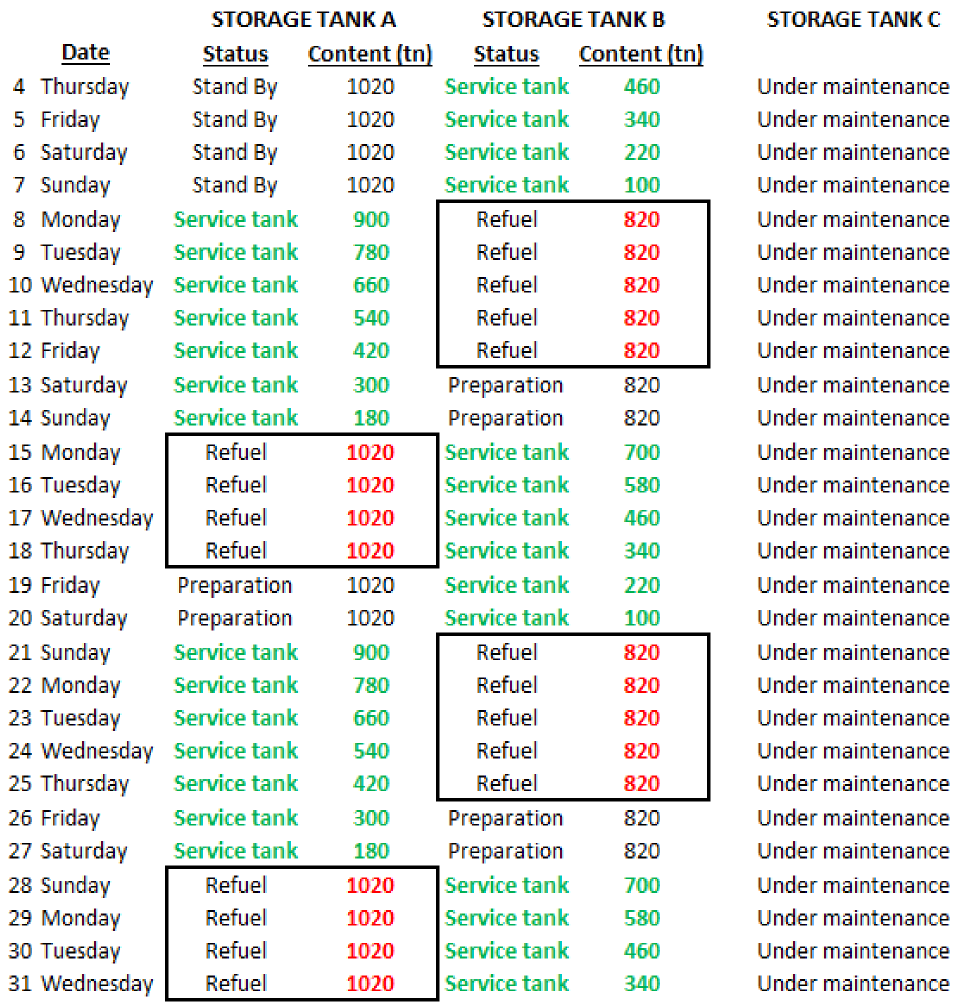
In any case, a new era begun and immediately after acceptance tests, all Genset were introduced in the production scheduling, harvesting their higher fuel efficiency. As a result, certain Gensets started accumulating running hours while others didn’t.

Gensets not that fuel efficient were not used for production but kept as reserves, resulting in significant fuel cost savings. More fuel cost savings were to be realized when some of the installed Gensets could be able to run on the cheap heavy fuel oil.

Total number of Gensets was already high enough to cause management a constant head ache, for even simple daily routine operations. As a result, dividends of the new investments were not to come without effort and most accurate planning.

For example, Heavy fuel oil running capability depended upon suitable storage tanks and fuel handling installations. But power plants terrain was already saturated and no space was available to construct even one more extra heavy fuel oil tank that was in minimum needed.

As a result, during the fuel change over phase, a somehow big problem appeared. Facility could solely rely upon limited storage volume and refueling had to be as accurate as possible (see Figure 3-11, below).



		STORAGE TANK A		STORAGE TANK B		STORAGE TANK C
	Date	Status	Content (tn)	Status	Content (tn)	
4	Thursday	Stand By	1020	Service tank	460	Under maintenance
5	Friday	Stand By	1020	Service tank	340	Under maintenance
6	Saturday	Stand By	1020	Service tank	220	Under maintenance
7	Sunday	Stand By	1020	Service tank	100	Under maintenance
8	Monday	Service tank	900	Refuel	820	Under maintenance
9	Tuesday	Service tank	780	Refuel	820	Under maintenance
10	Wednesday	Service tank	660	Refuel	820	Under maintenance
11	Thursday	Service tank	540	Refuel	820	Under maintenance
12	Friday	Service tank	420	Refuel	820	Under maintenance
13	Saturday	Service tank	300	Preparation	820	Under maintenance
14	Sunday	Service tank	180	Preparation	820	Under maintenance
15	Monday	Refuel	1020	Service tank	700	Under maintenance
16	Tuesday	Refuel	1020	Service tank	580	Under maintenance
17	Wednesday	Refuel	1020	Service tank	460	Under maintenance
18	Thursday	Refuel	1020	Service tank	340	Under maintenance
19	Friday	Preparation	1020	Service tank	220	Under maintenance
20	Saturday	Preparation	1020	Service tank	100	Under maintenance
21	Sunday	Service tank	900	Refuel	820	Under maintenance
22	Monday	Service tank	780	Refuel	820	Under maintenance
23	Tuesday	Service tank	660	Refuel	820	Under maintenance
24	Wednesday	Service tank	540	Refuel	820	Under maintenance
25	Thursday	Service tank	420	Refuel	820	Under maintenance
26	Friday	Service tank	300	Preparation	820	Under maintenance
27	Saturday	Service tank	180	Preparation	820	Under maintenance
28	Sunday	Refuel	1020	Service tank	700	Under maintenance
29	Monday	Refuel	1020	Service tank	580	Under maintenance
30	Tuesday	Refuel	1020	Service tank	460	Under maintenance
31	Wednesday	Refuel	1020	Service tank	340	Under maintenance

Figure 3-11: Refueling time windows

In any case, accurate system demand forecasts not only had to be used but were more than mandatory. Power plant reliable operation, would be highly depended upon refueling but the naval way of fuel transportation always incorporated arrival uncertainty, due to bad weather conditions instances. Since load shedding due to fuel shortage is something most embarrassing, accurate production scheduling was a prerequisite for a realistic fuel demand forecasting.

We shall now examine some important aspects, common to all power plants, to highlight the complexity involved in our test case power station.

3.6.1 Inventory Management

Every power plant warehouse has to have readily available upon request, a plethora of spare parts for maintenance activities. For sure, capital spent should be kept as low as possible but that’s far from easy. For example, an aged power plant to sustain a reliable operation usually exhibits an increased inventory cost.

It’s practical in any case to further discern spare parts, in respect to:

a) Consumables (filters etc.) and spares used in routine (frequent) maintenance activities

b) Spares necessary for scheduled maintenances and in particular major overhauls.

It must be stated though, that additional classifications do exist but those already mentioned can serve our scope.

Consumables demand relates to running hours of particular Gensets so if production planning is realized, an economic order quantity can be derived through management science technics.

Spares concerning repairs relate in general to maintenance quality and maintenance scheme adopted (preventive maintenance, condition-based maintenance etc.). In any case, a failure rate could indicate necessary quantities but as it is obvious, a production planning must be present.

Major overhauls spare list, is practically big enough including many costly items. It’s in the best interest of any power plant to acquire these costly spares, just when needed. If those items are pilled for prolonged time, a valuable company resource (money) is not best utilized. In practice, procurement division is best advised to take under consideration any uncertainties regarding availability and delivery time. It’s crystal clear that Generation maintenance scheduling serves as the reference point for many important warehouse decisions concerning acquisition of materials.

3.6.2 Man power planning

In a power plant there exist 2 main areas of interest, namely technical personnel (shifts and maintenance) and white collars. Typically, what concern more maintenance activities, is the available total number of maintenance personnel. This fixed number of personnel should be allocated among various clusters of job assignments, but there is far more to it. Especially if qualifications diversification is high enough among technical personnel.

It is common that during peak load periods, personnel from maintenance mitigates to shifts (extra shift post) and during maintenance periods, a personnel rotation may even occur. In general, if most qualified personnel belong to shifts, a more reliable operation (failures can be avoided beforehand) is expected. Also, if most qualified personnel belong to maintenance, more reliable maintenance services are to be realized. As a result, a balance is mandatory for obvious reasons.

Furthermore, we need to realize that when running units are near service hours, failure rate is higher than normal. In that case, a greater portion of adequate qualified personnel should attend the shifts but man power left for maintenance may not be adequate to carry out scheduled services. As a result, decisions about hiring properly qualified personnel for a certain period of time or even completely outsource a maintenance activity are of great importance.

In practice, if maintenance activities are scheduled during low peak periods, less Gensets are running and the shifts job is somehow less demanding. As a consequence, a higher flexibility exists so as to provide more qualified personnel to maintenance teams.

What was already mentioned is enough to reveal that Man power availability is closely related to Generation Maintenance Scheduling and does not simply refer to just the total number of available technical personnel in each time unit. The later should always be under consideration.

3.6.3 Production scheduling & Capacity Planning

Production scheduling simply put refers to which Gensets to run meeting demand. As a general statement, the more the Gensets the greater the flexibility offered but it comes with some cost. Complexity is extremely high and the task becomes demanding and is tricky in nature.

Production Scheduling above all determines the operation cost mainly thanks to fuel burnt. In case a power plant is dual-fuel fired, efforts should concentrate on running on the cheapest fuel. The reason is two-fold since heavy fuel oil costs almost half the price of diesel oil and the overall Power plant fuel cost stands for the 80% of total operating cost, in many cases.

But production scheduling also determines Gensets accumulated running hours over a certain period. If we are forced to keep running a Genset despite it has reached certain running hours and should be stopped for maintenance, reliability is a critical point of concern since catastrophic failure possibilities are always present.

In practice, a substantial amount of money could be saved with the right combination of Gensets running and Gensets under maintenance, taking under consideration some constraining factors as well. In any case, Generator Maintenance Scheduling is tightly correlated to Production Scheduling since what is not under maintenance potentially can be in service producing energy.

It is more than obvious that capacity planning may affect production scheduling the most. If extra nominal power is available after some time with lower fuel oil consumption, production scheduling will be affected. It is easily derived that Generation Maintenance Scheduling will also be affected.

3.7 Reliability & the higher capacity running unit redundancy.

The worst-case scenario for any power plant is that, for a given production schedule the higher capacity running Genset fails during operation for whatever a reason. The malfunction itself in conjunction to repair time is critical. Having in mind that any production schedule refers to a well-defined period, if that period we have a Genset of equal or higher capacity in reserve, problem is alleviated.

In other words, during any period of time in case of any Genset failure, reserve power could always sustain un-interrupted power supply to end users. It is true that if a Genset malfunctions during peak time, load shedding or even a blackout might appear but the temporal nature of is not a concern. The reserve power will quickly chip in and demand will be met.

This philosophy actually depicts the reliability frame set by management and it is valid in practice since not only safeguards against a bad scenario but in some cases provides much more. Suppose peak power was not accurately forecasted. In that case we can rely on the “redundancy” unit since it can contribute to power production (usually necessary for a small period of time).

3.8 Informal problem description

The starting point of any attempt to increase operational cost effectiveness and reliability, is the Generator Maintenance Scheduling.

System demand, Capacity Planning, inventory management, production and maintenance scheduling are all correlated and impose constraints (see Figure 3-12 below). For example, system demand serves as input for capacity planning and also dictates production scheduling via Generation maintenance scheduling.

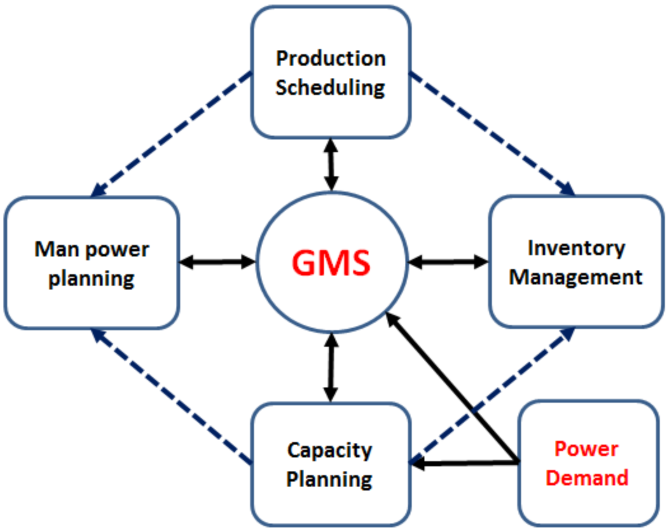


Figure 3-12: GMS dependencies

To make things even harder we can say that Generator Maintenance scheduling in conjunction to maintenance “capability” and other factors actually determine any deviation between Genset nominal output and Genset available power. Alas, bad Maintenance scheduling may diminish maintenance quality and in case of unusual or even major failures, shortage of available power represents a huge problem.

Simply put, we want to choose a Generation Maintenance Schedule such that:

All necessary Genset maintenances will be carried out in time and system demand would be reliably met in such a way that overall fuel and maintenance cost is kept minimum.

Chapter 4

The GMS problem

From the early work of Dopazo and Merril (1975) to the implementation of the Kapila model (Duval and Poilpot, 1983) and since today, a lot of research and attention was focused on optimizing Power systems. A literature review research by Yamayee (1982), Krali and Petrovic (1987), Dekker 1996) and Al-Arfaj, Karamitsos (2012) validates the constantly increasing efforts aimed at cost and reliability aspects. In current practice, optimal decisions are due to a plethora of available tools yet available.

4.1 The Horizon (planning period)

GMS refers to actions that will commence in the future within a predefined time period. This time period is called the Horizon and despite is a managerial decision, how far in the future we are willing to plan, it also depends on Genset specifications. We could say that when many Gensets are involved, specifications (maintenance duration) suggest a first approach in deciding the lower bound for the horizon (minimum span). In practice the horizon may refer to some weeks or months or even years. Typically, scheduling horizon refers to 1 year but narrower or larger spans up to some years are not that uncommon. That is the reason GMS is sometimes regarded as a long-term planning activity.

It must be noted though that within the horizon, several critical data such as load demand must be forecasted. It is evident that the longer the horizon the more difficult for a deterministic approach but can still serve as a valuable managerial decision aid. Every approach has its limitations and with respect to them, solutions are extremely useful.

The most critical perhaps consideration in conjunction with the horizon is the time unit selection. Time unit varies from hours and days to weeks and months and as a rule of thumb, the greater the system detail the smaller the time unit has to be.

4.2 The time Unit

The horizon is divided in to discrete time units. The most often used time unit is 1 week but it can otherwise be years, months, days, hours, see Figure 4-1 below. The choice is freely upon the taste or needs of the modeler, the latter being crucial.

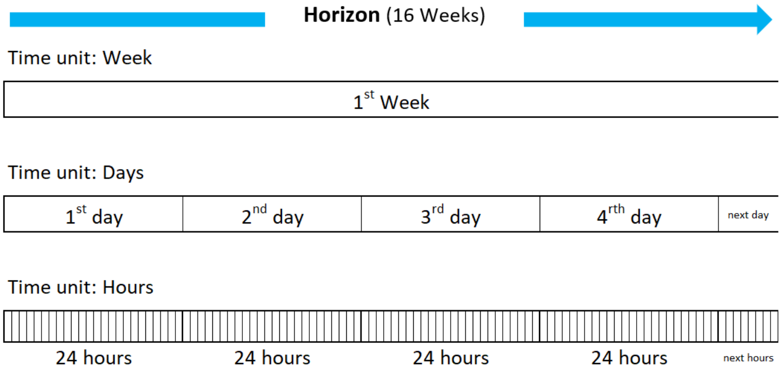


Figure 4-1: Different time units

The dimensions of the problem are determined by the number of Gensets and the combination of horizon and time unit used. For a given number of Gensets and for certain horizon if the time unit is changed from weeks to days, the domain of solutions becomes significantly larger. As a rule of thumb, the smaller the time unit the harder the problem to solve but the greater detail we achieve in modeling.

Consequently, any real system modeling calls for many variables to be introduced. Fourcade et al. (1997) studied the refueling of 54 nuclear reactors in a study involving 5 additional groups of fossil fuel plants. The five (5) year horizon and the weekly time unit (260 weeks) rendered a large enough problem. If realistic solving time is a prerequisite, loss of system detail helps to retrieve an exact solution. It is true however that significant role plays the available computing power.

4.3 GMS and relevant problems

The output of a GMS problem simply put should provide for each time unit the list of Gensets that are under maintenance and the list of Gensets that are available to run meeting system demand. This is the simplest approach but is insufficient in practice as will be clearly seen in chapter 7.

Usually, the GMS is coupled with the Unit Commitment (UC) problem and as a result, for each time unit we know which Gensets are under maintenance, which are committed in operation providing output and which serve as system reserves. The latter is crucial since by this way we can settle for a certain degree of reliability. But the demerit is that fuel cost cannot take part in any optimization stage. This approach will be thoroughly presented in chapter 8.

A holistic approach is to couple the GMS + UC with the Economic Dispatch (ED) problem. In doing so, fuel cost plays a significant role and heavily influences scheduling. In cases of dual fired power plants this is a one way only and in chapter 9 we present the full extend.

4.4 Common Solution techniques

GMS despite a problem difficult to solve since is a combinatorial problem in nature, usually exhibits non linearity. Operating cost and in particular fuel cost many times involve some quadratic function. A piece wise approximation may well enable exact solutions to be retrieved (Carrion and Arroyo, 2006) and Commonly used methods are: MILP (Niazi, Sheikholeslami and Varaki, 2012), Branch and Bound, (Niazi, Khoshnoud and Goudarzi, 2014), Benders decomposition (Canto, 2006) and Dynamic programming (Toni and Rakic, 2010).

When too many variables and constraints are involved, they render problem large and it is there for hard to solve, especially when non linearity is also present. The demonstration of the NP-hard complexity supports the approach for a heuristic or meta-heuristic adoption (Manzini et al., 2015). These techniques can provide a feasible solution in practical time and in most of the times claim to be close enough to optimality. But exact solutions cannot be retrieved. Commonly used heuristic and metaheuristic approaches involve: Simulated annealing (Saraiva et al., 2011), Genetic Algorithms (Mohanta, Sadhu and Chakrabarti, 2005), Particle swarm optimization (Yare, Venayagamoorthy and Aliyu 2008), Tabu search (Charest and Ferland, 1993) and Evolutionary programming. Hybrid techniques are also common (Dahal and Chakpitak, 2006).

In our study we will use MILP with binary variables and the powerful Branch and Bound algorithm will provide the means to find an optimal solution (if exist) in reasonable time.

4.5 Decision Variables

Typically, binary decision variables are introduced to state if a particular Genset is on maintenance (1) or not (0). Another approach is also valid, using integer variables. Auxiliary variables are usually binary and continuous variables are used to state the power output of each Genset, among others.

4.6 Objectives and solution approaches

The utmost scope of GMS is to schedule preventive maintenance activities over a period of time, provided an objective function is optimized and constraints inherent to the system are not violated. But the objective function is a point of strong diversification since there is usually an explicit conflict among criterions. For single objective problems, objective function usually refers to cost criteria or reliability criteria.

Cost criteria usually include operating cost (fuel cost, startup/shut down cost etc.) and maintenance cost. Additional costs (Niazi, Sheikholeslami and varaki, 2012) or even earnings (Barot and Bhattacharya, 2008) may also be introduced. Economic criteria aim in general at minimizing operating costs and among them, fuel cost acquires the major portion of overall cost.

In the power production industry and with what concerns liquid fuel fired Gensets, fuel consumption is not linear in respect to power output. As a result, the insertion of a single quadratic function for each one of the Genset fleet may pose problems. Solution is hard to find due to non-linearity and computational time is an issue. In our study, a piecewise approximation is used in an interesting way as will be presented in chapter 9.

Reliability criteria aim in general at safeguarding that end users will be able to use electric power, at any time (or most of the time). Some established approaches do exist divided in principle in deterministic and stochastic.

It must be stated that reliability criteria may also be introduced in the model as constraints, either hard or soft. As will present in chapter 8 in our approach, by using soft constraints we achieve reserve power leveling in an optimal way.

Reliability criteria as stated are either deterministic or stochastic. For a deterministic approach, the most commonly used are:

(1). Maximize the minimum reserves. In a straight forward manner, reserves among time units are levelled as possible. As a linear function of Nominal power, system demand and maintenance outage power, it poses no other real solving problem than the dimensionality of the model itself. Wang et al. (2015) present an alternative minimization index formulation, also levelling the reserves.

(2). Minimize sum of the squares of reserves (Anandhakumar, Subramanian and Ganesan, 2011). By doing so, variation among reserves is kept minimum. This formulation renders problem nonlinear and classical approaches are not valid. Set as a single objective, Mohanta, Sadhu and Chakrabarti (2005) used GA/SA-based hybrid techniques, Dahal and Chakpitak (2006) used metaheuristic-based hybrid approaches and Yare, Venayagamoorthy and Aliyu (2008) a Modified Discrete PSO.

Both of the above approaches though, don’t account for system demand forecasting uncertainties. A stochastic reliability index compensates for, and the most commonly used are (Eygelaar, Lötter and van Vuuren, 2017): Minimize loss of load probability (LOLP), Minimize loss of load expectation (LOLE), Minimize annual expected unserved energy (EUE). But these approaches render in the difficulty of finding exact solutions.

Efforts concentrating on optimizing for reliability also incorporate the use of indexes based on the ratio of Net reserve to gross reserve. Set as a single objective function, Conejo, Bertrand and Salazar (2005) utilized a heuristic approach to retrieve a solution based on maximizing the average value. The same objective was used by Balaji, Balamurugan and Lakshminarasimman (2015), utilizing a Differential Evolution Algorithm. Canto and Romero (2013) taking under consideration system demand uncertainty, enriched ratio with the probabilities of corresponding demand scenarios.

But uncertainties also apply to sudden Genset failures. Eygelaar, Lötter and van Vuuren (2017) introduced a linear criterion for “maximizing the probability that no Power Generating Unit in the system will fail during the current scheduling window”. It is evident that this approach heavily depends on the availability, validity and applicability of historical data for establishing failure rates.

It is clearly seen that uncertainties due to system demand, Genset failure, maintenance duration and others, if taken under consideration reflect to a more realistic and safer representation of any real system. Suraj and Mantosh (2016) include uncertainties in the crucial issues that hinder development of a feasible and practical scheduling plan. Leou (2001) applied a Fuzzy approach to address uncertain constraints and acquired a solution that minimized the level of violation. Wu, Shahidehpour and Li (2007), taking under consideration Genset availability and system demand uncertainties used the Monte Carlo simulation method to create scenarios and retrieve a solution for the stochastic security-constraint Unit Commitment.

Kamali et al. (2018) used the modified Electro Search Optimization method to solve a problem for restructured markets. Some system was tested and results were obtained for a deterministic approach but also for a model considering uncertainties. Final conclusion was that uncertainties led to increased total cost. This is not something bad on the contrary; increased cost enables a safer handling of the system and real time adjustments are always possible.

In any case, a stochastic approach may well address uncertainties and in most of the cases a heuristic approach can provide at least a feasible solution, in practice something extremely important. On the other hand, it is hard to say how close to optimality this solution is, if optimal solution is not actually known. And in addition, we need to have in mind the work of Kamali et al. (2018). In a deterministic approach, parameters uncertainty may raise skepticism concerning the implementation of exact solutions. But if variability of influential parameters is small, by carefully estimating them based on confidence intervals, the possibility of implementing solutions is in practice not hindered, on a realistic probability base. In any case we can just apply nominal values if there is great confidence in them. At the end, optimality of the solution is a matter of the solving methodology and real time adjustments are always possible. As a result, when exact solutions are possible it is not that hard to opt for a deterministic or a stochastic approach but it is rather a matter of taste.

Convenience criteria also, among others refer to soft constraints that penalize Objective function.

Frequently met, cost criteria or reliability criteria form an objective function and other criterions of secondary importance or just by necessity are set as hard constraints (Badri, Niazi and Hoseini, 2011) or soft constraints. Violation of these constraints, further penalize objective function and at the end a solution is obtained upon methodology used.

But an objective function may also include cost and reliability criteria or others, altogether. In such a case, no argue GMS is a multiobjective problem (Krali and Raikovic, 1994). A trade off among criteria is possible by weighting them; alternatively, solutions are obtained with goal programming techniques (Moro and Ramos, 1999). Mollahassani-pour et al. (2017) used MILP for a system under the smart grid environment and acquired solution by applying the Lexicographic method.

Balaji, Balamurugan and Lakshminarasimman (2016) used an Objective function consisting of operational cost, maintenance cost and a reliability index driven reliability criterion. A fuzzy Clustered Multi Objective Differential Evolution algorithm was applied to retrieve a best compromise solution. Findings made clear that system reliability increases with increasing cost, something expected. But on a managerial decision level, no tradeoffs concern reliability. The reliability of a system has always to meet operators’ requirements. From a point of view, much interest lies in the elasticity of reliability and not that much on the best compromise solution. If we were to know the cost of mitigating from some reliability state to some other (perhaps of higher reliability), alternative decisions could be considered. And in such a case, extreme points are of great interest. Any system has some inherent to it maximum reliability however the later in defined or measured.

Chattopadhyay (2000) in his multi objective study regarding the power system of India used a stochastic approach for Genset outages. With Monte Carlo simulation combined to heuristics managed after all to balance among various costs and the uniform allocation of energy shortages to all states. That system was pushed to the limits during peak times imposing an around 20% load shedding and constraints formulation imply that power shortages were mainly due to capacity deficit. And for sure, any forced outages were a further major concern since no reserves existed.

It is evident that parameter uncertainty, dimensionality, complexity and other issues favor less detailed approaches when tackling a specific problem. In addition, when solving time is a prerequisite, exact solutions are not appealing.

Never the less, in this thesis we follow a multi objective holistic approach encapsulating all costs, namely fuel cost, maintenance cost and the cost of reaching desired reliability status. The latter is realized (also) by means of a newly proposed non-spinning reserve constraint. Exact solutions easily retrieved reveal systems real costs (fuel and maintenance) in respect to reliability status.

4.7 Typical Constraints

Constraints are used to represent systems functionality and limitations that usually heavily depend upon instance and scope. Restructured systems for example pose additional challenges especially when transmission aspects have to be considered.

A point of concern is always the validity of parameter values since constraints represent assumptions, we need to make beforehand. Arguably, any optimal solution (schedule) provides just a starting point for each Genset maintenance. All that is left to do during the implementation stage is to continuously check for parameter values consistency meanwhile, where ever possible, trying to minimize any additional cost stemming from corrective counter measures in case of deviations.

Typically used constraints are presented shortly after in a descriptive way since the mathematical formulation is exhibited in relevant chapters. There is no reason to present the formulation twice.

4.7.1 System demand constraints

Ensure that for each time period, power stemming from Gensets not in maintenance is enough to meet system demand. This can be done a couple of ways, depending on the overall formulation. In a simple GMS problem, the constraint simply imposes that the sum of Nominal Power of Gensets not under maintenance is sufficient enough to meet demand.

In a more sophisticated manner when the Economic Dispatch problem is introduced, the sum of Gensets power output has to equal system demand. It will all become clear in the formulation used in chapters 7 and 8.

4.7.2 Spinning reserve constraints

For each time period, spinning reserve power has to be available to meet system demand fluctuations. This is usually specified by a factor representing a percentage of system demand. The evaluation of that percentage is of crucial interest. If the factor is set too high, power plant can sustain operation under higher fluctuations but (possibly unnecessary) extra amount of fuel is burnt. That’s a constituent cost factor of reliability, we can say.

If the factor is set too low, power plant can achieve fuel cost savings but will have a hard time meeting the intermittency of renewable energy sources for example.

In any case, we could state that among different time units, the amount of spinning reserve necessary is different. For example, during high humidity periods, a higher spinning reserve power alleviates dangers of blackouts.

Formulation used in chapter 8 and chapter 9 enable us to set different factors among time units rendering a more flexible real system approximation.

4.7.3 Generating capacity constraints

These kinds of constraints simply impose the maximum and minimum output of any Genset. The evaluation of these limits is of utmost importance and has to be done by experts.

We do not delve into it any more since in chapter 6 we provide a dedicated section aiming at providing some insight into the subject.

4.7.4 Resource constraints

In general, we are interested in resource availability. Typical examples of resources are man power and spare parts but many other do exist. It is safe to assume that what really serves as a limited resource has to do primarily with each company policy. As a result, in regard to resource constraints there exists significant divergence among different instances.

As an example, we can note that man power availability is best suit for companies seeking to keep knowledge and knowhow within the company limits. Dividends of this policy are significant since such companies, gradually accumulating technical experience, are capable of fast reactions to unexpected situations. Technical department is practically capable of effectively troubleshooting and restoring the operation of a malfunctioning Genset, in most of the instances.

In other cases, it is preferable to outsource maintenance activities. This policy has many advocates mainly due to the in a sense fixed maintenance duration time, despite the generally higher cost. In such a case, maintenance duration is a contractual agreement with the provision of penalties so the interested part struggles to keep up with the schedule. Quality of the services offered as a whole, is a cause of many disputes but a minimum is in general achieved. Advocates of this policy also emphasize on the practically infinite resources offered by the local or offshore market.

A hybrid approach is sometimes best suit. Insource and outsource allocation of maintenances, achieve a compromise in goals. In practice, other factors are also influential.

4.7.5 Exclusion constraints

For some reason, certain Gensets are not allowed to be at maintenance during some time period. For example, we do not want the higher capacity Gensets to be out of service simultaneously. Process flow reasons also are important. For example, in a single engine room with only one bridge crane it is strongly advised not to carry simultaneous maintenance activities.

4.7.6 Precedence constraints

Precedence constraints can be included in any model since there are strong reasons urging for. Other than technical reasons, usually there exist a philosophy or policy behind. For example, some power plant managers prefer to have the higher output Gensets overhauled at least a couple of months before peak period. It's not mandatory that these Gensets shall operate continuously until then but that time in practice is more than enough to reveal any technical issues not met by maintenance activities and trial tests. After all, it's better for the higher output Gensets to have proven their reliability for some time, before entering the peak period.

In addition, maintenance activities are not the same. We are not referring to different types of Gensets or even brands. Our approach has to do more with the "experience" accumulated regarding the maintenance of each one Genset. Maintenance manuals do provide insights and useful information about spares needed, man power required e.t.c. But in practice only after the strip down of a Genset and in particular during inspection the truth can reveal. For example, a thrust bearing not included in the manuals' list of mandatory spares, may urge for replacement. Suppose that part is not available in our warehouse or even in the ware house of the other power plant of the company that possess same Genset. In the case we can find the part in the market we face maybe just a logistics problem (no budget limits under consideration). But nowadays, global fiscal instance calls for suppliers to keep stocks in low levels. As a result, in the worst-case scenario that part is not readily available in the market and we face a big problem. In many cases, genuine or even OEM parts are hard to find, especially if these parts exhibit extremely low demand.

Another point to take under consideration is the fact that not all maintenance activities have a positive result. The maintenance is concluded just after trials. During trials, some problems may emerge calling for additional activities. In some cases the problems are time consuming to face and may even put off the rails all maintenance planning. In such a case we will have to re-schedule the maintenance plan conforming to the new data (maintenances overlapping etc) but above all we need to guarantee optimal power flow meeting customers demand, with previously stated considerations met.

It is clear that if maintenance duration is regarded as deterministic, we need something to "safeguard" against the inherent uncertainty demonstrated in practice. By using precedence constraints we can decide for certain Gensets to start maintenance as soon as possible. This way we have more time to react to any unusual situations (shortage of spares, implications during maintenance etc.).

4.7.7 Maintenance window constraints

The availability of certain resources (specialized personnel, special tools etc.) are mandatory for any maintenance activity to commence. In some cases, maintenance crew for example has already scheduled activities in some other power plant, so a particular Genset maintenance has to finish before a certain date. Many other reasons do exist pinpointing in total that in some cases a Genset maintenance cannot start before some date and cannot go beyond another. This information is critical so we have to assign a time window within the horizon, where a certain maintenance might start end evolve.

Another interesting option offered by this kind of constraints is to enforce some kind of policy regarding Gensets running hours. No argue that when overhauling a Genset prior to meeting typical running hours we spent money. It constitutes a practice then, to forcefully start maintenance of the “most expensive” Gensets somewhere during the end of the horizon. By this way, we accumulate more running hours, utilizing most of the capital spent in the past for maintenance. In such cases extreme caution is mandatory since additional fuel costs may hinder the approach.

4.7.8 Maintenance duration constraints

These constraints simply impose for each Genset the mandatory allocated time units for the successful integration of maintenance activities. In plain English, how much time is needed to complete the maintenance task.

4.7.9 Maintenance contiguity constraints

This kind of constraint simply imposes that whenever a maintenance activity starts it is not allowed to pause. Intermittency is not allowed in practice for countless reasons.

4.7.10 Network flow constraints

As the interconnection of regulated markets gradually expands, existing networks form a new transmission network but limitations due to existing design and infrastructure become burdensome. These limitations give birth to some problems, for example:

-No adequate maintenance time is available for some network parts, since auxiliary routing is hard to find for some reasons.

-Some network parts are overloaded reaching their capacity limit and as a result auxiliary routing is mandatory if not for new investments to provide extra capacity.

-In case of some Power plant failure, reserve power will be injected in the system from some other point probably causing congestion or overloading to some points.

These kinds of constraints play a significant role in reliability terms (not only) and as a result must be carefully incorporated in the model.

Some more constraints worth mentioning may refer to transmission lines capacity and reliability, Genset produced energy, emission controls, fuel reserves, startups and shut downs and operating hours. Ideally, any GMS should take under consideration Genset operating hours (Fattahi et al., 2014) and even incorporate equivalent operation hours (Sangheon et al., 2016) due to start/stops.

4.8 Operating reserves constraints

At this point it is extremely helpful to shed some light on the particular area of operating reserves. Operating reserves are mandatory during actual operation of any system and are classified into spinning reserves and non-spinning reserves.

Spinning reserves mainly serve to meet sudden demand fluctuations altogether providing sufficient time to dispatch extra units when demand rises. In a simplified manner, spinning reserve is usually set for all periods as a fixed minimum percentage of system demand. In literature we can find instances of as low as 6% (Sangheon et al. 2016), 10% (Carrion and Arroyo, 2006) while Eygelaar, Lötter and van Vuuren (2017) used 15%. Typically, a 10%-20% margin is used (Canto, Romero 2013). If spinning reserve is not a requirement during modeling, it is set to 0 (Umamaheswari et al., 2017).

An interesting approach is presented in Conejo, Bertrand and Salazar (2005) where spinning reserves are set different among periods, rendering to higher reserve set points during increased system demand. This approach is also validated among periods of an expected high rate of disturbances (high humidity for example). But as spinning reserve express minimum requirements, model output may suggest even higher reserves. For example, in Sangheon et al. (2016) the average and minimum reserve rates were 14.6 and 6.6 respectively.

The ability of a power plant to meet sudden demand fluctuations is closely related to its actual performance and not that much on the actual magnitude of spinning reserve. This is the reason that there is no general rule on setting a percentage, since it should be tailor made for any particular system in respect. It is true however that a minimum should be rock-solid set by any system operator.

Special care is mandatory when renewables are involved since not only conventional units are the main contributors of spinning reserve but the intermittent nature of the former pose additional requirements. In any case, higher spinning reserve rate leads to different schedules but also in higher total fuel and maintenance cost, as validated in Niazi, Sheikholeslami, Varaki (2012). On the contrary, too low spinning reserves may result in a technically infeasible schedule during implementation, despite feasible and optimal in principle. It is evident that on setting a suitable rate, expert information is necessary.

This is certainly not the case for instances of fixed minimum requirements. In Mollahassani, Abdollahi and Rashidinejad (2013) studying the IEEE reliability system, spinning reserves were set 400Mw corresponding to the largest unit capacity. Despite the static approach, it is evident that spinning reserves constraint also served for reliability purposes. While this approach is valid for a system of more than 3-GigaWatt capacity with dispersed production, for small systems is quite an extremely costly luxury and applicable only when renewables are involved. The possibility for a wind park to meet sudden power loss is real and the impact devastating.

As Huang, Y., Pardalos P.M. and Zheng (page 3) state, "…an unplanned outage of generators or transmission element is considered a low probability event…" they conclude, "In more instances, power system is not built for avoiding any uncertainties, but an operational schedule for power generation should be a robust solution to handle the impacts from most uncertainties". This is an approach frequently applied in small systems hence non-spinning reserves play the most important role in handling the impact of any outage.

Speaking of the "robust solution" it would be interesting to consider the spinning reserve constraint as a chance constraint, a prelude to robust optimization but this is out of our scope.

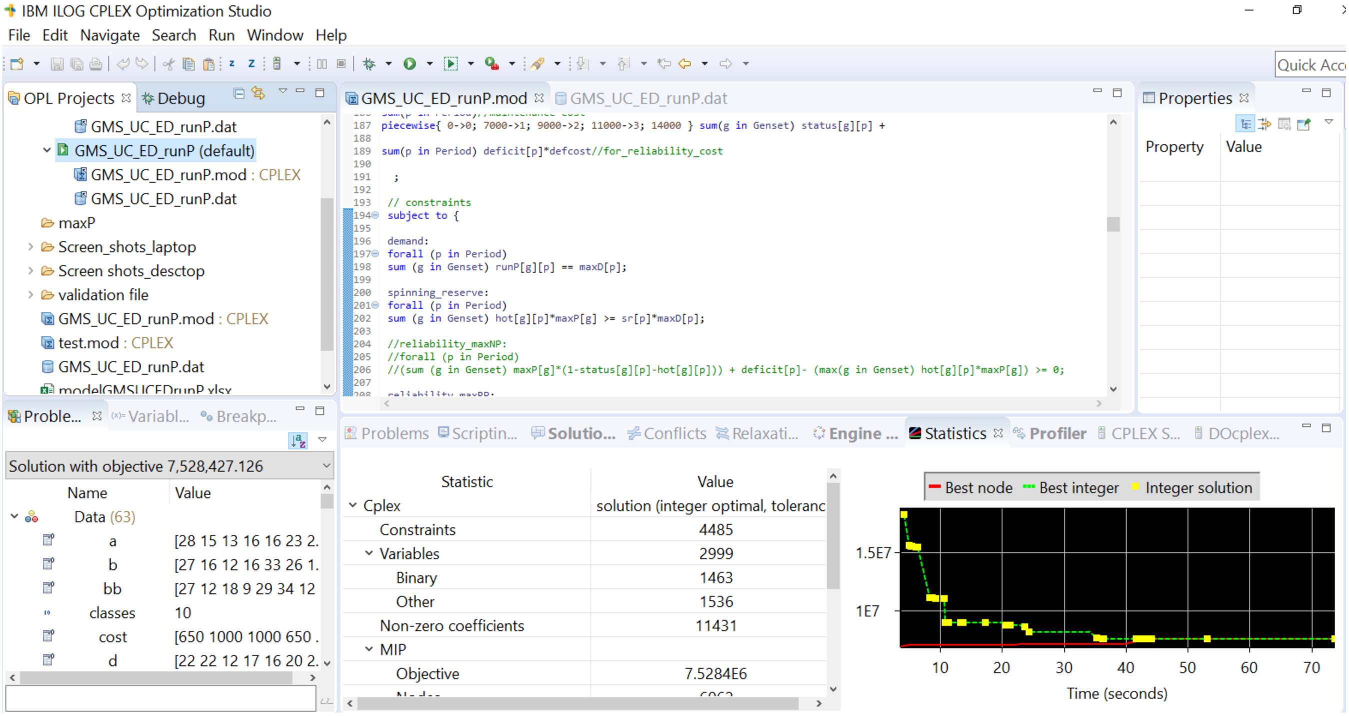
Non spinning reserves usually refer to Gensets capable of connecting to the grid within 5-10 minutes. The capacity in reserve involved depends upon actual needs. It may be set as a fixed amount (Bisanovic, Hajro and Dlakic, 2011) or as usually, set as the higher redundancy (Canto, 2006). In other words, for any time unit at least the equivalent of the higher capacity running Genset has to be standby, as hot start reserve. If this approach is introduced by hard constraints, despite ensuring system reliability a side effect is the possibility of leading to infeasible solutions. If on the other hand soft constraints are set, a plethora of useful managerial information can be extracted. This is the approach used in this thesis in conjunction to enlarging the notion of higher redundancy.

Chapter 5

Solution tools used

In our study we translated the mathematical model in to suitable code using Optimization Programming Language (OPL). OPL is a powerful and flexible enough language offering many modeling possibilities.

The generated code served as input for a state-of-the-art solver that provided the solutions. In particular we used IBM ILOG CPLEX Optimization Studio, see Figure 5-1 below.



```
piecewise{ 0->0; 7000->1; 9000->2; 11000->3; 14000 } sum(g in Genset) status[g][p] +

sum(p in Period) deficit[p]*defcost//for_reliability_cost


 ;

// constraints
subject to {

demand:
forall (p in Period)
sum (g in Genset) runP[g][p] == maxD[p];

spinning_reserve:
forall (p in Period)
sum (g in Genset) hot[g][p]*maxP[g] >= sr[p]*maxD[p];

//reliability_maxNP:
//forall (p in Period)
//(sum (g in Genset) maxP[g]*(1-status[g][p]-hot[g][p])) + deficit[p]- (max(g in Genset) hot[g][p]*maxP[g]) >= 0;
```

Solution with objective 7,528,427.126

Name	Value
Data (63)	
a	[28 15 13 16 16 23 2.
b	[27 16 12 16 33 26 1.
bb	[27 12 18 9 29 34 12
classes	10
cost	[650 1000 1000 650 .
d	[22 22 12 17 16 20 2.

Statistic	Value
Cplex	solution (integer optimal, toleranc
Constraints	4485
Variables	2999
Binary	1463
Other	1536
Non-zero coefficients	11431
MIP	
Objective	7.5284E6

Figure 5-1: Screen shot of test run in IBM ILOG CPLEX Optimization Studio

In the main central window, we can see part of the code and on the bottom left side the Objective Function Value. The graph on the bottom right side depicts solution time for the instance. As we can notice, current solution is optimal.

Chapter 6

System considerations & assumptions.

This small chapter summarizes the general framework of the optimization attempt and aims to provide useful insight in what concerns the determination of some critical system parameters. As it is obvious text is adjusted for the audience lucking technical expertise but in any case, can surely provide fresh ideas and modeling inspiration to the interested.

The case system refers to an isolated power system of a highly touristic island. Generally, any small in capacity grid is vulnerable to heavy demand fluctuations and depends merely on its own resources to meet any abnormality. This fact highlights the importance of accurate and reliable production schedules to be implemented. On the contrary, no special interest exists concerning transmission aspects.

6.1 General framework

As a result of the seasonal touristic activity, load factor is low and full capacity is only realized among peak demands during summer. Arguably, base load Gensets constantly accumulate more running hours compared to peak contributing Gensets. Management, decided to keep in cold reserve any production equipment that possess many leftover running hours, until next major overhaul. Consequently, seven (7) liquid fueled Gensets constitute the chosen available production equipment portfolio that has to meet system demand and simultaneously be overhauled, among a certain period of time. Management wants to retrieve an optimal maintenance schedule, paying special attention to reliability against Genset outages.

Traditionally, no major maintenance activity is carried out from mid-June to late September due to seasonal high loads. The end of each tourist season serves as the starting point of preparations to meet next season system demand. So, each year during mid-October to mid-December the job is (as hard as ever) to prepare a valid and trustworthy Generation maintenance schedule. Possibly there might exist more than one maintenance schedules that can be delivered accurately but with different cost in each case. Our job is to choose the one that corresponds best to the company's "objectives".

As a result, maintenance activities can be freely scheduled among 16 weeks starting from the first Monday of February. That is almost 4 months of operation and the 7 Gensets taken under consideration provide a sufficiently realistic system approach. In reality, there are more than 7 Gensets in the power plants production equipment portfolio. For our purpose, we suppose the ones not participating in scheduling are the ones reserved for operation during high season, a strictly managerial decision at the end.

Simply put, we want to choose a Generation Maintenance Schedule such that:

All necessary Genset maintenances will be carried out with-in 16 weeks and system demand would be reliably met in such a way that overall fuel and maintenance cost is kept minimum.

Having said that, one way or another some schedule shall be finalized but many actions have to be synchronized in order to achieve the objective. It is evident that a holistic approach is necessary and an overall Project Management philosophy has to be applied for delivering the chosen Generator Maintenance scheduling.

Best practice is to stick to the original schedule and make whatever possible to prove it since plants budget heavily depends on it. It is important to realize that any deviation (not available spares for example) may heavily influence later actions due to the fact that any corrective measures may take long to put in effect. In some cases though, cost of alternative corrective measures is high enough to characterize plants budget misleading, at least. But the big impact is on the reliability side and it's detrimental.

Maintenance duration for each Genset is known and four (4) at most maintenance activities can be running simultaneously. System demand for each period is known and fixed. All spare parts necessary before starting any Genset maintenance activity shall be readily available just in time but if availability is an issue, special attention should be paid.

The above list of statements well describes the test case system at hand but there is certainly more to it.

6.2 Maintenance duration

Maintenance duration is not simply a number following a deterministic approach or maybe something stochastic based on previous endeavors.

It is true that maintenance duration actual results have to follow more or less some kind of distribution. By appointing the RHS of a hard maintenance constraint a carefully selected value we are theoretically on the right track.

Suppose 95% percent of the time, maintenance duration of a Genset is less than or equal to 4 weeks. By appointing this value, during modeling stage we disregard extreme cases by making the assumption that they are rare. As a result, we assume that a deterministic period of 4 weeks is sufficient enough so as to provide handy and reliable results.

But there a philosophy and level of experience is hidden behind any RHS determination. We should be aware of that and prior to any fast and easy conclusions, the opinion of each system expert is more than needed.

Preventive maintenance is in principal complex and demand extreme caution during all stages. Even the smallest detail can play significant role. No wonder why experienced engineers demand thorough cleaning of a Genset just before starting any dismantling activity. No wonder why they inspect engine repair log. No wonder why they tear apart used oil filter cartridges to inspect debris found. The list is big enough simply because maintenance duration may shift for really countless reasons and in extreme cases it’s advised to stop any activities and focus resources elsewhere.

6.2.1 Spare parts availability assumption

During the dismantling of engine parts, inspection of components and critical parts starts immediately. The aim is to obtain critical information (concerning maintenance duration), about unexpected deterioration of any part. Unexpected is something simply not listed in the manufacturers inspection, repair or overhaul manual but urges for additional activities. In case an extra part is needed, it’s better to know it just at the beginning of the maintenance or at least as soon as possible. In any case, if extra findings are present, uncertainty has already entered our model. Clearly, most part of the duration uncertainty somehow corresponds to the inspection stage since despite extra findings, we might respond fast and alleviate the extra problem in time. In other cases, a spare part may arrive late enough, causing our schedule to become infeasible. The most qualified personnel should be assigned this task, otherwise true will inevitable be revealed soon enough.

During the rest of the stages such as repair or overhauling of equipment, replacement of worn parts etc. uncertainty is still present but only in extreme cases a problem may arise.

6.2.2 Absence of Genset breakdowns assumption

The moment of truth comes during trials regarding acceptance of services done. Quality of spare parts play significant role (original, OEM, aftermarket, reconditioned, used etc.) but in general during trials hardly ever someone might notice the difference occurred in the long run.

Something important worth mentioning, not generally acknowledged in the full extend is the notion of, to what equipment the maintenance duration refers to. We are talking about Gensets and the misconception that maintenance of a Genset strictly adheres to the maintenance of the prime mover or at the best including auxiliary equipment (fuel treatment system etc.) persists.

It is true however that mechanical, electrical or electronic protection devices are serviced or should be serviced during the preventive maintenance. It is also true that if the prime mover is not properly serviced, risk of total or catastrophic failure is present and many occurrences do exist in practice. But this is a tricky misconception, especially to what concerns reliability and assumptions we make in general. We explain.

Except critical equipment like transformers, circuit breakers etc. that are (maybe not) serviced in different time periods (other than preventive maintenance), a plethora of somehow minor electrical and electronic equipment exists, closely related to the operation of any Genset. For example, lose contacts in a junction box may cause erratic behavior of an engine or even cripple a protection scheme (a pressure switch despite serviced on bench not safeguarding in practice, since disconnected). A single cable in a damaged cable way may cause false trip triggering or even no triggering at all when actually needed. All these are causes of Genset unavailability

All the relevant checks may be time consuming or even boring for technical staff since great findings may not ever appear. On the other hand, existing redundancy results in omitting certain check points. If one circuit fails for some reason, there is another, someone could think. But the redundancy of various circuits of a Genset is diminished over time due to simple oversights and luck of preventive/corrective actions. No wonder why some aged Gensets have crippled circuits. After some point, repair actions are too time and money consuming and hence are disregarded.

It must be clear by now that maintenance duration should correspond to maintenance activities concerning the Genset in general and not concentrating only on the mechanical part or in general to some discrete parts of extreme interest.

6.2.3 Conclusions

Estimated maintenance duration (and the inherent uncertainty involved) is realized in practice if only best maintenance practices are involved. That is not the case in some occasions and it has always to be considered before any scheduling attempt.

6.3 Forecasts and capacity

In any power system, system demand forecasting is vital. Forecasts may refer to some years to come or just concern only next year. Yet, both represent the utter most vital information for any power plant.

Long term forecasting mainly involves annual peak load demand forecasts and is mandatory mainly for strategic planning such as installation of extra Gensets to meet demand. This kind of decision involves investments and is not at all easy to take. On the other hand, for a Genset to be delivered turnkey, in addition to the relatively long installation period (see Figure 6-1 below), a lot of uncertainty is involved (market availability, construction stage pitfalls, trial test failures e.t.c).

Figure 6-1: Foundation construction for a new Genset

Our estimation has to be realistic so as to safeguard against some worst-case scenario. That is important because reliability factor concerning meeting peak demand is strictly 1. No power shortage is allowed due to bad image and there is no room for hypothesis tested here. On the other hand, if we over power a power station we tie down valuable investment capital, not a wise approach. In any case some new expensive and state of the art production equipment inevitably will have to be put in service, sometime in the future (see Figure 6-2 below). Accurate demand forecasting is the main prerequisite for achieving the best timing.

But next year forecast is necessary for more immediate actions such as the GMS that concern us the most and so we will focus our attention on the year to come only.

Generally, we need to forecast next year peak demand but if fuel expenses are of great interest we need to forecast accurately next year’s system demand curve, something extremely hard.

Figure 6-2: Some millions (€) entering the engine room

6.3.1 Next year peak demand

As a starting point we can base our calculations to previous, historical data and realize a trend. But, many influential factors that could define next summer’s peak demand do change. As a result a scenario based forecast is more than suitable.

It’s obvious though, in order to make an as accurate as possible forecast we need to acquire reliable and relevant information from different origins. For example, info about new end users and corresponding extra power demand may be acquired from the local power distribution company. The rate of bookings is a good start but requires insight in to the tourist industry.

Alas, some information may even not be accessible during the scheduling stage. Tourism ministry campaigns, airport fee tax reductions, new investments in the market or even terrorism activities in competing markets may cause a last-minute shift in destination for many travellers. As a result, not only peak demand is affected but also energy demand, think for example a prolonged tourist season.

In practice, it is possible for estimations of peak demand to be roughly accurate and underestimations or overestimations mainly refer to climate. For sure, the larger share of uncertainty involved is attributed to a non-controllable variable, that is ambient air-temperature, no one can argue with.

As a general remark, estimated peak power must always be treated in conjunction to nominal and available power, this is a key point. The former (nominal power) has to do in principle with capacity planning and the later (available power) has to do in principle with maintenance scheduling. A good plant manager utilizes as few resources as necessary to narrow the gap (as close as possible) between nominal and available power and a good maintenance schedule serves as a starting point.

Luckily enough, daily energy demand forecasting especially to what concerns our GMS horizon is somehow more easy or safe to handle. During winter and spring, tourist activity is minor and temperatures don’t exhibit significant variation effecting demand. It is also safe to assume that any increase in demand is due to growth, in principle. As a result, a fixed % increase is adequate to compensate for. As shall be thoroughly explained in chapter 9, we don’t even need to forecast a weekly demand curve but based on previous data we can indirectly account for a rate of growth.

We must state that any hourly system demand data set is the result of a complex procedure since adjustments corresponding to special events (Easter time for example) must be made. We shall not delve more in to it since it is out of our scope.

6.4 Generating capacity derating

Hardly ever a Genset operates at nominal output after acceptance tests. For reasons thoroughly explained a Genset usually operates bellow the nominal power either by choice either by necessity. It shall be seen that the crucial fact concerning our modeling attempt is to know by how the Nominal generating capacity is reduced and equally important, when this derating exists.

In general, the power output of a Genset decreases over time due to aging, even if all previous maintenance activities were carried out successfully and on time. Aging is not the only contributing factor though. For example, in case of a Genset not fatal crankshaft main bearing failure, the subsequent repair implies predefined oversized bearings to be used but with a power output reduction (suggested by manufacturer or experienced personnel). In general, a permanent new power reduction is somehow rare in practice and we shall omit the possibility.

In practice (within any period under consideration), generating capacity decreases mainly to factors temporal in nature (but frequently time consuming to face). As an example worth mentioning is a dysfunctional turbocharger. Despite the time consuming inspection activities, if a spare turbocharger is readily available, the Genset might be put back in service before long. These instances of Genset unavailability are somehow rare to lead to failure of the equipment but after all can be effectively met by a well-organized procurement and maintenance division.

During daily operation, power reduction in most of the cases is due to just simple causes. A dysfunctional fuel oil treatment system, a bad injection nozzle or even a partial clogged air filter will cause high exhaust gas temperatures forcing operation crew to instantly limit the output of a Genset. And here is where details play the most important role and makes a power plant significantly differ from another. An experienced and motivated shift shall be able to quickly troubleshoot and pinpoint the cause of a problem. If not able to fix the problem itself, maintenance division will have a good starting point so as to quickly restore optimal operation. For example, a sticky high pressure fuel pump will be easily noticed by the experienced shift and the replacement part will be quickly put in place by maintenance crew.

Restoration or response time is crucial in any case but specially in cases where the cause of a problem is not easily seen. The hard part is when a combination of causes exists: a hunting engine may be due to a dirty/loose magnetic pick-up and a poorly adjusted governor. It is more than evident by now that not only the magnitude of the power reduction is important but also the recovery time. In a well-coordinated power plant, temporal causes are met quickly and are not an issue. This is our case since we assume that management provided the best. We must notice however that despite all efforts, as the fleet of Gensets increase in number (comprising a power station), troubleshoot and repair activities are challenging due to the time factor.

A predictable (but unfortunately often omitted) cause of derating is the case where local climate (engine room or free space) is harsh. Mainly ambient temperature but also humidity plays an important role and manufacturers well inform equipment users with easy to use graphs.

At the end, nominal power is reduced to some extent, in many cases high enough for certain types of Gensets and especially when concerning aged ones. The most vulnerable are the air-cooled Gensets.

In this case system, maintenance window is during spring where we assume that even with a gradual rise in ambient temperature we always remain far below any critical point. That is certainly not the case during summer operation where high enough differences in temperature are common even during same day (morning to evening). Not to flatten, for a model concerning a whole year, we should allocate different capacities during different time periods and dimensionality of the model would be an issue.

It is worth mentioning that not only nature defines the local climate but management activities also may play an important role and extreme care is mandatory. Poor decisions may have detrimental effects. Suppose a power plant needs rental (mobile) Gensets to support energy production during summer peak period. If the newcomers are placed in the proximity of other mobile Gensets, exhaust gases supported by terrain obstacles and depending on wind velocity may form a local Greenhouse effect. All Gensets are exposed to high temperatures (due to exhaust gases) resulting in a significant derating concerning all of them.

To sum up, we assume that during all periods the generating capacity of each Genset remains the same and at a predefined magnitude. Temporal causes of derating such as inefficient coolers urging for cleaning should be met before hand with at least adequate staffing and sudden big or small failures being rare are omitted altogether.

All necessary Genset data are presented in APENDIX A. No start up or shut down costs exist (negligible) and ramp rates is not a concern due to Genset technology. A 5% to 10% percent derating is usual in practice for various reasons as in our case. Higher deratings are usually due to some technical issues of permanent nature as is the case for Genset No 7. The fuel sources are diesel oil and heavy fuel oil. In other words, power plant is dual fired but no fuel consumption limitations exist for either case.

Fuel consumption of all Gensets obeys a quadratic function and data used stem from on-site acceptance tests (ISO conditions). A simple transformation enable us to accurately linearize fuel consumption.

Chapter 7

A simple GMS model

Gms in the simplest form offers little choice, see Figure 7-1 (below).

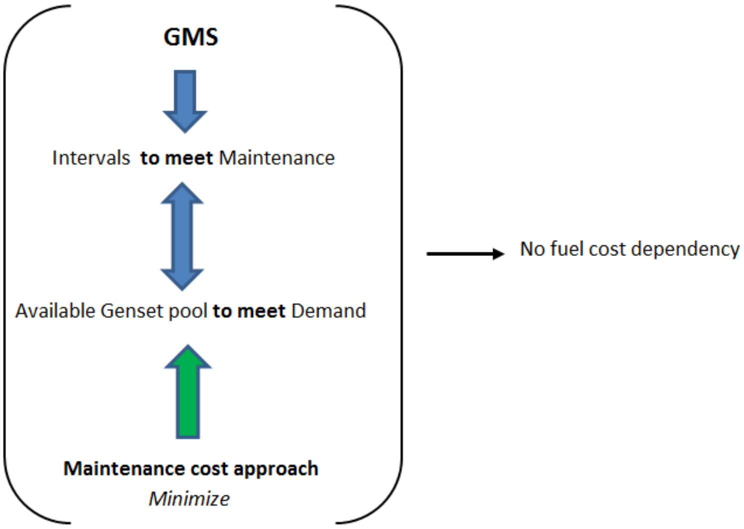


Figure 7-1: Simple GMS problem

For each time unit (week), some Gensets are under maintenance and the rest form an available to run Genset pool. As a result, for each time unit there exist no distinction among the available to run Gensets in respect to which will operate to meet demand and which will not, serving as reserve Gensets.

With this simple approach, the objective is just to acquire a feasible maintenance schedule meeting demand for each time unit, at a lower overall cost the only cost under consideration being maintenance cost.

7.1 Definitions

Indexes: Two (2) indexes are used referring to each time unit and Genset:

t: index of week ∈ (1, T)

i: index of Genset ∈ (1, N)

Parameters: Parameters involved refer to system demand, Nominal Genset power etc. The complete listing follows:

T: Number of weeks

N: Number of Gensets

D_t: System peak demand for each week (Mw)

NP_i: Nominal power (or Capacity) of Genset i (Mw)

M: Maximum number of simultaneous maintenances

DUR_i: Maintenance duration of each Genset

MC: Variable cost of simultaneous maintenances (€)

Variables: Binary variables are used to indicate the starting point of any maintenance and Genet status during instances.

$x_{i,t}$: Binary variable (1: Genset i starts maintenance during week t, 0: otherwise)

$s_{i,t}$: Binary variable (1: Genset i is under maintenance during week t, 0: otherwise)

7.2 Model constraints

Maintenance window: All Gensets shall be overhauled only 1 time within the horizon and the following constraint enables the starting point of each maintenance to float inside all weeks.

$$\sum_{t \in T} x_{i,t} = 1, \quad \forall\, i \in N$$

Maintenance duration: Maintenance duration of each Genset is fixed and as a result the sum of each Genset status (1: maintenance, 0: otherwise) for all weeks has to be equal to the corresponding duration.

$$\sum_{t \in T} s_{i,t} = DUR_t, \quad \forall\, i \in N$$

Non-stop maintenance constraint: Once a maintenance activity has started, it cannot be interrupted. This is imposed by the following constraints that are easily validated with the use of a truth table.

$$s_{i,t} - s_{i,t-1} \leq x_{i,t}\,, \ \forall\, i \in N, \ \forall\, t \in T$$

$$\text{For t} = 1, \qquad s_{i,0} = 0, \ \forall\, i \in N$$

Resource constraint: Total number of simultaneous maintenance instances has to be at most M. As a result, the sum of all Genset status (1: maintenance, 0: otherwise) for each week is limited to M.

$$\sum_{i \in N} s_{i,t} \leq M, \quad \forall\, t \in T$$

Demand constraint: Nominal output of Gensets capable of serving each week to meet system demand, has to be at least equal to system demand,

$$\sum_{i \in N} NP_i\,(1 - s_{i,t}) \geq D_t, \qquad \forall\, i \in N, \forall\, t \in T$$

7.3 The objective function

The Objective function refers to maintenance cost that increases as the number of simultaneous maintenance activities increase. This is expressed as a step wise function and the notion is simple yet somehow free to interpretation. It represents the additional cost of utilizing more resources (maintenance crews) and our preference for the least simultaneous activities present (for safety reasons among others).

$$F_1 = \sum_{i \in N} s_{i,t} * MC, \forall\, t \in T$$

Where MC as the variable cost of simultaneous maintenances is defined as:

$$MC = \begin{cases} for \sum_{i\in N} s_{i,t} = 1, MC = 7.000€ \\ for \sum_{i\in N} s_{i,t} = 2, MC = 16.000€ \\ for \sum_{i\in N} s_{i,t} = 3, MC = 27.000€ \\ for \sum_{i\in N} s_{i,t} = 4, MC = 41.000€ \end{cases}$$

7.4 OPL code

The OPL code used is presented bellow with some short comments for ease of understanding.

(a)_: .mod file

```
/*********************************************
 * OPL 12.8.0.0 Model
 * Author: Jim
 * Creation Date: 20/04/2019
 *********************************************/

int Gensets=...;  //Number of Gensets
int periods=...;  //Number of time units (weeks)
range Genset=1..Gensets;
range Period=1..periods;

float maxP[Genset]=...;  //Nominal Output
float maxD[Period]=...;  //max system demand per time unit
int dur[Genset]=...;     //maintenance duration per Genset
float nul[Genset]=...;   //auxiliary

dvar boolean startIn[Genset][Period];    //start of maintenances
dvar boolean status[Genset][0..periods]; // maintenance=1, run=0

minimize //Objective Function

sum(p in Period)
piecewise{ 0->0; 7000->1; 9000->2; 11000->3; 14000 } sum(g in Genset)
status[g][p]
 ;

 subject to {

 duration:
 forall (g in Genset)
 sum (p in Period) status[g][p] == dur[g];
```

```
 nonstop:
 forall (g in Genset, p in Period )
 status[g][p-1] + startIn[g][p] >= status[g][p];

 forall (g in Genset )
 status[g][0] == nul[g];  //auxiliary definition for non-stop

 window:
 forall (g in Genset)
 sum (p in Period) startIn[g][p] == 1; //Only one maintenance with-in the
Horizon

 simult:
 forall (p in Period)
 sum (g in Genset) status[g][p] <= 4; //Maximum number of simult
maintenances

 demand:
 forall (p in Period)
 sum (g in Genset) maxP[g]*(1-status[g][p]) >= maxD[p]; //meet system
demand

 };
```

(b)_ .dat File

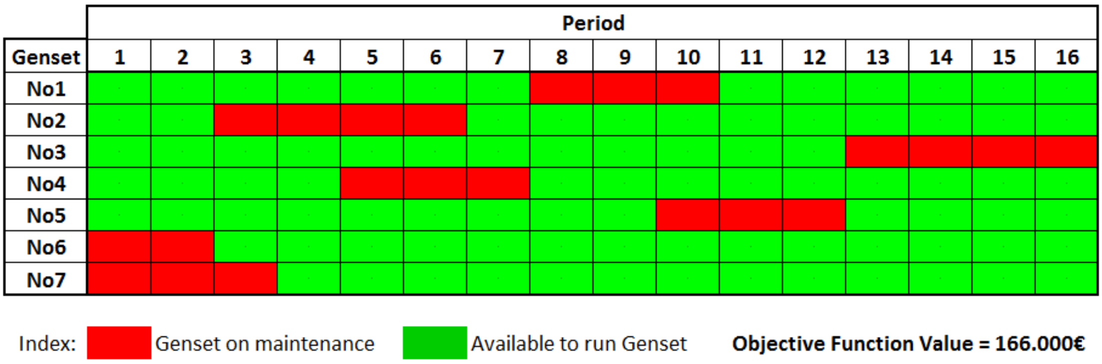
```
/*********************************************
 * OPL 12.8.0.0 Model
 * Author: Jim
 * Creation Date: 20/04/2019
 *********************************************/

 Gensets=7;  //Number of Gensets
 periods=16;  //Number of timeunits (weeks)

SheetConnection sheetData("C:\\Users\\gadak\\opl\\GMS\\modelGMS.xlsx");
nul from SheetRead(sheetData,"nul");
maxP from SheetRead(sheetData,"maxP");
maxD from SheetRead(sheetData,"maxD");
dur from SheetRead(sheetData,"dur");
status to SheetWrite(sheetData,"status");
```

7.5 Solution with IBM ILOG CPLEX

The solution obtained is optimal and presented in Figure 7-2(below).



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
No2	🟩	🟩	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥
No4	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩
No6	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No7	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Index: 🟥 Genset on maintenance 🟩 Available to run Genset **Objective Function Value = 166.000€**

Figure 7-2:Maintenance schedule for the simple GMS problem

As can be seen all Gensets are scheduled for maintenance with a total cost of 166.000€. That cost once again, only refers to maintenance cost activities all other costs excluded.

7.6 Comments

Practically, no reliability approach can be imposed since available output is free to oscillate from 0 Mw to whatever magnitude (see Figure 7-3, below).

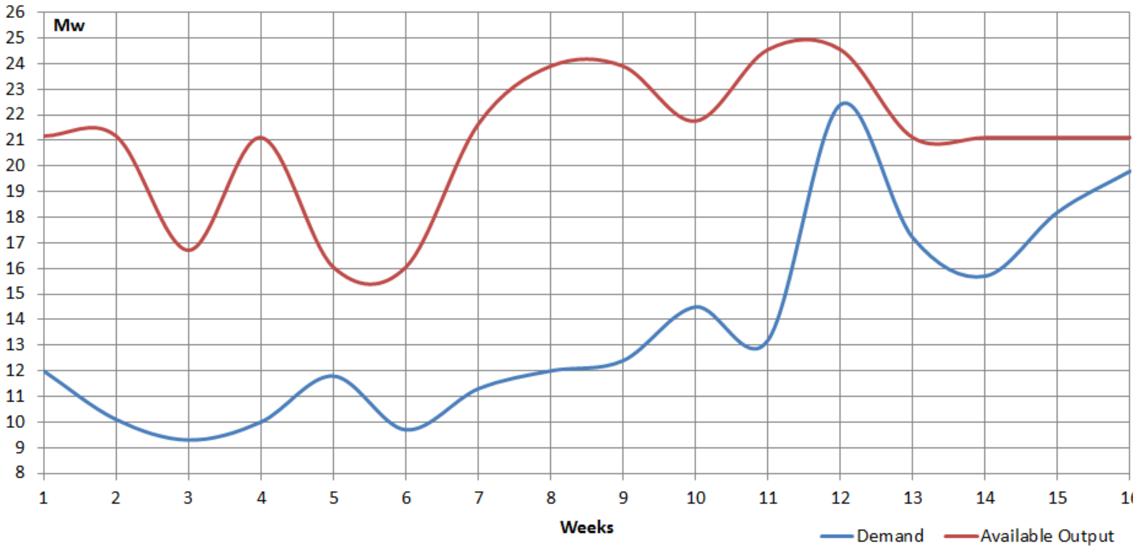


Figure 7-3: System Demand vs Available power

As a result, for example we notice that during week 12 where we expect peak load demand, Genset N^o 5 is under maintenance practically minimizing reserve capacity. This is crucial and at least calls our immediate attention.

We also notice that maintenance intervals are somehow balanced since spread quite uniformly among the horizon. In addition, reserve capacity in later weeks where system demand increases, is significantly less than other periods.

This behavior is worth noticing and as seen in Figure 7-4 (below) system reserves fluctuate significantly. This is because by the existing GMS formulation we cannot “steer” system reserves to periods where needed the most.

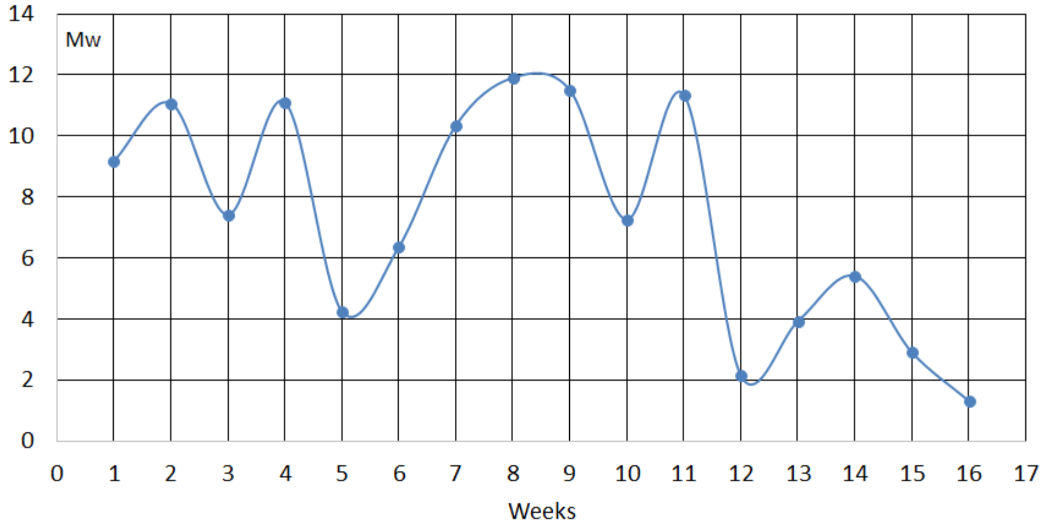


Figure 7-4: System reserves

Thinking critically, luck of adequate system reserves during some weeks, represents in practice un-reliable Power plant operation. That problem can be addressed in some different ways, at some cost of course. Preferably, before any thoughts about renting Power (if timely possible) a shift in specific critical maintenance interval should be considered. In our example it is evident that during week 12, no maintenance activities should occur. But if this shift happens, maintenance cost will increase. This does not need any proof since the solution presented in Figure 7-2 is optimal and unique. Any shift towards a higher level of reliability (change in schedule) if possible (if feasible) has to come with some additional maintenance cost.

A point of interest probably is what “adequate system reserves” means in practice or how they are translated quantitatively. Surely it depends on the modeler in addition to some established approaches that readily exist.

With the incorporation of the Unit commitment problem addressed in chapter 8, we shall introduce an interesting approach concerning reliability and the problem will be partially alleviated.

Chapter 8

GMS (simple)+ UC model

By introducing the UC problem, the available Genset pool is further divided in to a Hot start pool and a Reserve pool (see Figure 8-1, below). Hot start pool includes Gensets specifically dedicated to run meeting demand and Reserve pool includes Gensets the Nominal output of, will serve some reliability criteria.

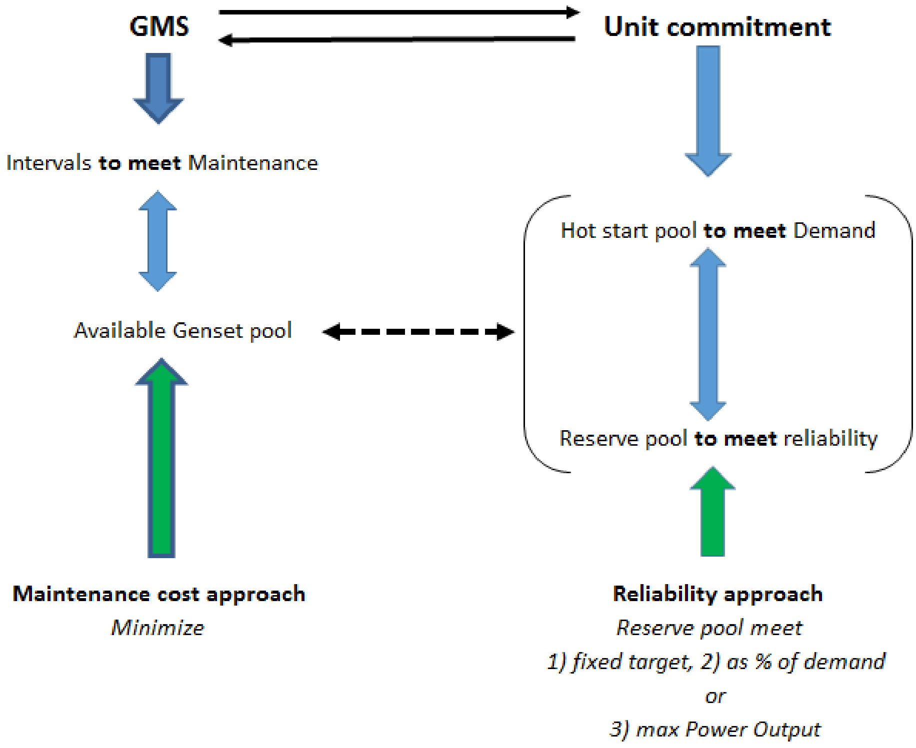


Figure 8-1: Simple GMS & UC problem

We need to notice that the hot start pool of each week is actually the available to run Gensets list. It is extremely practical that this list does not change significantly from week to week. The aim is to realize which Gensets will serve as base load Gensets and to generalize a bit which Gensets will operate the most as basis Gensets, let’s call them.

In any case it’s at least handy to have the list to run Gensets for a given time unit since we can realize a priority among them. As system demand increases, operators know beforehand which Gensets to synchronize in order to meet demand in the most fuel-efficient way. Practically, this way the system is well optimized in respect to the Objective Function formula used.

8.1 Reliability approach

In our approach since now, we take under consideration peak system demand during each week. This instance occurring for certain time is the hardest to meet for the power plant. If any Genset malfunction should happen, peak demand time is the hardest to occur.

As a result, the reliability approach takes as granted that one (1) Genset will certainly fail during each time unit constituting a framework for safe handling of the system. Model output compared to no failure instances approach may suggest some extra cost but this is simply the cost we have to pay for reliability.

An interesting approach is to set reserve margins at least equal to the highest Nominal capacity of Gensets operating at that time. This way, non-spinning reserves should be at least equal to the maximum Nominal power of a certain Genset, among Gensets operating during each weekly peak system demand. This is the maxNP approach.

In our study we will refrain from inserting the reliability approach as a hard constraint for a couple of reasons. First of all, if adequate Nominal power is not present (as in our case), no feasible schedule could be ever realized. This aspect has to be handled efficiently by higher level managerial decisions (investments in production equipment etc.) and it is out of our current scope.

Secondly, if we set a penalty factor to any possible deficit, we can compare expenses if we were to mitigate to a higher level of reliability. How we measure reliability shall be clearly seen shortly after. The important point though is to realize the marginal cost of reliability that comes in increments of maintenance cost. This valid and interesting approach actually eases many managerial decisions since by introducing a deficit cost, the impact of the absolute Objective function value is not important. The relative change is what practically matters and, in our approach, we will use multiplies of 10 for deficit cost.

8.2 Reliability Index

A Reliability Index for each period (by post processing results), accounting for corresponding deviations serve as input for the instrument measuring overall system reliability. Reliability as stated above does not take part in modeling instead is used for sensitivity analysis purposes.

The reliability index used is simple enough. For each time unit if deficit = 0 then reliability is 1. If deficit ≥ 0 then reliability is analogously reduced and calculated for each time unit as:

$$\frac{Sum\ of\ reserve\ Gensets\ Nominal\ Power}{Max\ Nominal\ Power\ of\ hot\ reserve\ Gensets}$$

For example, if during the 5th period, sum of reserve power is 3 Mw and the higher capacity Genset of all hot reserve Gensets possess 5.7Mw Nominal Output, reliability R_5 is:

$$\frac{3}{5,7} = 0.53$$

At this point we need to think critically. In our approach, any time unit (week) can be addressed separately from the others.

The possibility for a Genset failure during some period even with some deficit present, does not influence next period, since next period demand can be met by existing scheduling. This is true due to the realistic assumption that any Genset failure or temporal unavailability could be met with in each period. That means within 7 days, any technical issues can be resolved. If on the other hand that is not possible, we are facing a whole different problem. In such a case rescheduling is mandatory, since the overall Genset pool is now significantly different.

As a result, in formulating an overall reliability index we can retrieve the average value for all periods or consider the sum that adds to 10. Alternatively, we can set weights corresponding to each time unit. Consequently, the Reliability Index can be formulated as:

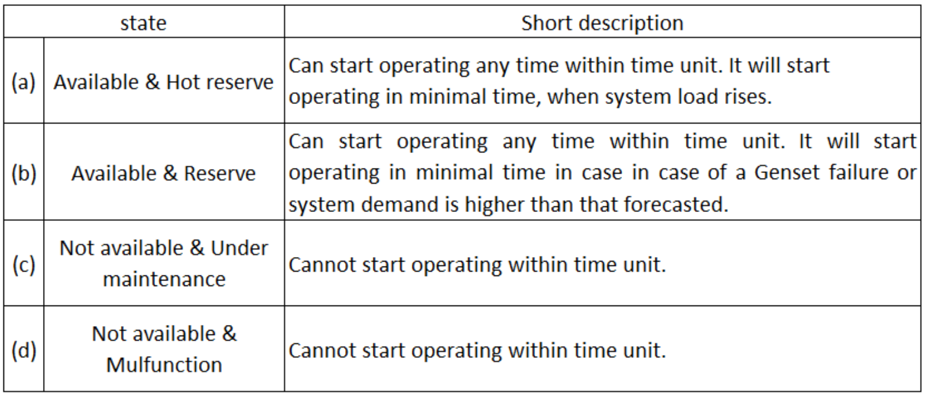
$$R.I. = \sum_{t \in T} R_t\, P_t \ \leq 1$$

Interpreting possibilities are quite enough. A valid approach is to assume weights as the probability of a worst-case scenario Genset failure. Corresponding to the higher capacity Genset, which ever that is, may be set the same for all periods or weighted: for example, proportional to energy produced per period to total energy produced per horizon.

Weights may well represent some impact (on customer di-satisfaction for example) or importance and in our approach are assumed equal among periods.

8.3 Model considerations

The model should be able to define the state of each Genset except state (d), see Figure 8-2 below.



state		Short description
(a)	Available & Hot reserve	Can start operating any time within time unit. It will start operating in minimal time, when system load rises.
(b)	Available & Reserve	Can start operating any time within time unit. It will start operating in minimal time in case in case of a Genset failure or system demand is higher than that forecasted.
(c)	Not available & Under maintenance	Cannot start operating within time unit.
(d)	Not available & Mulfunction	Cannot start operating within time unit.

Figure 8-2: Possible Genset states

We need to pinpoint that temporary un-availability of any Genset for whatever reason (short term maintenance, failure etc.) if alleviated in short time (maybe some hours up to 7 days at most) practically does not influence power plant operation based on an established schedule. If on the other hand a long-lasting un-availability occurs, the established schedule provides the means to tackle the problem with the reserve margin at hand and obviously, re-scheduling has to commence at some point soon.

8.4 Definitions

Indexes: Two (2) indexes are used referring to each time unit and Genset:

t: index of week ∈ (1, T)

i: index of Genset ∈ (1, N)

Parameters: Parameters involved refer to system demand, Nominal Genset power etc. The complete listing follows:

T: Number of weeks

N: Number of Gensets

D_t: System peak demand for each week (Mw)

NP_i: Nominal power (or Capacity) of Genset i (Mw)

M: Maximum number of simultaneous maintenances

DUR_i: Maintenance duration of each Genset

SR_t: Spinning reserve of period t (Mw)

MC: Variable cost of simultaneous maintenances (€)

DEFC: Deficit cost (€/Mw)

Variables

A continuous variable is introduced to state deficit at any instance:

deft (Real positive): Deficit of nominal power

Binary variables are used to indicate the starting point of any maintenance and Genet status during instances.

$x_{i,t}$: Binary variable (1: Genset i starts maintenance during week t, 0: otherwise)

$s_{i,t}$: Binary variable (1: Genset i is under maintenance during week t, 0: otherwise)

$hr_{i,t}$: Binary variable (1: Genset i is running during week t, 0: otherwise)

8.5 Model Constraints

Constraints explained in previous chapter are presented only with their mathematical formulation. Newly introduced or modified are provided with explanations.

Maintenance window:

$$\sum_{t \in T} x_{i,t} = 1, \quad \forall\, i \in N$$

Maintenance duration:

$$\sum_{t \in T} s_{i,t} = DUR_t, \quad \forall\, i \in N$$

Non-stop maintenance constraint:

$$s_{i,t} - s_{i,t-1} \le x_{i,t}\,, \quad \forall\, i \in N, \quad \forall\, t \in T$$

$$\text{For t} = 1, \qquad s_{i,0} = 0, \quad \forall\, i \in N$$

Resource constraint:

$$\sum_{i \in N} s_{i,t} \le M, \quad \forall\, t \in T$$

States lock: Each Genset during each week can either be under maintenance or available to run. What is implicitly imposed by the constraint is that if one Genset is available to run, it may belong to the hot-start Genset pool of each week delivering power or may belong to the reserve Genset pool of the same week thus providing stand-by power.

$$s_{i,t} + hr_{i,t} \leq 1 , \ \forall i \in N, \ \forall t \in T$$

Spinning reserve constraint: Nominal output of Gensets serving each week meeting system demand, has to be adequate enough so as to provide the specified amount of spinning reserve.

$$\sum_{i \in N} NP_i * (1 - s_{i,t} - hr_{i,t}) \geq D_t * SR_t, \qquad \forall i \in N, \forall t \in T$$

Reliability constraint "maxNP": For each week, Sum of nominal power of Gensets belonging in the reserve Genset pool has always to be greater than nominal power of each Genset belonging in the hot start pool.

$$\sum_{i \in N} NP_i \left(1 - s_{i,t} - hr_{i,t}\right) + def_t \ - \ hr_{i,t} NP_i \geq 0, \qquad \forall i \in N, \forall t \in T$$

This constraint what really imposes in practice is that for each week, Sum of nominal power of Gensets belonging in the reserve Genset pool has always to be greater than the maximum nominal power Genset, belonging in the hot start pool. OPL offers the flexibility to state the constraint as:

$$\sum_{i \in N} NP_i \left(1 - s_{i,t} - hr_{i,t}\right) + def_t \ - \max\left(hr_{i,t} NP_i\right) \geq 0,$$

$$\forall i \in N, \forall t \in T$$

8.6 The Objective function

The Objective function refers to two (2) parts namely F_1 and F_2.

The first part (F_1) refers to maintenance cost that increases as the number of simultaneous maintenance activities increase. This is expressed as a step wise function and the notion is simple yet somehow free to interpretation. It represents the additional cost of utilizing more resources (maintenance crews) and our preference for the least simultaneous activities present (for safety reasons among others).

$$F_1 = \sum_{i \in N} s_{i,t} * MC, \forall t \in T$$

Where MC as the variable cost of simultaneous maintenances is defined as:

$$MC = \begin{cases} for \sum_{i \in N} s_{i,t} = 1, MC = 7.000€ \\ for \sum_{i \in N} s_{i,t} = 2, MC = 16.000€ \\ for \sum_{i \in N} s_{i,t} = 3, MC = 27.000€ \\ for \sum_{i \in N} s_{i,t} = 4, MC = 41.000€ \end{cases}$$

The second part (F_2) simply introduces deficit cost which is closely related to the reliability index used.

$$F_2 = \sum_{t \in T} def_t * DEFC$$

8.7 OPL code

In order not to cause confusion by stating the differences to the GMS model introduced in chapter 7, its preferable to provide the full code. The OPL code used is presented below.

(a)_: .mod file

```
 int Gensets=...;
 int periods=...;
 int defcost=...;
 range Genset=1..Gensets;
 range Period=1..periods;

 float maxP[Genset]=...;
 float maxD[Period]=...;
 int dur[Genset]=...;
 float nul[Genset]=...;

 dvar boolean startIn[Genset][Period];
 dvar boolean status[Genset][0..periods];
 dvar boolean hot[Genset][Period];
 dvar float+ deficit[Period];

 minimize

 sum(p in Period)
 piecewise{ 0->0; 7000->1; 9000->2; 11000->3; 14000 } sum(g in Genset)
status[g][p] +

 sum(p in Period) deficit[p]*defcost
 ;

 subject to {
```

```
 duration:
 forall (g in Genset)
 sum (p in Period) status[g][p] == dur[g];

 nonstop:
 forall (g in Genset, p in Period )
 status[g][p-1] + startIn[g][p] >= status[g][p];

 forall (g in Genset )
 status[g][0] == nul[g];

 window:
 forall (g in Genset)
 sum (p in Period) startIn[g][p] == 1;

 simult:
 forall (p in Period)
 sum (g in Genset) status[g][p] <= 4;

 forall (g in Genset, p in Period)
 status[g][p] + hot[g][p]  <=1;

 demand:
 forall (p in Period)
 sum (g in Genset) hot[g][p]*maxP[g] >= 1.10*maxD[p];

 reliability:
 forall (p in Period)
 (sum (g in Genset) maxP[g]*(1-status[g][p] - hot[g][p])) + deficit[p]-
(max(g in Genset) hot[g][p]*maxP[g]) >=0;

 };
```

(b)_ .dat File

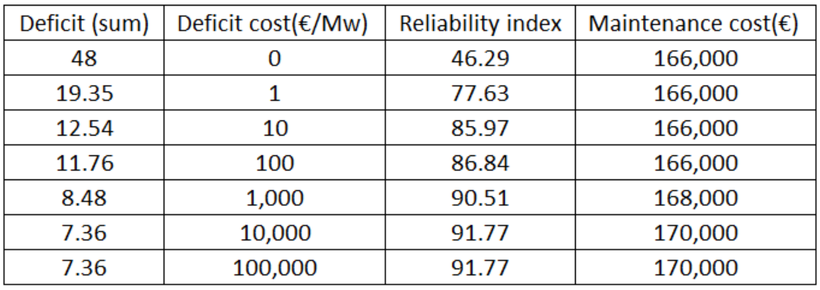
```
 Gensets=7;
 periods=16;

 SheetConnection
sheetData("C:\\Users\\gadak\\opl\\GMS_UC_maxP\\modelGMSUCmaxP.xlsx");
nul from SheetRead(sheetData,"nul");
maxP from SheetRead(sheetData,"maxP");
maxD from SheetRead(sheetData,"maxD");
dur from SheetRead(sheetData,"dur");
defcost from SheetRead(sheetData,"deficitcost");

status to SheetWrite(sheetData,"status");
hot to SheetWrite(sheetData,"hot");
deficit to SheetWrite(sheetData,"deficit");
```

8.8 Solution with IBM ILOG CPLEX

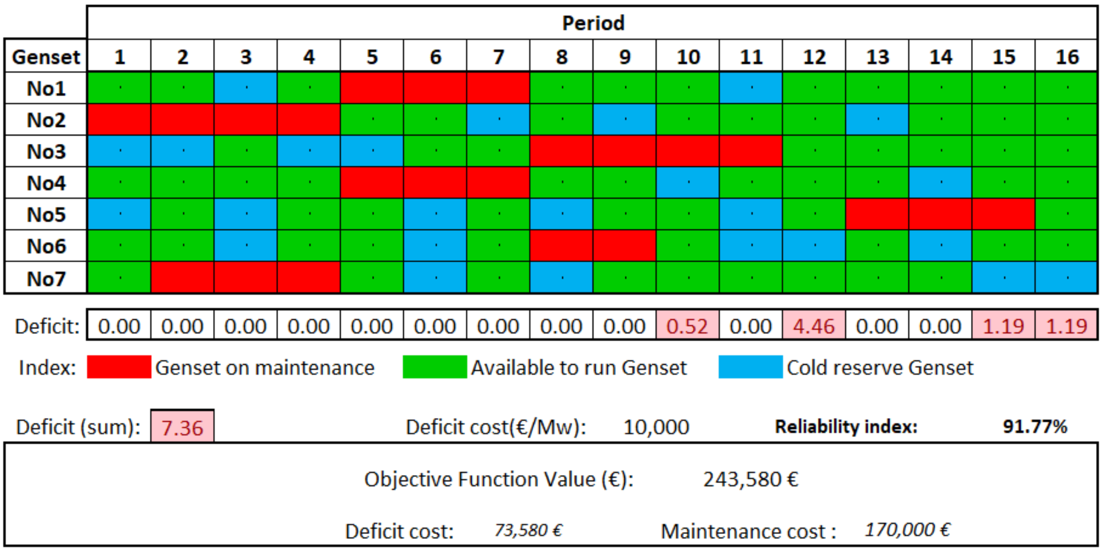
Solutions were obtained for various deficit costs, namely 0, 10, 100, 1.000, 10.000, 100.0000. The important points of this analysis are summarized in Figure 8-3 below



Deficit (sum)	Deficit cost(€/Mw)	Reliability index	Maintenance cost(€)
48	0	46.29	166,000
19.35	1	77.63	166,000
12.54	10	85.97	166,000
11.76	100	86.84	166,000
8.48	1,000	90.51	168,000
7.36	10,000	91.77	170,000
7.36	100,000	91.77	170,000

Figure 8-3: GMS+UC Results summary

We notice that reliability cannot increase beyond a point that corresponds to 10.000€/Mw deficit cost. Corresponding Scheduling outcome is presented in figure below.



Genset	Period 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
No1	🟩	🟩	🟦	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟩	🟩
No2	🟥	🟥	🟥	🟥	🟩	🟩	🟦	🟩	🟦	🟩	🟩	🟩	🟦	🟩	🟩	🟩
No3	🟦	🟦	🟩	🟦	🟦	🟩	🟩	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No4	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟦	🟩	🟩	🟩	🟦	🟩	🟩
No5	🟦	🟩	🟦	🟩	🟩	🟦	🟩	🟦	🟩	🟩	🟦	🟩	🟥	🟥	🟥	🟩
No6	🟩	🟩	🟦	🟩	🟩	🟦	🟩	🟥	🟥	🟩	🟦	🟦	🟩	🟦	🟩	🟩
No7	🟩	🟥	🟥	🟥	🟩	🟦	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟦
Deficit:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.52	0.00	4.46	0.00	0.00	1.19	1.19

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

Deficit (sum): 7.36 Deficit cost(€/Mw): 10,000 **Reliability index:** **91.77%**

Objective Function Value (€): 243,580 €

Deficit cost: *73,580 €* Maintenance cost : *170,000 €*

Figure 8-4: GMS+UC maintenance schedule output

System reserves are presented in figure below and as we can notice they are quite leveled among time units, except week 12. This is not at all strange since at that point of higher system demand, production equipment capacity is test to the limits. In other words, it is inherent to the system that during week 12, none combination can result in reserves as high as the highest Nominal Power Genset. To alleviate that problem, higher level managerial decisions need to be applied.

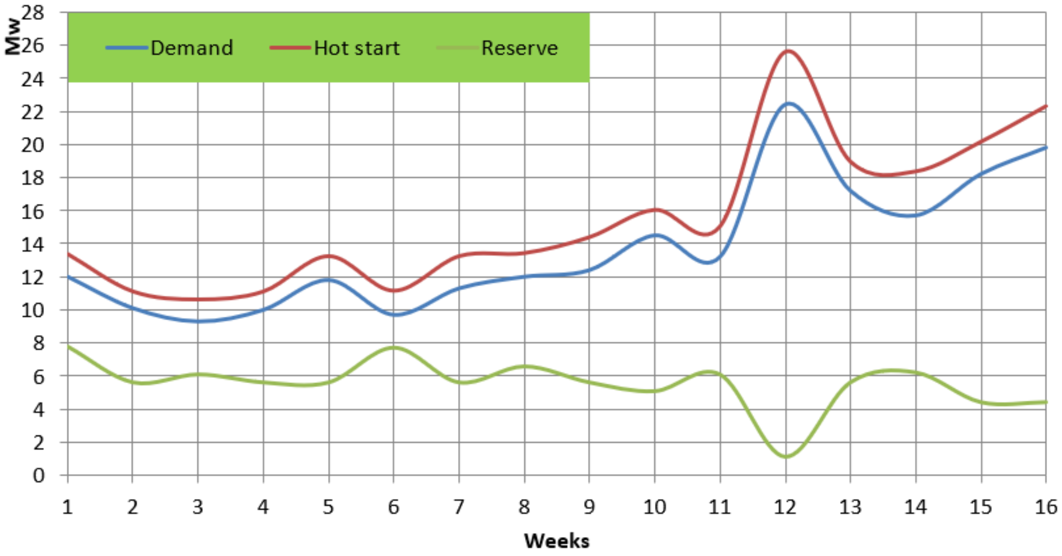


Figure 8-5: GMS+UC system reserves

8.9 Comparison and Comments

In comparison to the simple GMS problem presented in chapter 7, we managed to steer reserves in our favor. With this approach, reliability deviations are well realized providing valuable information serving as input for later decisions.

A critical problem is still not addressed since fuel cost is still not introduced and cannot influence scheduling at all. We have to admit that in some cases, this approach is fairly valid since fuel cost differences among roughly same efficiency Gensets might play no significant role.

But our case is significantly different. Three out of seven Gensets run on the extremely expensive diesel oil (compared to Heavy Fuel Oil) and this should be taken under consideration. Otherwise not, it would be extremely misleading since there exist the possibility of the most economical Gensets to be excluded from operation for some time. As differences in Genset efficiencies increase, the impact is higher and generally, for the whole horizon we would like to operate the most economic Gensets the most, harvesting the highest possible share of energy production.

That problem will be efficiently met in chapter 9 where the Economic Dispatch problem will be introduced into our approach.

Chapter 9

GMS(Simple) + UC + ED model

The incorporation of the Economic Dispatch problem is depicted in Figure 9-1 below.

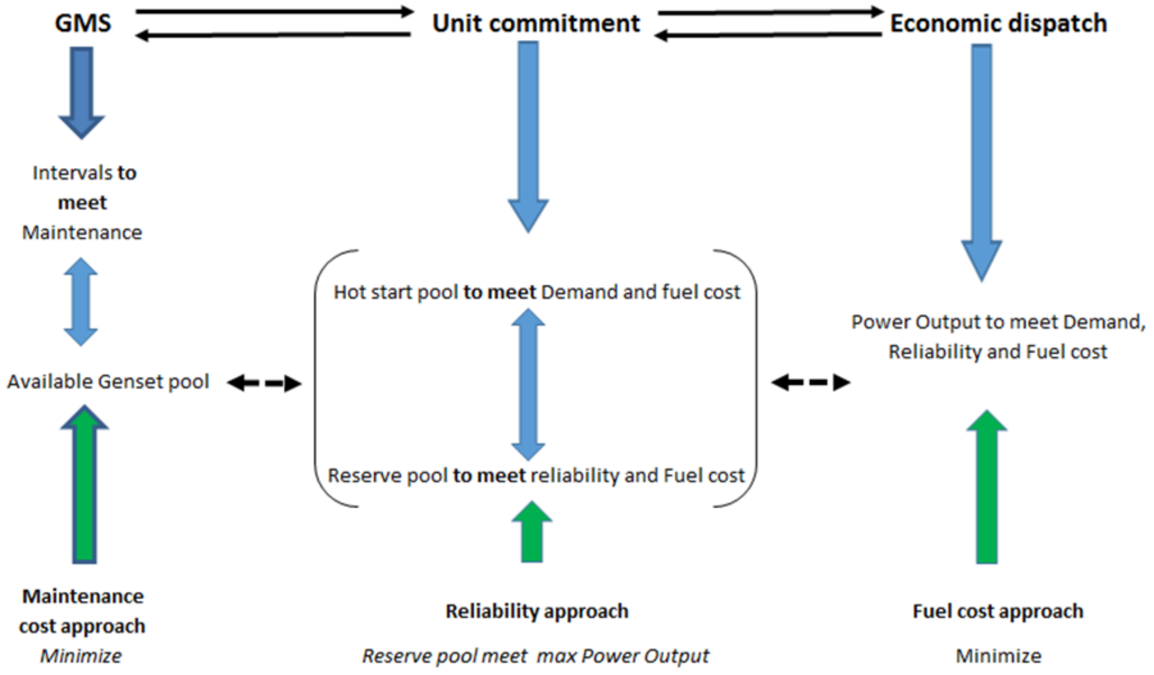


Figure 9-1: GMS(Simple) + UC + ED model

With this approach, the actual energy produced by each Genset included in the Hot start pool, contributes for the total fuel cost of each time unit and the whole horizon in total. In the next paragraph the importance of the chosen time unit will be revealed in terms of dimensionality explosion and a proposed approach to address the problem will be introduced.

9.1 The importance of time unit selection

Our aim is to model the system in a way to enable Gensets fuel efficiency alter maintenance schedule, in the most economical way.

If we were to construct the whole tree of possible combinations, Figure 9-2 below depicts the underlying logic.

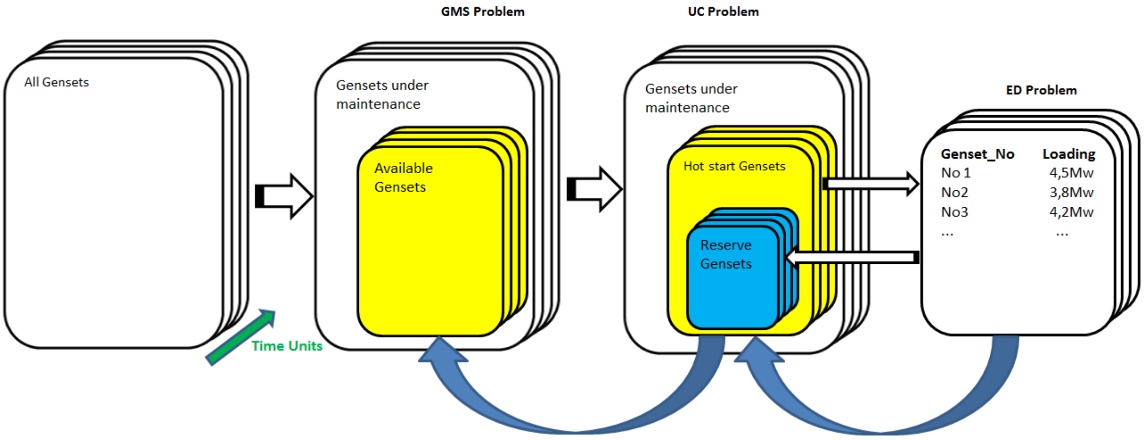


Figure 9-2: Possible combinations

For a given feasible maintenance schedule 1 there exists only one Available Genset pool 1 but different Hot start and reserve pools we need to examine in terms of total cost. Next, we have to take under consideration another, different feasible maintenance schedule 2 that obviously results in only one but different Available Genset pool 2. As the number of time units increases, dimensionality of the problem becomes a critical concern.

It’s now to focus on the time unit subject. For closer to reality approaches, time unit might set to be weeks, days or even hours, the later offering greater modeling detail (see Figure 9-3).

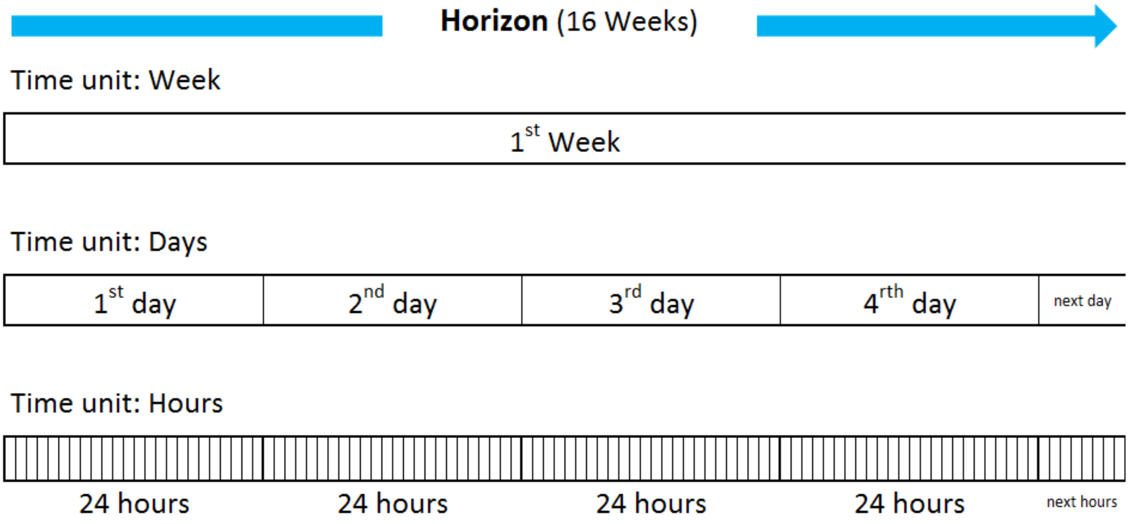
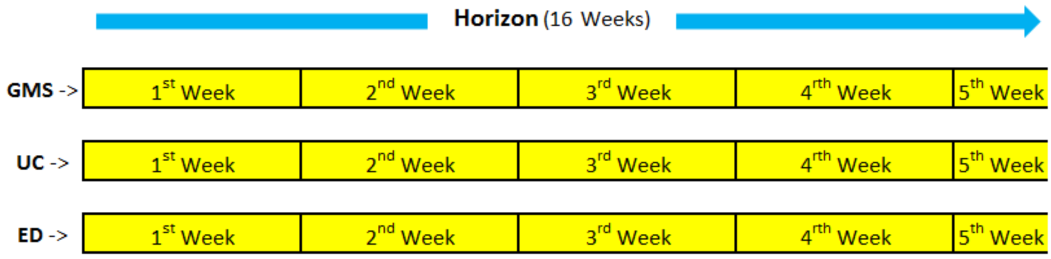


Figure 9-3: Different time units

It is evident that the hourly time unit requires many variables to be introduced in the model while the least are evident for the weekly time unit. It is interesting though to navigate through these and some other possibilities.

As a first approach to meet the problem we could use the weekly time unit, depicted in Figure 9-4 below



Total number of Weeks	16
Total number of Gensets	7

Required variables

Start of maintenance	112
Status of Gensets	112
Hot reserve Gensets	112
Output of Gensets	112
Deficit per time unit	16
	464

Figure 9-4: Weekly time unit

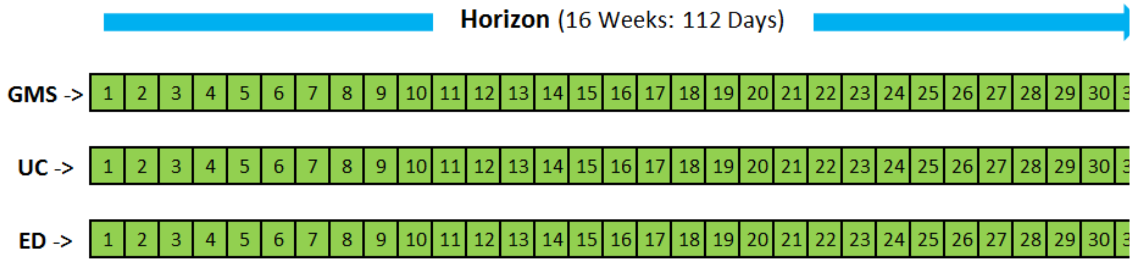
For comparison reasons that will reveal shortly after, we consider the absolutely necessary number of variables to be introduced in a model. These correspond to: Start of each maintenance, status of each Genset, Hot reserve Gensets, Output of each Genset and deficit per time unit. In this case we need 464 vars since the corresponding time unit for GMS, UC and ED is the week.

The problem with this approach is that the only input for the ED is the peak load of each week. In particular, the peak value presented during a certain hour interval and recorded in the power plants log.

If peak load was stable with in each time unit (flat curve) the model could efficiently produce the optimal scheduling. But this is not the case since what really represents is operation during a really small fraction of total time. Even if we make the assumption that during this particular hour system demand is stable, in comparison to total energy production involved during each time unit, the influence on maintenance scheduling is practically un noticeable. Possibly or even luckily enough, just a couple of the most economical Gensets shall be efficiently introduced in the scheduling.

We have always to keep in mind that the output of this initial stage, in other words the maintenance scheduling, will serve as input for a more detailed ED problem put in action, during actual operation.

It is evident that the model is “blind” and cannot produce a reliable output. A better approximation is realized by considering a daily time unit (see Figure 9-5 below).



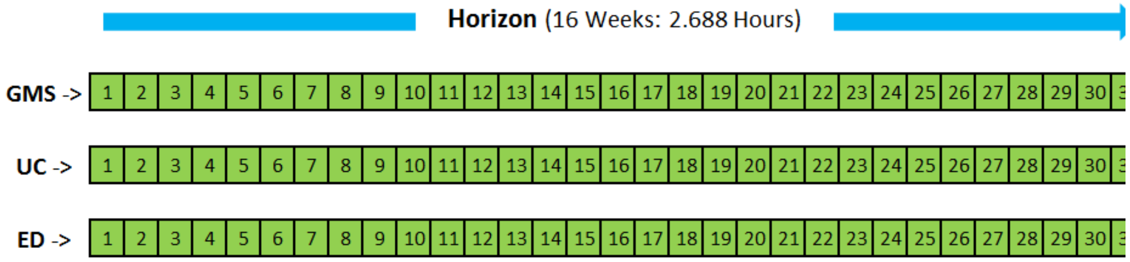
Total number of days	112
Total number of Gensets	7

Required variables

Start of maintenance	784
Status of Gensets	784
Hot reserve Gensets	784
Output of Gensets	784
Deficit per time unit	112
Total:	3.248

Figure 9-5: Daily time unit

In this case we need 3.248 vars that represents a 600% increase in required variables. But, daily system demand is not stable and as a result, accuracy is still low. The problem can be alleviated if the hourly time unit is selected, see Figure 9-6 below.



Total number of Hours	2688
Total number of Gensets	7

Required variables

Start of maintenance	18.816
Status of Gensets	18.816
Hot reserve Gensets	18.816
Output of Gensets	18.816
Deficit per time unit	2.688
Total:	77.952

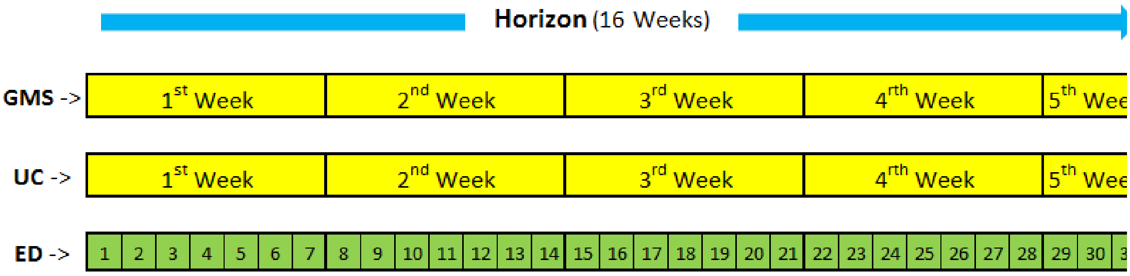
Figure 9-6: Hourly time unit

We notice that required variables are reaching the thousands range. Some 77.952 variables are necessary to retrieve reliable output simultaneously rendering problem hard to solve. But some side effects are yet implicitly present. Such a problem is that despite the achieved accuracy, we face the risk of an erratic behavior concerning reserve Genset pool. The daily basis could possible alter in an in-practical daily routine. Despite all Gensets are practically capable of starting operation in a very short time and without any cost, we generally prefer reserve Genset pool to stay un-altered for as many time as it can be, at least for 1 week in our case.

It is evident that there exists the need to enable the model realize the actual system demand profile, without excessive number of variables to be necessary.

In doing so, we have to somehow enable ED to act as if it referred to a different time unit, all others referring to weeks. How this is achieved is technicalities, irrelevant here since will be shown after in full extend.

A first approach could be to introduce peak loads of each day involved in each time unit, see Figure 9-7 below.



Total number of Weeks	16
Total number of Gensets	7

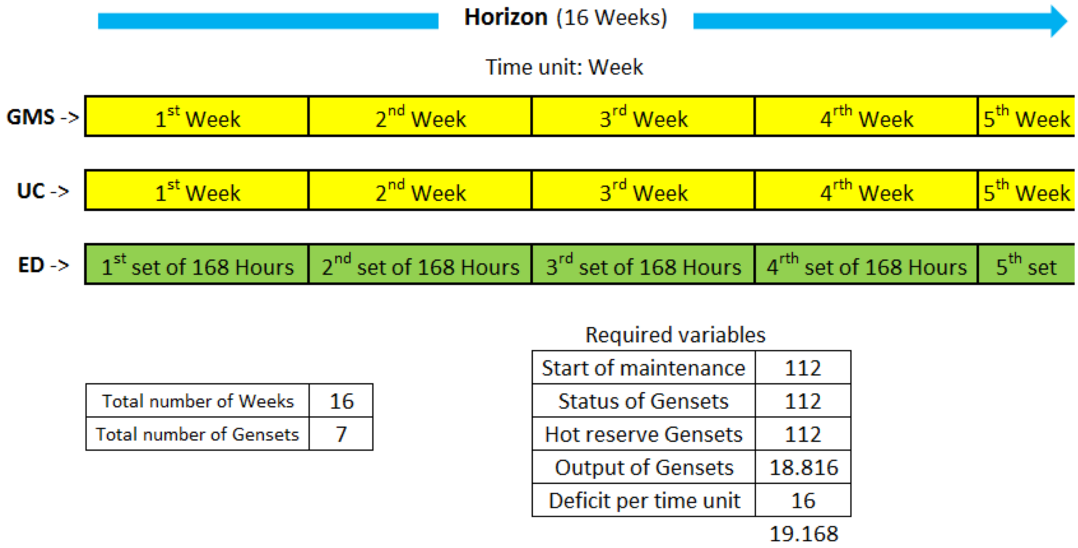
Required variables

Start of maintenance	112
Status of Gensets	112
Hot reserve Gensets	112
Output of Gensets	784
Deficit per time unit	16
	1.136

Figure 9-7: ED referring to days

In this case we need just 1.136 variables. The important point is that this way, more energy is “injected” in the model. Despite this improved approach, fuel cost differences as the result of taking under consideration more energy production, may possibly not enable the model to produce a reliable schedule. Fuel cost differences may still not be sufficient to shift maintenance intervals taking under consideration that each day presents a different energy production profile.

It’s evident that for a realistic approach, we have to consider the hourly time unit. So, we keep our initial approach and in this case we need 19.168 variables, as shown in Figure 9-8 below.



Total number of Weeks	16
Total number of Gensets	7

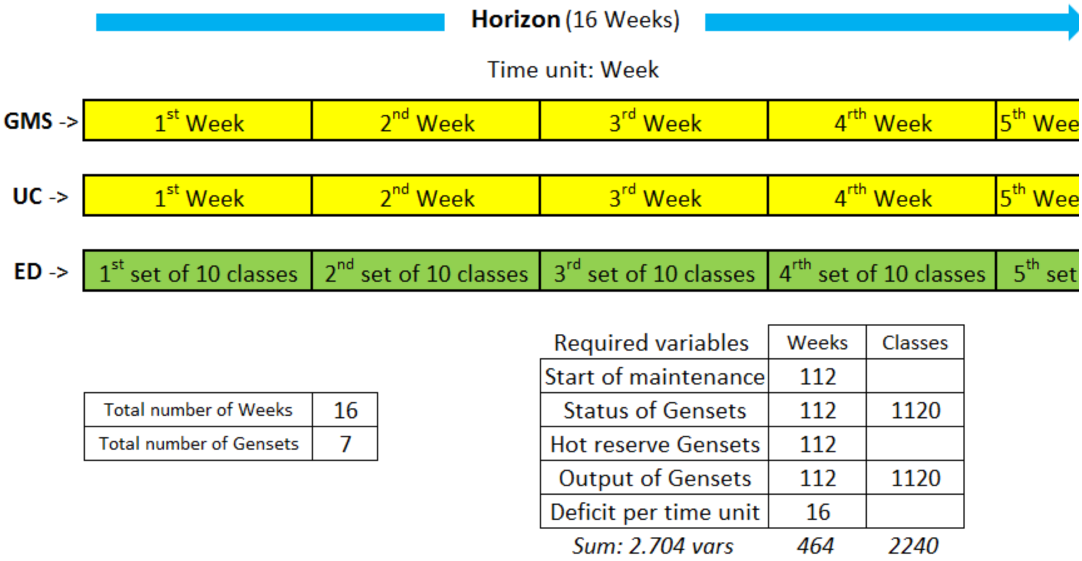
Required variables

Start of maintenance	112
Status of Gensets	112
Hot reserve Gensets	112
Output of Gensets	18.816
Deficit per time unit	16
	19.168

Figure 9-8: Weekly time unit and **hourly Economic Dispatch** with in each Week

Since ED enters the hour time unit, almost all energy is “injected” in the model. Once again, how this is achieved is technicalities shown after in full extend. The important point is that we achieve our goal by realizing a 75% reduction in required variables.

What is more interesting though is the possibility to further reduce required variables introducing the notion of classes of system demand (see Figure 9-9 below).



Total number of Weeks	16
Total number of Gensets	7

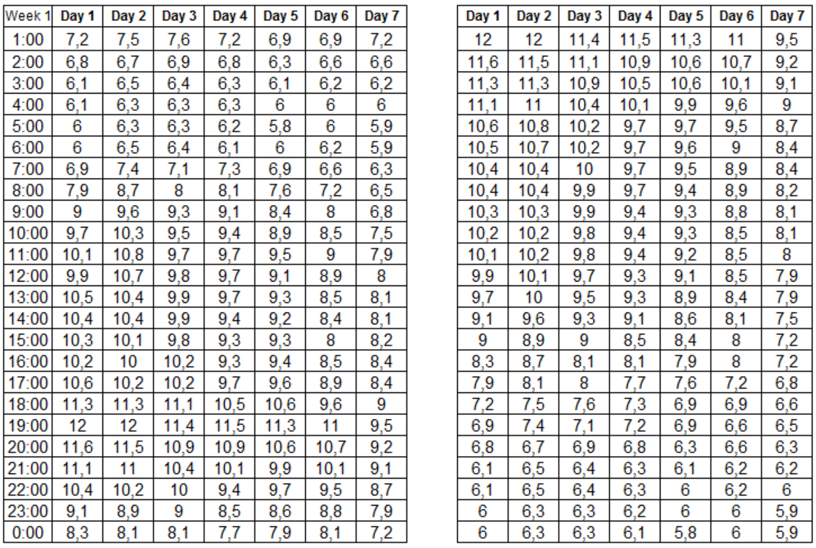
Required variables	Weeks	Classes
Start of maintenance	112	
Status of Gensets	112	1120
Hot reserve Gensets	112	
Output of Gensets	112	1120
Deficit per time unit	16	
Sum: 2.704 vars	*464*	*2240*

Figure 9-9: Weekly time unit and Economic Dispatch based on classes with in each week

This approach requires some data preparation but the extra effort will pay off. If a set of 10 classes is used to reliably describe system demand for each week, required variables are just 2.704. The following paragraph presents in full detail all the necessary steps.

9.2 Energy injection

We will focus on Week 1. System demand raw data for week 1 is presented in Figure 9-10 below. The right table presents sorted data.



Week 1	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
1:00	7,2	7,5	7,6	7,2	6,9	6,9	7,2
2:00	6,8	6,7	6,9	6,8	6,3	6,6	6,6
3:00	6,1	6,5	6,4	6,3	6,1	6,2	6,2
4:00	6,1	6,3	6,3	6,3	6	6	6
5:00	6	6,3	6,3	6,2	5,8	6	5,9
6:00	6	6,5	6,4	6,1	6	6,2	5,9
7:00	6,9	7,4	7,1	7,3	6,9	6,6	6,3
8:00	7,9	8,7	8	8,1	7,6	7,2	6,5
9:00	9	9,6	9,3	9,1	8,4	8	6,8
10:00	9,7	10,3	9,5	9,4	8,9	8,5	7,5
11:00	10,1	10,8	9,7	9,7	9,5	9	7,9
12:00	9,9	10,7	9,8	9,7	9,1	8,9	8
13:00	10,5	10,4	9,9	9,7	9,3	8,5	8,1
14:00	10,4	10,4	9,9	9,4	9,2	8,4	8,1
15:00	10,3	10,1	9,8	9,3	9,3	8	8,2
16:00	10,2	10	10,2	9,3	9,4	8,5	8,4
17:00	10,6	10,2	10,2	9,7	9,6	8,9	8,4
18:00	11,3	11,3	11,1	10,5	10,6	9,6	9
19:00	12	12	11,4	11,5	11,3	11	9,5
20:00	11,6	11,5	10,9	10,9	10,6	10,7	9,2
21:00	11,1	11	10,4	10,1	9,9	10,1	9,1
22:00	10,4	10,2	10	9,4	9,7	9,5	8,7
23:00	9,1	8,9	9	8,5	8,6	8,8	7,9
0:00	8,3	8,1	8,1	7,7	7,9	8,1	7,2

Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
12	12	11,4	11,5	11,3	11	9,5
11,6	11,5	11,1	10,9	10,6	10,7	9,2
11,3	11,3	10,9	10,5	10,6	10,1	9,1
11,1	11	10,4	10,1	9,9	9,6	9
10,6	10,8	10,2	9,7	9,7	9,5	8,7
10,5	10,7	10,2	9,7	9,6	9	8,4
10,4	10,4	10	9,7	9,5	8,9	8,4
10,4	10,4	9,9	9,7	9,4	8,9	8,2
10,3	10,3	9,9	9,4	9,3	8,8	8,1
10,2	10,2	9,8	9,4	9,3	8,5	8,1
10,1	10,2	9,8	9,4	9,2	8,5	8
9,9	10,1	9,7	9,3	9,1	8,5	7,9
9,7	10	9,5	9,3	8,9	8,4	7,9
9,1	9,6	9,3	9,1	8,6	8,1	7,5
9	8,9	9	8,5	8,4	8	7,2
8,3	8,7	8,1	8,1	7,9	8	7,2
7,9	8,1	8	7,7	7,6	7,2	6,8
7,2	7,5	7,6	7,3	6,9	6,9	6,6
6,9	7,4	7,1	7,2	6,9	6,6	6,5
6,8	6,7	6,9	6,8	6,3	6,6	6,3
6,1	6,5	6,4	6,3	6,1	6,2	6,2
6,1	6,5	6,4	6,3	6	6,2	6
6	6,3	6,3	6,2	6	6	5,9
6	6,3	6,3	6,1	5,8	6	5,9

Figure 9-10: System demand week 1

We make the assumption that hourly data represent a stable system demand over each reference hour. In practice, this approach enables us to calculate total system demand generally with fairly good accuracy. As a result, by adding all week 1 system demand values, generated energy is some 1.443 Mwh. For our purpose though, this approach in general fits best as shall be clearly seen.

As can be also seen from Figure 9-11, for certain hours system demand is the same and we use that in our advantage.

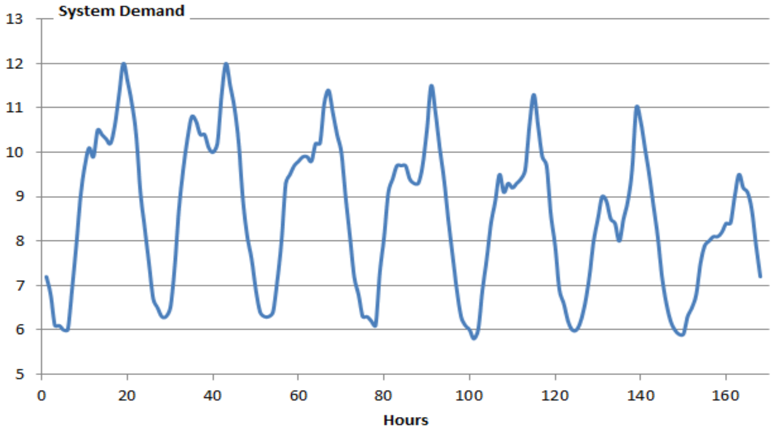
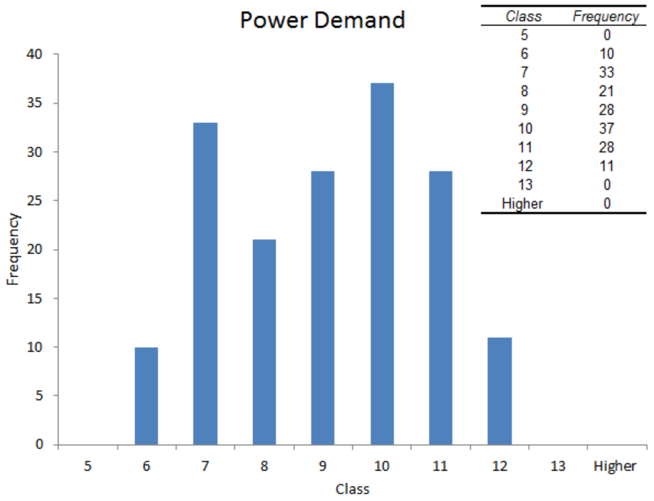


Figure 9-11: Random week, hourly system demand

So, next step is to allocate hourly System demand in to classes. With the introduction of classes, we realize a great advantage. Practically, we can model Energy production for the whole horizon, by using little variables. Dimensionality reduction is huge; compare the 77.952 vars needed for hourly time unit to the 1.472 vars needed for the weekly time unit. That's more than 98% reduction.

We take under consideration the lower and higher value and as a first approach we use a fixed span of 1 Mw among classes. Results are shown in Figure 9-12 below.



Class	*Frequency*
5	0
6	10
7	33
8	21
9	28
10	37
11	28
12	11
13	0
Higher	0

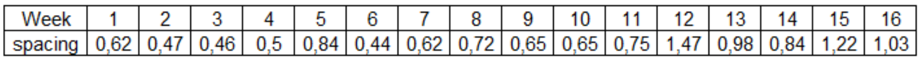
Figure 9-12: Frequency allocation of system demand week 1

The figure suggests that system demand up to 6Mw occurs for 10 hours, system demand up to 7Mw occurs for 10 hours etc.

We make the assumption that each class upper bound represents a stable system demand for certain hours (frequency) and as a consequence, loss or even better, a difference from energy demand would be true. But that difference for reasons to come not only may be accepted as minor but also wanted in some cases. For week 1, using the frequency distribution in figure we calculate 1.442,5 Mwh and practically there is no difference to 1.443Mwh.

In general, as the class span gets smaller, so does the difference but since now energy demand corresponds to the given tabulated data, serving as forecasts. In practice, the effect of class span to real energy "loss" is expected to be negligible compared to the effect of uncertainty, introduced by vague hourly system demand forecasts. This is crucial since hourly system demand is at least extremely hard (if not possible) to obtain by even a sophisticated forecast methodology. But we can surely rely upon past years actual demand, maybe plus some % representing annual growth.

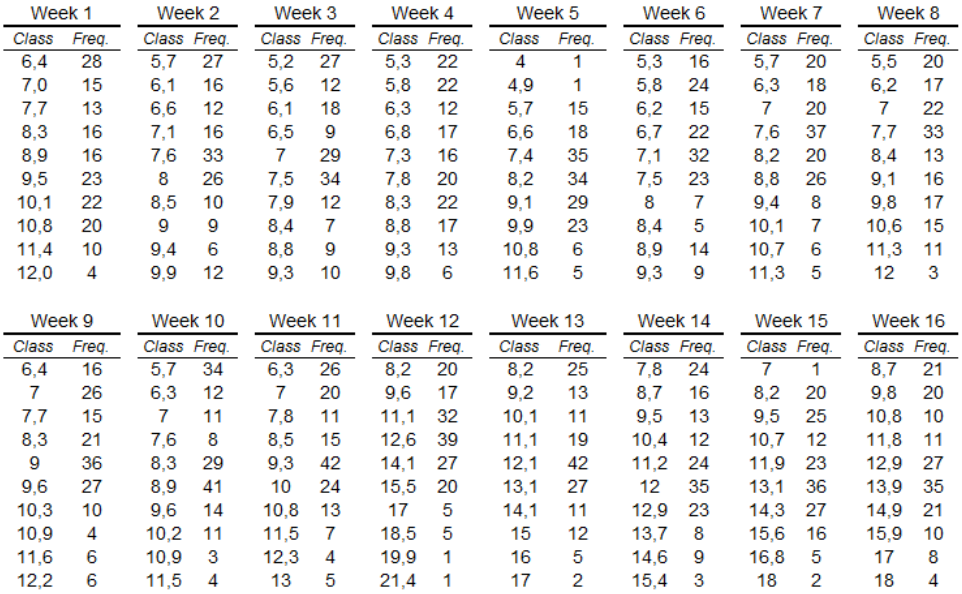
As a general approach to compensate for classes different lower and upper bounds, if we anchor at 10 classes for all weeks, the automated span among classes (see Figure 9-13 below) would be on average 0.8 Mw.



Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
spacing	0,62	0,47	0,46	0,5	0,84	0,44	0,62	0,72	0,65	0,65	0,75	1,47	0,98	0,84	1,22	1,03

Figure 9-13: Automated classes span for all weeks

It must be stated though that if we carefully choose different spans, a better approximation could be possible. But that is out of our scope so we use the automated spans.For reasons to become clear shortly after, for each time unit peak load is excluded from the frequency distributions, tables of are presented in Figure 9-14 below.



Week 1		Week 2		Week 3		Week 4		Week 5		Week 6		Week 7		Week 8	
Class	*Freq.*	*Class*	*Freq.*	*Class*	*Freq.*	*Class*	*Freq.*	*Class*	*Freq.*	*Class*	*Freq.*	*Class*	*Freq.*	*Class*	*Freq.*
6,4	28	5,7	27	5,2	27	5,3	22	4	1	5,3	16	5,7	20	5,5	20
7,0	15	6,1	16	5,6	12	5,8	22	4,9	1	5,8	24	6,3	18	6,2	17
7,7	13	6,6	12	6,1	18	6,3	12	5,7	15	6,2	15	7	20	7	22
8,3	16	7,1	16	6,5	9	6,8	17	6,6	18	6,7	22	7,6	37	7,7	33
8,9	16	7,6	33	7	29	7,3	16	7,4	35	7,1	32	8,2	20	8,4	13
9,5	23	8	26	7,5	34	7,8	20	8,2	34	7,5	23	8,8	26	9,1	16
10,1	22	8,5	10	7,9	12	8,3	22	9,1	29	8	7	9,4	8	9,8	17
10,8	20	9	9	8,4	7	8,8	17	9,9	23	8,4	5	10,1	7	10,6	15
11,4	10	9,4	6	8,8	9	9,3	13	10,8	6	8,9	14	10,7	6	11,3	11
12,0	4	9,9	12	9,3	10	9,8	6	11,6	5	9,3	9	11,3	5	12	3

Week 9		Week 10		Week 11		Week 12		Week 13		Week 14		Week 15		Week 16	
Class	*Freq.*	*Class*	*Freq.*	*Class*	*Freq.*	*Class*	*Freq.*	*Class*	*Freq.*	*Class*	*Freq.*	*Class*	*Freq.*	*Class*	*Freq.*
6,4	16	5,7	34	6,3	26	8,2	20	8,2	25	7,8	24	7	1	8,7	21
7	26	6,3	12	7	20	9,6	17	9,2	13	8,7	16	8,2	20	9,8	20
7,7	15	7	11	7,8	11	11,1	32	10,1	11	9,5	13	9,5	25	10,8	10
8,3	21	7,6	8	8,5	15	12,6	39	11,1	19	10,4	12	10,7	12	11,8	11
9	36	8,3	29	9,3	42	14,1	27	12,1	42	11,2	24	11,9	23	12,9	27
9,6	27	8,9	41	10	24	15,5	20	13,1	27	12	35	13,1	36	13,9	35
10,3	10	9,6	14	10,8	13	17	5	14,1	11	12,9	23	14,3	27	14,9	21
10,9	4	10,2	11	11,5	7	18,5	5	15	12	13,7	8	15,6	16	15,9	10
11,6	6	10,9	3	12,3	4	19,9	1	16	5	14,6	9	16,8	5	17	8
12,2	6	11,5	4	13	5	21,4	1	17	2	15,4	3	18	2	18	4

Figure 9-14: System weekly demand frequency distributions

Total energy demand for the whole horizon (tabulated data) is 23.935 Mwh and in comparison, using the frequency tables energy is approximated to 24.635 Mwh. We notice a less than 3% on average over estimation of energy demand since each class serves as the higher system demand for certain time. Provided this 3% is fairly stable among weeks, this over estimation is well accepted as a nearly on average 3% increase in system demand, if previous years actual system demand is used as input for next year.

It is evident that by using this approach on previous year hourly system demand, automatically we derive a pretty good forecast for next year, provided weekly peak demands are separately and adequately compensated. Another interesting approach is to a-posteriori adjust each class limit, with some forecast compensating factor. In any case, our treaty does not concern how to obtain system demand, figures of should be known one way or another beforehand to serve as input for the model.

In our approach, upper bound of each class represent system load to be met by Gensets. As a result, we have to define as many as 1.120 variables, representing the output of each Genset for the total number of classes.

9.3 Fuel consumption modeling

Usually fuel consumption versus Genset power output is described by a quadratic function. This fact poses additional solving problems and in practice a linearization approximation is used. In literature we can find examples of four (4) segments piecewise linear approximation (Carrion, 2006).

For every Genset we have the specific fuel oil consumption curve and we recall that sfo is expressed in gr/Kwh units. This format does not serve our needs so a transformation is mandatory to exploit the unique features offered by the way we have modeled power and energy system demand.

We need to think that an alternative way of stating the output of a running Genset except from Mw terms is also in terms of gr/Kwh, since there is a well-defined relation. In other words, if we say Genset 1 run on 2,5 Mw output or it consumes say 208gr/Kwh, in practice the information contained is exactly the same.

For the purpose of illustrating the methodology, we will use data concerning Genset 1(see Figure 9-15, below). Rest of the data for all other Gensets used in our model can be found in APPENDIX A with an introductory section providing useful insight into the area.

Genset No1 with 3.104Mw nominal power runs on Heavy fuel oil. This Genset exhibits (see Figure 9-15 below) best efficiency around 85-90% of Nominal Power (propulsion engine old design) and taking under consideration the overall working condition, the output is limited to 90% of NP namely 2.794Mw.

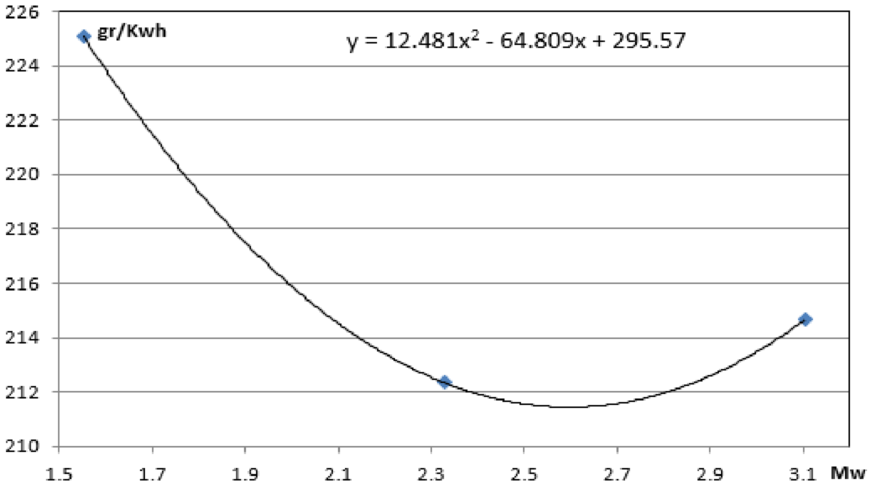


Figure 9-15: Genset N^{o}1 Specific Fuel Consumption (Quadratic function)

Now, let α be the specific fuel oil consumption (gr/Kwh) corresponding to any P output (Mw).

We plot the diagram where: x axis corresponds to Mw output, y axis corresponds to the “fuel oil consumption” as the product of:

$$y_G = \frac{a * P}{1.000}\left[\frac{tn}{hour}\right] = a\left[\frac{gr}{Kwh}\right] * \frac{1}{1.000}\left[\frac{Kg}{gr}\right] * \frac{1}{1.000}\left[\frac{tn}{Kg}\right] * \frac{1.000}{1}\left[\frac{Kw}{Mw}\right] * P[Mw]$$

The existing relation, unique for each Genset is represented by an almost straight line (see Figure 9-16, below) and can be easily introduced in the model by a piece wise linear function in respect to output. This way we can define for any given output the amount of fuel burnt fairly accurately.

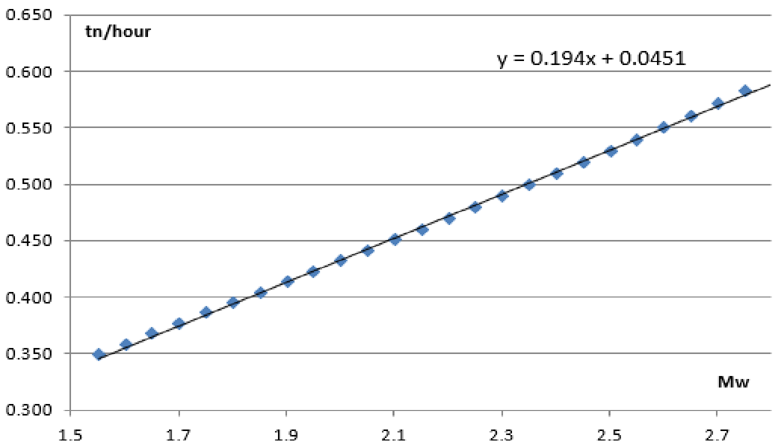


Figure 9-16: Genset N^{o}1 Fuel Consumption (Linear Approximation)

Thanks to the acute "hook shape" Specific Fuel Consumption curve (old design Genset), this Genset when linearly modeled exhibits near the higher band the greatest deviation (0,88%), among all other Gensets (see Figure 9-17 below).

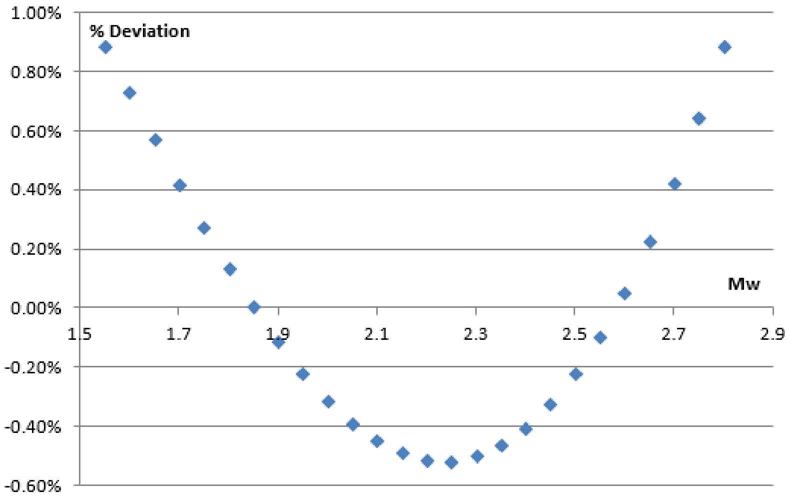


Figure 9-17: Absolute values of fuel oil consumption deviation, both approximations

But in practice, this Genset only operates up to 95% of Nominal Power. As a result, within the technical minimum and set maximum Output band, linear approximation in respect to real Specific Fuel Consumption deviates within acceptable limits. Other than that, technical minimum is set to 50% of NP that is 1.552Mw.

In Figure 9-18 below we can see the Fuel oil consumption rates for all Gensets expressed in tn/hour.

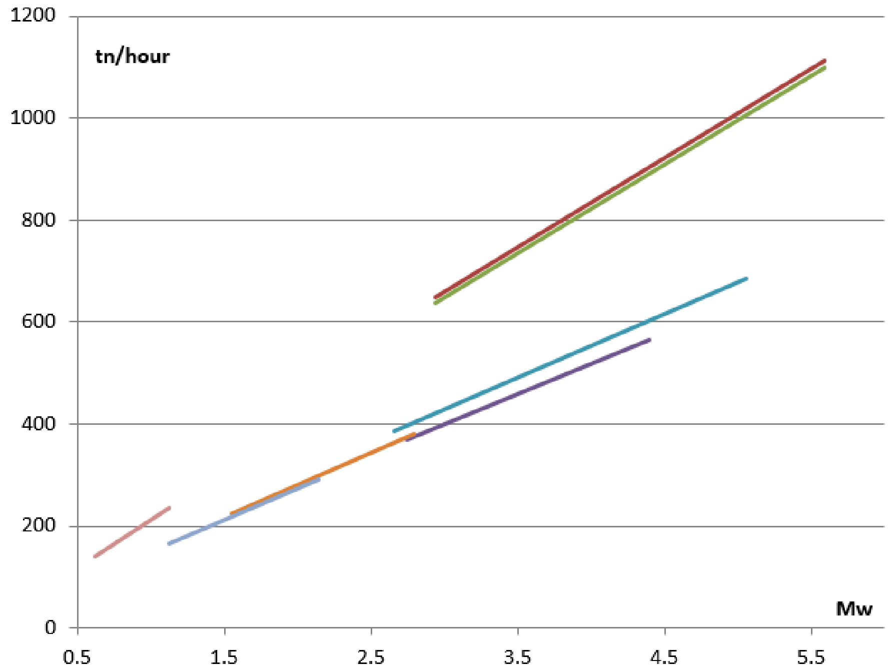


Figure 9-18: Fuel consumption of all Gensets

It is actually these lines that determine among different Gensets, beyond which output one is preferable to the other, in respect to fuel cost, the most important parameters being the slope and constant of each linear equation.

9.4 Reliability approach

In chapter 8 we followed the maxNP approach. For further improvement, we could set reserve margins at least equal to the highest running output of Gensets operating during peak demand (maxRP approach). This could possibly involve the maximum running power of the maximum nominal output Genset but it is not binding. When a malfunction to a Genset occurs the actual power loss is not the nominal power of the Genset but its current output. Analogously, the hardest case is during peak system demand when the maximum running output of Genset is diminished.

The reliability index is hence as follows:

$$\frac{Sum\ of\ reserve\ Gensets\ Nominal\ Power}{Max\ Running\ Power\ of\ hot\ reserve\ Gensets}$$

In any case the difference in reserve power might be slight but sufficient enough to unlock a great potential. Since less power is kept in reserve, comparably additional combinations of maintenance and

Gensets output schemes are injected into search space, rendering potential savings. A soft constraint formulation enables to penalize deviations (deficits) thanks to a deficit cost (€/Mw).

For comparison reasons, both maxNP and maxRP approaches will be examined.

9.5 Definitions

Indexes: Three indexes are used referring to each time unit, class and Genset:

t: index of week ∈ (1, T)

i: index of Genset ∈ (1, N)

j: index of class ∈ (1, C)

Parameters: Parameters involved refer to system demand, Nominal Genset power etc. The complete listing follows:

T: Number of weeks

N: Number of Gensets

C: Number of classes

D_t: System peak demand for each week (Mw)

$CD_{t,j}$: Classes limits for each week

$FR_{t,j}$: Classes frequency for each week

NP_i: Nominal power (or Capacity) of Genset i (Mw)

MP_i: Technical minimum of Genset i (Mw)

M: Maximum number of simultaneous maintenances

DUR_i: Maintenance duration of each Genset

SR_t: Spinning reserve of period t (Mw)

MC: Variable cost of simultaneous maintenances (€)

FC_i: Fuel cost of Genset i (€/tn)

DEFC: Deficit cost (€/Mw)

C_i: constant of Fuel consumption for Genset i (tn)

S_i: slope of Fuel consumption for Genset i (tn/Mw)

Variables

Continuous variables are introduced to state Genset output and deficit for any instance:

$rp_{i,t}$ (Real positive): Run power of Genset i for each week peak load

$rpc_{i,t,j}$ (Real positive): Run power of Genset i for each class limit for each week

def_t (Real positive): Deficit of nominal power

Binary variables are used to indicate the starting point of any maintenance and Genet status during instances.

$x_{i,t}$: Binary variable (1: Genset i starts maintenance during week t, 0: otherwise)

$s_{i,t}$: Binary variable (1: Genset i is under maintenance during week t, 0: otherwise)

$hr_{i,t}$: Binary variable (1: Genset i is running during week t, 0: otherwise)

$hrc_{i,t,j}$: Binary variable (1: Genset i is running during class j of week t, 0: otherwise)

9.6 Model Constraints

Constraints explained in previous chapter are presented only with their mathematical formulation. Newly introduced or modified are provided with explanations.

Maintenance window:

$$\sum_{t \in T} x_{i,t} = 1, \quad \forall\, i \in N$$

Maintenance duration:

$$\sum_{t \in T} s_{i,t} = DUR_t, \quad \forall\, i \in N$$

Non-stop maintenance constraint:

$$s_{i,t} - s_{i,t-1} \le x_{i,t}\,, \quad \forall\, i \in N, \ \forall\, t \in T$$

$$\text{For t = 1,} \qquad s_{i,0} = 0, \ \forall\, i \in N$$

Resource constraint:

$$\sum_{i \in N} s_{i,t} \le M, \quad \forall\, t \in T$$

States lock (1):

$$s_{i,t} + hr_{i,t} \leq 1 , \ \forall\, i \in N, \ \forall\, t \in T$$

Demand constraint: Gensets serving each week have to provide certain power output so as to meet weekly system peak demand.

$$\sum_{i \in N} rp_{i,t} = D_t, \qquad \forall\, t \in T$$

Spinning reserve constraint: Nominal output of Gensets serving each week meeting demand, has to be adequate enough so as to provide the specified amount of spinning reserve.

$$\sum_{i \in N} (NP_i * hr_{i,t} - rp_{i,t}) \geq D_t * SR_t, \qquad \forall\, i \in N, \forall\, t \in T$$

Max Genset output constraint: Power output of Gensets serving each week meeting demand has to be lower than corresponding nominal power.

$$hr_{i,t} * NP_i \geq rp_{i,t} , \ \forall\, i \in N, \ \forall\, t \in T$$

Min Genset output constraint: Power output of Gensets serving each week has to be at least equal to corresponding technical minimum.

$$hr_{i,t} * MP_i \leq rp_{i,t} , \ \forall\, i \in N, \ \forall\, t \in T$$

Exclusion constraint: Genset 1 and Genset 2 are not allowed to be simultaneously under maintenance. This constraint was not used in our model but is simply referenced since being extremely typical.

$$s_{1,t} + s_{2,t} \leq 1 , \ \ i,j \in N, \ \forall\, t \in T$$

(1) Reliability constraint “maxNP”:

$$\sum_{i \in N} NP_i \left(1 - s_{i,t} - hr_{i,t}\right) + def_t - hr_{i,t} NP_i \geq 0, \qquad \forall\, i \in N, \forall\, t \in T$$

(2) Reliability constraint “maxRP”: The same logic as above in formulation but with one big difference since maximum run power substitutes for maximum Nominal Power:

$$\sum_{i \in N} NP_i \left(1 - s_{i,t} - hr_{i,t}\right) + def_t - rp_{i,t} \geq 0, \qquad \forall\, i \in N, \forall\, t \in T$$

Important! Only one reliability constraint was used per model instance.

The Economic Dispatch problem concerning classes is introduced by the following constraints:

States lock (2): Gensets that are available to run for each class of a week (so as to provide power output meeting classes' upper limit), is a subset of the hot-start Genset pool of the corresponding week. This is generalized for all weeks by the constraint:

$$hrc_{i,t,j} \leq hr_{i,t}\ , \ \forall\, i \in N,\ \forall\, t \in T,\ \forall\, j \in C$$

Demand constraint: Gensets serving for each class of a week have to provide certain power output so as to meet classes upper limit, serving as system demand. This is generalized for all weeks by the constraint:

$$\sum_{i \in N} rpc_{i,t,j} = CD_{t,j}\ , \qquad \forall\, t \in T, \forall\, j \in C$$

Spinning reserve constraint: Nominal output of Gensets serving for each class of all weeks meeting demand, has to be adequate enough so as to provide the specified amount of spinning reserve.

$$\sum_{i \in N} (NP_i * hrc_{i,t,j} - rpc_{i,t,j}) \geq CD_{t,j} * SR_t, \forall\, i \in N, \forall\, t \in T, \forall\, j \in C$$

Max Genset output constraint: Power output of Gensets serving for each class of all weeks meeting demand has to be lower than corresponding nominal power.

$$hrc_{i,t,j} * NP_i \geq rpc_{i,t,j}\ , \ \forall\, i \in N, \forall\, t \in T, \forall\, j \in C$$

Min Genset output constraint: Power output of Gensets serving for each class of all weeks has to be at least equal to corresponding technical minimum.

$$hrc_{i,t,j} * MP_i \leq rpc_{i,t,j}\ , \ \forall\, i \in N,\ \forall\, t \in T, \forall\, j \in C$$

9.7 The Objective function

One part of the objective function is maintenance and reliability cost as put in chapter 8. The other part will refer to fuel cost. We recall that within each week secondary time unit is set to hour and there exist 10 classes. Each class represents system demand for a given time the later accounted by a related frequency. All frequencies add to 168. The output of each Genset for each class is also defined as well as the running time on that output which is simply the frequency of the class.

For example, suppose during week 3 Genset 7 has to operate at $M_{3,1,7}$ output for the 1st class. One part of fuel cost , let's call it the variable cost, is derived from the slope as $Cost_{3,1,7}$ (see Figure 9-19 below).

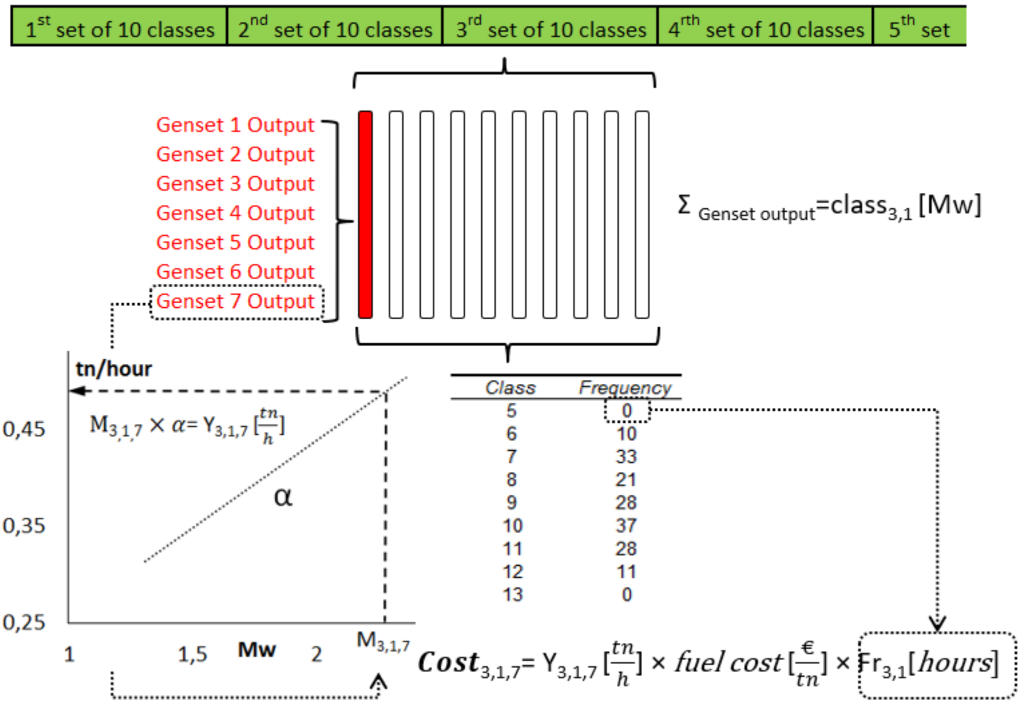


Figure 9-19: Variable fuel cost

The other part of fuel cost has to do with the fact if the Genset is operating. If the Genset is operating the constant of the respective fuel consumption linear equation cuts in.

In our modeling approach we exclude peak load of each week (to be treated in conjunction with reliability) and as a result, for each class frequencies add to 167, not 168.

The Objective function hence refers to three (3) parts: F_1, F_2 and F_3.

The first part (F_1) constitutes total fuel cost.

$$F_1 = \sum_N \sum_T \sum_C rpc_{i,t,j} * S_i + \sum_N \sum_T \sum_C hrc_{i,t,j} * C_i + \sum_N \sum_T rp_{i,t} * S_i + \sum_N \sum_T hr_{i,t} * C_i$$

The second part (F_2) refers to maintenance cost that increases as the number of simultaneous maintenance activities increase. This is expressed as a step wise function and the notion is simple yet somehow free to interpretation. It represents the additional cost of utilizing more resources (maintenance crews) and our preference for the least simultaneous activities present (for safety reasons among others).

$$F_2 = \sum_{i \in N} s_{i,t} * MC, \forall\, t \in T$$

Where MC as the variable cost of simultaneous maintenances is defined as:

$$MC = \begin{cases} for \sum_{i\in N} s_{i,t} = 1, MC = 7.000€ \\ for \sum_{i\in N} s_{i,t} = 2, MC = 16.000€ \\ for \sum_{i\in N} s_{i,t} = 3, MC = 27.000€ \\ for \sum_{i\in N} s_{i,t} = 4, MC = 41.000€ \end{cases}$$

The latest part (F_3) simply introduces deficit cost which is closely related to the reliability index used.

$$F_3 = \sum_{t\in T} def_t * DEFC$$

The overall simple enough formulation enables to accurately monitor the reliability shift in respect to varying deficit cost. The economic dispatch problem as well detailed provide the means to reliably account for fuel cost (F_1) which corresponds to the cost leading factor. The “reliability” cost (F_3) can be easily deducted from OFV, rendering real total costs.

9.8 OPL code

(a)_: .mod file

```
/*********************************************
 * OPL 12.8.0.0 Model
 * Author: jim
 * Creation Date: 20/04/2019
 *********************************************/

int Gensets=...;
int periods=...;
int defcost=...;
range Genset=1..Gensets;
range Period=1..periods;
float minP[Genset]=...; //technical minimum
float maxP[Genset]=...; //available power
float sr[Period]=...;  //spinning_reserve
float maxD[Period]=...;  //max system demand
int dur[Genset]=...;  //maintenance duration
float nul[Genset]=...;
float cost[Genset]=...;  //for each Genset
```

```
float slope[Genset]=...;
float fixed[Genset]=...;


int classes=...;//Energy_injection_from_classes

range week1=1..classes;
float da[week1]=...;
float a[week1]=...;

range week2=1..classes;
float db[week2]=...;
float b[week2]=...;

range week3=1..classes;
float dc[week3]=...;
float bb[week3]=...;

range week4=1..classes;
float dd[week4]=...;
float d[week4]=...;

range week5=1..classes;
float de[week5]=...;
float e[week5]=...;

range week6=1..classes;
float df[week6]=...;
float f[week6]=...;

range week7=1..classes;
float dg[week7]=...;
float gg[week7]=...;

range week8=1..classes;
float dh[week8]=...;
float h[week8]=...;

range week9=1..classes;
float di[week9]=...;
float i[week9]=...;

range week10=1..classes;
float dj[week10]=...;
float j[week10]=...;

range week11=1..classes;
float dk[week11]=...;
float k[week11]=...;

range week12=1..classes;
float dl[week12]=...;
float l[week12]=...;

range week13=1..classes;
float dm[week13]=...;
float m[week13]=...;
```

```
range week14=1..classes;
float dn[week14]=...;
float n[week14]=...;

range week15=1..classes;
float do[week15]=...;
float o[week15]=...;

range week16=1..classes;
float dp[week16]=...;
float p[week16]=...;

dvar boolean startIn[Genset][Period]; //start of maintenance
dvar boolean status[Genset][0..periods]; // maintenance=1, run=0
dvar boolean hot[Genset][Period]; // pool of hot start (running) Gensets
dvar float+ runP[Genset][Period]; //  Genset Power output
dvar float+ deficit[Period]; //Reliability Power shortage

///////////////////////Weeks_dvar/////////////
dvar float+ run1[Genset][week1];
dvar float+ run2[Genset][week2];
dvar float+ run3[Genset][week3];
dvar float+ run4[Genset][week4];
dvar float+ run5[Genset][week5];
dvar float+ run6[Genset][week6];
dvar float+ run7[Genset][week7];
dvar float+ run8[Genset][week8];
dvar float+ run9[Genset][week9];
dvar float+ run10[Genset][week10];
dvar float+ run11[Genset][week11];
dvar float+ run12[Genset][week12];
dvar float+ run13[Genset][week13];
dvar float+ run14[Genset][week14];
dvar float+ run15[Genset][week15];
dvar float+ run16[Genset][week16];
//////////////end_of_weeks_dvar

dvar boolean hot1[Genset][week1];
dvar boolean hot2[Genset][week2];
dvar boolean hot3[Genset][week3];
dvar boolean hot4[Genset][week4];
dvar boolean hot5[Genset][week5];
dvar boolean hot6[Genset][week6];
dvar boolean hot7[Genset][week7];
dvar boolean hot8[Genset][week8];
dvar boolean hot9[Genset][week9];
dvar boolean hot10[Genset][week10];
dvar boolean hot11[Genset][week11];
dvar boolean hot12[Genset][week12];
dvar boolean hot13[Genset][week13];
dvar boolean hot14[Genset][week14];
dvar boolean hot15[Genset][week15];
dvar boolean hot16[Genset][week16];

 minimize //Objective function
```

```
sum(g in Genset, p in Period)
((runP[g][p]*slope[g]+hot[g][p]*fixed[g])*cost[g])+

sum(g in Genset, w in week1)
((run1[g][w]*slope[g]+hot1[g][w]*fixed[g])*a[w]*cost[g])+

sum(g in Genset, w in week2)
((run2[g][w]*slope[g]+hot2[g][w]*fixed[g])*b[w]*cost[g])+

sum(g in Genset, w in week3)
((run3[g][w]*slope[g]+hot3[g][w]*fixed[g])*bb[w]*cost[g])+

sum(g in Genset, w in week4)
((run4[g][w]*slope[g]+hot4[g][w]*fixed[g])*d[w]*cost[g])+

sum(g in Genset, w in week5)
((run5[g][w]*slope[g]+hot5[g][w]*fixed[g])*e[w]*cost[g])+

sum(g in Genset, w in week6)
((run6[g][w]*slope[g]+hot6[g][w]*fixed[g])*f[w]*cost[g])+

sum(g in Genset, w in week7)
((run7[g][w]*slope[g]+hot7[g][w]*fixed[g])*cost[g]*gg[w] )+

sum(g in Genset, w in week8)
((run8[g][w]*slope[g]+hot8[g][w]*fixed[g])*h[w]*cost[g])+

sum(g in Genset, w in week9)
((run9[g][w]*slope[g]+hot9[g][w]*fixed[g])*i[w]*cost[g])+

sum(g in Genset, w in week10)
((run10[g][w]*slope[g]+hot10[g][w]*fixed[g])*j[w]*cost[g])+

sum(g in Genset, w in week11)
((run11[g][w]*slope[g]+hot11[g][w]*fixed[g])*k[w]*cost[g])+

sum(g in Genset, w in week12)
((run12[g][w]*slope[g]+hot12[g][w]*fixed[g])*l[w]*cost[g])+

sum(g in Genset, w in week13)
((run13[g][w]*slope[g]+hot13[g][w]*fixed[g])*m[w]*cost[g])+

sum(g in Genset, w in week14)
((run14[g][w]*slope[g]+hot14[g][w]*fixed[g])*n[w]*cost[g])+

sum(g in Genset, w in week15)
((run15[g][w]*slope[g]+hot15[g][w]*fixed[g])*o[w]*cost[g])+

sum(g in Genset, w in week16)
((run16[g][w]*slope[g]+hot16[g][w]*fixed[g])*p[w]*cost[g])+

//End_of_weeks

sum(p in Period)//maintenance cost
piecewise{ 0->0; 7000->1; 9000->2; 11000->3; 14000 } sum(g in Genset) status[g][p] +

sum(p in Period) deficit[p]*defcost//for_reliability_cost
```

```
  ;

 // constraints
 subject to {

 demand:
 forall (p in Period)
 sum (g in Genset) runP[g][p] == maxD[p];

 spinning_reserve:
 forall (p in Period)
 sum (g in Genset) hot[g][p]*maxP[g] >= sr[p]*maxD[p];

 //reliability_maxNP:
 //forall (p in Period)
 //(sum (g in Genset) maxP[g]*(1-status[g][p]-hot[g][p])) + deficit[p]- (max(g in
Genset) hot[g][p]*maxP[g]) >= 0;

 reliability_maxRP:
 forall (p in Period)
 (sum (g in Genset) maxP[g]*(1-status[g][p]-hot[g][p])) + deficit[p]- (max(g in Genset)
runP[g][p]) >= 0;

 exclusion:
 forall (p in Period)
 status[2][p] + status[3][p] <=1;

 forall (g in Genset, p in Period)
 status[g][p] + hot[g][p] <=1;

 duration:
 forall (g in Genset)
 sum (p in Period) status[g][p] == dur[g];

 nonstop_a:
 forall (g in Genset, p in Period )
 status[g][p-1] + startIn[g][p] >= status[g][p];

 nonstop_b:
 forall (g in Genset )
 status[g][0] == nul[g];

 forall (g in Genset)
 sum (p in Period) startIn[g][p] == 1;

 simult:
 forall (p in Period)
 sum (g in Genset) status[g][p] <= 4;

 coupling_1:
 forall (g in Genset, p in Period)
 hot[g][p]*maxP[g] >= runP[g][p] ;

 coupling_2:
 forall (g in Genset, p in Period)
 hot[g][p]*minP[g] <= runP[g][p];
```

```
//////////////////////////////week1////////////////////////
forall (w in week1)
sum (g in Genset) run1[g][w] == da[w];

forall (g in Genset, w in week1)
hot1[g][w]*maxP[g] >= run1[g][w] ;

forall (g in Genset, w in week1)
hot1[g][w]*minP[g] <= run1[g][w];

forall (g in Genset, w in week1)
hot1[g][w] <=  hot[g][1];

sr1:
forall (w in week1)
sum (g in Genset) hot1[g][w]*maxP[g] >= sr[1]*da[w];

//////////////////////////////week2////////////////////////
forall (w in week2)
sum (g in Genset) run2[g][w] == db[w];

forall (g in Genset, w in week2)
maxP[g]*hot2[g][w] >= run2[g][w] ;

forall (g in Genset, w in week2)
hot2[g][w]*minP[g] <= run2[g][w];

forall (g in Genset, w in week2)
hot2[g][w] <=  hot[g][2];

sr2:
forall (w in week2)
sum (g in Genset) hot2[g][w]*maxP[g] >= sr[2]*db[w];

  //////////////////////////////week3////////////////////////
forall (w in week3)
sum (g in Genset) run3[g][w] == dc[w];

forall (g in Genset, w in week3)
maxP[g]*hot3[g][w] >= run3[g][w] ;

forall (g in Genset, w in week3)
hot3[g][w]*minP[g] <= run3[g][w];

forall (g in Genset, w in week3)
hot3[g][w] <=  hot[g][3];

sr3:
forall (w in week3)
sum (g in Genset) hot3[g][w]*maxP[g] >= sr[3]*dc[w];



//////////////////////////////week4////////////////////////
forall (w in week4)
sum (g in Genset) run4[g][w] == dd[w];
```

```
forall (g in Genset, w in week4)
maxP[g]*hot4[g][w] >= run4[g][w] ;

forall (g in Genset, w in week4)
hot4[g][w]*minP[g] <= run4[g][w];

forall (g in Genset, w in week4)
hot4[g][w] <=  hot[g][4];

sr4:
forall (w in week4)
sum (g in Genset) hot4[g][w]*maxP[g] >= sr[4]*dd[w];

/////////////////////////////week5///////////////////////
forall (w in week5)
sum (g in Genset) run5[g][w] == de[w];

forall (g in Genset, w in week5)
maxP[g]*hot5[g][w] >= run5[g][w] ;

forall (g in Genset, w in week5)
hot5[g][w]*minP[g] <= run5[g][w];

forall (g in Genset, w in week5)
hot5[g][w] <=  hot[g][5];

sr5:
forall (w in week5)
sum (g in Genset) hot5[g][w]*maxP[g] >= sr[5]*de[w];

  /////////////////////////////week6///////////////////////
forall (w in week6)
sum (g in Genset) run6[g][w] == df[w];

forall (g in Genset, w in week6)
maxP[g]*hot6[g][w] >= run6[g][w] ;

forall (g in Genset, w in week6)
hot6[g][w]*minP[g] <= run6[g][w];

forall (g in Genset, w in week6)
hot6[g][w] <=  hot[g][6];

sr6:
forall (w in week6)
sum (g in Genset) hot6[g][w]*maxP[g] >= sr[6]*df[w];

/////////////////////////////week7///////////////////////
forall (w in week7)
sum (g in Genset) run7[g][w] == dg[w];

forall (g in Genset, w in week7)
maxP[g]*hot7[g][w] >= run7[g][w] ;

forall (g in Genset, w in week7)
hot7[g][w]*minP[g] <= run7[g][w];
```

```
forall (g in Genset, w in week7)
hot7[g][w] <=  hot[g][7];

sr7:
forall (w in week7)
sum (g in Genset) hot7[g][w]*maxP[g] >= sr[7]*dg[w];

/////////////////////////////week8//////////////////////
forall (w in week8)
sum (g in Genset) run8[g][w] == dh[w];

forall (g in Genset, w in week8)
maxP[g]*hot8[g][w] >= run8[g][w] ;

forall (g in Genset, w in week8)
hot8[g][w]*minP[g] <= run8[g][w];

forall (g in Genset, w in week8)
hot8[g][w] <=  hot[g][8];

sr8:
forall (w in week8)
sum (g in Genset) hot8[g][w]*maxP[g] >= sr[8]*dh[w];

  /////////////////////////////week9//////////////////////
forall (w in week9)
sum (g in Genset) run9[g][w] == di[w];

forall (g in Genset, w in week9)
maxP[g]*hot9[g][w] >= run9[g][w] ;

forall (g in Genset, w in week9)
hot9[g][w]*minP[g] <= run9[g][w];

forall (g in Genset, w in week9)
hot9[g][w] <=  hot[g][9];

sr9:
forall (w in week9)
sum (g in Genset) hot9[g][w]*maxP[g] >= sr[9]*di[w];

  /////////////////////////////week10//////////////////////
forall (w in week10)
sum (g in Genset) run10[g][w] == dj[w];

forall (g in Genset, w in week10)
maxP[g]*hot10[g][w] >= run10[g][w] ;

forall (g in Genset, w in week10)
hot10[g][w]*minP[g] <= run10[g][w];

forall (g in Genset, w in week10)
hot10[g][w] <=  hot[g][10];

sr10:
forall (w in week10)
```

```
sum (g in Genset) hot10[g][w]*maxP[g] >= sr[10]*dj[w];

  /////////////////////////////week11///////////////////////

forall (w in week11)
sum (g in Genset) run11[g][w] == dk[w];

forall (g in Genset, w in week11)
maxP[g]*hot11[g][w] >= run11[g][w] ;

forall (g in Genset, w in week11)
hot11[g][w]*minP[g] <= run11[g][w];

forall (g in Genset, w in week11)
hot11[g][w] <=  hot[g][11];

sr11:
forall (w in week11)
sum (g in Genset) hot11[g][w]*maxP[g] >= sr[11]*dk[w];

    /////////////////////////////week12///////////////////////
forall (w in week12)
sum (g in Genset) run12[g][w] == dl[w];

forall (g in Genset, w in week12)
maxP[g]*hot12[g][w] >= run12[g][w] ;

forall (g in Genset, w in week12)
hot12[g][w]*minP[g] <= run12[g][w];

forall (g in Genset, w in week12)
hot12[g][w] <=  hot[g][12];

sr12:
forall (w in week12)
sum (g in Genset) hot12[g][w]*maxP[g] >= sr[12]*dl[w];

/////////////////////////////week13///////////////////////
forall (w in week13)
sum (g in Genset) run13[g][w] == dm[w];

forall (g in Genset, w in week13)
maxP[g]*hot13[g][w] >= run13[g][w] ;

forall (g in Genset, w in week13)
hot13[g][w]*minP[g] <= run13[g][w];

forall (g in Genset, w in week13)
hot13[g][w] <=  hot[g][13];

sr13:
forall (w in week13)
sum (g in Genset) hot13[g][w]*maxP[g] >= sr[13]*dm[w];

   /////////////////////////////week14///////////////////////
forall (w in week14)
sum (g in Genset) run14[g][w] == dn[w];
```

```
forall (g in Genset, w in week14)
maxP[g]*hot14[g][w] >= run14[g][w] ;

forall (g in Genset, w in week14)
hot14[g][w]*minP[g] <= run14[g][w];

forall (g in Genset, w in week14)
hot14[g][w] <=  hot[g][14];

sr14:
forall (w in week14)
sum (g in Genset) hot14[g][w]*maxP[g] >= sr[14]*dn[w];

/////////////////////////////week15//////////////////////
forall (w in week15)
sum (g in Genset) run15[g][w] == do[w];

forall (g in Genset, w in week15)
maxP[g]*hot15[g][w] >= run15[g][w] ;

forall (g in Genset, w in week15)
hot15[g][w]*minP[g] <= run15[g][w];

forall (g in Genset, w in week15)
hot15[g][w] <=  hot[g][15];

sr15:
forall (w in week15)
sum (g in Genset) hot15[g][w]*maxP[g] >= sr[15]*do[w];

/////////////////////////////week16//////////////////////
forall (w in week16)
sum (g in Genset) run16[g][w] == dp[w];

forall (g in Genset, w in week16)
maxP[g]*hot16[g][w] >= run16[g][w] ;

forall (g in Genset, w in week16)
hot16[g][w]*minP[g] <= run16[g][w];

forall (g in Genset, w in week16)
hot16[g][w] <=  hot[g][16];

sr16:
forall (w in week16)
sum (g in Genset) hot16[g][w]*maxP[g] >= sr[16]*dp[w];

    ///////////end_of_weeks/////////////

 };
```

(b)_ .dat File

```
/*********************************************
 * OPL 12.8.0.0 Data
 * Author: Jim
```

```
 * Creation Date: 20/04/2019
 *****************************************************/
Gensets=7;
periods=16;
classes=10;

SheetConnection
sheetData("C:\\Users\\john\\opl\\GMS_UC_ED_runP\\modelGMSUCEDrunP.xlsx");
nul from SheetRead(sheetData,"nul");
maxP from SheetRead(sheetData,"maxP");
minP from SheetRead(sheetData,"minP");
maxD from SheetRead(sheetData,"maxD");
sr from SheetRead(sheetData,"sr");
dur from SheetRead(sheetData,"dur");
cost from SheetRead(sheetData,"cost");
defcost from SheetRead(sheetData,"deficitcost");

slope from SheetRead(sheetData,"slope");
fixed from SheetRead(sheetData,"fixed");

da from SheetRead(sheetData,"da");
db from SheetRead(sheetData,"db");
dc from SheetRead(sheetData,"dc");
dd from SheetRead(sheetData,"dd");
de from SheetRead(sheetData,"de");
df from SheetRead(sheetData,"df");
dg from SheetRead(sheetData,"dg");
dh from SheetRead(sheetData,"dh");
di from SheetRead(sheetData,"di");
dj from SheetRead(sheetData,"dj");
dk from SheetRead(sheetData,"dk");
dl from SheetRead(sheetData,"dl");
dm from SheetRead(sheetData,"dm");
dn from SheetRead(sheetData,"dn");
do from SheetRead(sheetData,"do");
dp from SheetRead(sheetData,"dp");

a from SheetRead(sheetData,"a");
b from SheetRead(sheetData,"b");
bb from SheetRead(sheetData,"bb");
d from SheetRead(sheetData,"d");
e from SheetRead(sheetData,"e");
f from SheetRead(sheetData,"f");
gg from SheetRead(sheetData,"g");
h from SheetRead(sheetData,"h");
i from SheetRead(sheetData,"i");
j from SheetRead(sheetData,"j");
k from SheetRead(sheetData,"k");
l from SheetRead(sheetData,"l");
m from SheetRead(sheetData,"m");
n from SheetRead(sheetData,"n");
o from SheetRead(sheetData,"o");
p from SheetRead(sheetData,"p");

status to SheetWrite(sheetData,"status");
runP to SheetWrite(sheetData,"runP");
hot to SheetWrite(sheetData,"hot");
```

```
//cold to SheetWrite(sheetData,"cold");
deficit to SheetWrite(sheetData,"deficit");

run1 to SheetWrite(sheetData,"runp1");
hot1 to SheetWrite(sheetData,"hotp1");

run2 to SheetWrite(sheetData,"runp2");
hot2 to SheetWrite(sheetData,"hotp2");

run3 to SheetWrite(sheetData,"runp3");
hot3 to SheetWrite(sheetData,"hotp3");

run4 to SheetWrite(sheetData,"runp4");
hot4 to SheetWrite(sheetData,"hotp4");

run5 to SheetWrite(sheetData,"runp5");
hot5 to SheetWrite(sheetData,"hotp5");

run6 to SheetWrite(sheetData,"runp6");
hot6 to SheetWrite(sheetData,"hotp6");

run7 to SheetWrite(sheetData,"runp7");
hot7 to SheetWrite(sheetData,"hotp7");

run8 to SheetWrite(sheetData,"runp8");
hot8 to SheetWrite(sheetData,"hotp8");

run9 to SheetWrite(sheetData,"runp9");
hot9 to SheetWrite(sheetData,"hotp9");

run10 to SheetWrite(sheetData,"runp10");
hot10 to SheetWrite(sheetData,"hotp10");

run11 to SheetWrite(sheetData,"runp11");
hot11 to SheetWrite(sheetData,"hotp11");

run12 to SheetWrite(sheetData,"runp12");
hot12 to SheetWrite(sheetData,"hotp12");

run13 to SheetWrite(sheetData,"runp13");
hot13 to SheetWrite(sheetData,"hotp13");

run14 to SheetWrite(sheetData,"runp14");
hot14 to SheetWrite(sheetData,"hotp14");

run15 to SheetWrite(sheetData,"runp15");
hot15 to SheetWrite(sheetData,"hotp15");

run16 to SheetWrite(sheetData,"runp16");
hot16 to SheetWrite(sheetData,"hotp16");
```

9.9 Fuel consumption model validation

The model was tested in respect to validate the efficiency of calculating fuel cost. As a result, irrelevant code components referring to maintenance activities were removed and three scenarios were inserted with 0% spinning reserve requirement and 0 deficit cost.

1st scenario: Stable system demand for all weeks and classes at 50% of power plants Nominal Output

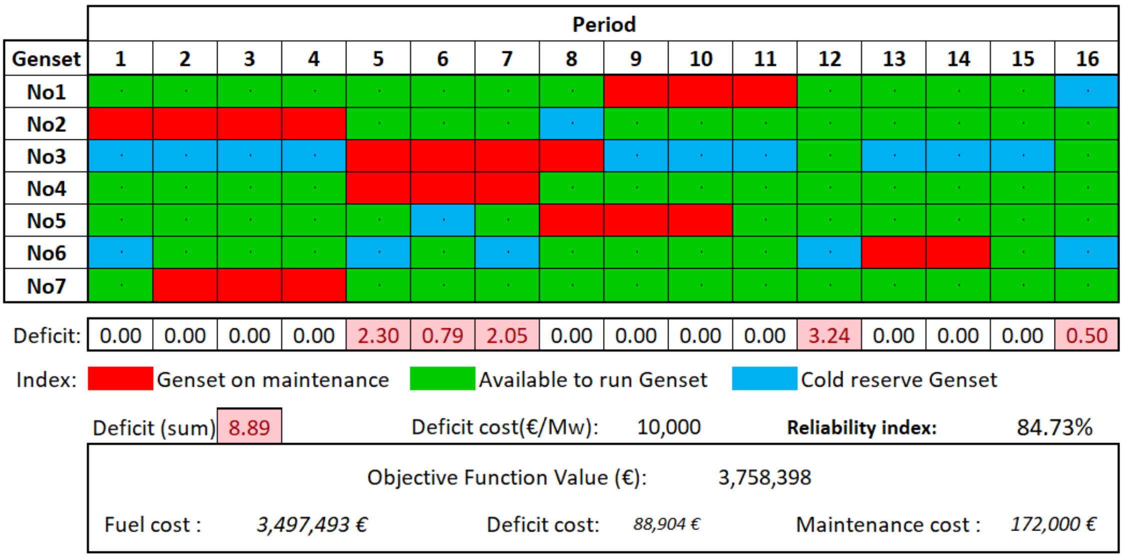
2nd scenario: Stable system demand for all weeks and classes at 75% of power plants Nominal Output

3rd scenario: Stable system demand for all weeks and classes at 100% of power plants Nominal Output

Results presented in APPENDIX A exhibited the absolute efficiency of the core code without any fault or deviation.

9.10 Solution with IBM ILOG CPLEX

Solutions were obtained for two (2) reliability approaches namely the maximum Nominal Power (maxNP) and maximum Run Power (maxRP). In particular, for each case analysis was conducted for various deficit costs, namely 1, 10, 100, 1.000, 10.000, 100.0000 and 1.000.000€. For each run, a schedule was produced as depicted in Figure 9-20.



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟦
No2	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟦	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟦	🟦	🟦	🟩
No4	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟦	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
No6	🟦	🟩	🟩	🟩	🟦	🟩	🟦	🟩	🟩	🟩	🟩	🟦	🟥	🟥	🟩	🟦
No7	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Deficit:	0.00	0.00	0.00	0.00	2.30	0.79	2.05	0.00	0.00	0.00	0.00	3.24	0.00	0.00	0.00	0.50

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

Deficit (sum) 8.89 Deficit cost(€/Mw): 10,000 **Reliability index:** 84.73%

Objective Function Value (€): 3,758,398

Fuel cost : *3,497,493 €* Deficit cost: *88,904 €* Maintenance cost : *172,000 €*

Figure 9-20: Optimal schedule for maxRP approach and deficit cost 10.000€/Mw

It is critical to realize that our reliability approach essence has to do with the capability of restoring system demand in worst-case scenario one (1) Genset failure. While this is true and all results are stand-alone valid, the reliability instrument used in the two approaches is misleading if for comparisons to take place. For example, if in maxNP approach we miss 2 Mw against maximum nominal power Genset, we might only miss

1,5Mw compared to maximum run power of some Genset. As a result, we adjust in order to acquire comparable results and for the maxNP approach we calculated the adjusted partial reliability as:

$$\frac{Sum\ of\ reserve\ Gensets\ Capacity}{max\ run\ power\ of\ hot\ reserve\ Gensets}$$

For sum of reserve Gensets Capacity ≥ max run power of hot reserve Gensets, partial reliability is 1.

Results for maxNP and maxRP runs are then summarized in tables 9.1 and 9.2 respectively. We notice that in both approaches, beyond some deficit cost, no further improvement in Reliability Index is realized. In other words, this is the highest reliability the system can realize, regardless deficit cost.

Deficit sum (Mw)	Deficit Unit Cost (€)	Reliability Index	Reliability Index ADJUSTED	OFV (€)	Fuel Cost	Deficit Cost (€)	Maintenance Cost (€)	Solution Time System 1 (sec)
39.10	1	56.25	56.25	3,617,293	3,445,254	39	172,000	24
33.52	10	62.50	62.5	3,617,681	3,445,346	335	172,000	26
33.52	100	62.50	62.5	3,620,727	3,445,376	3,352	172,000	22
27.93	1000	68.75	68.75	3,647,224	3,447,294	27,930	172,000	27
11.24	10,000	87.43	87.64	3,802,880	3,518,520	112,360	172,000	118
7.36	100,000	91.77	92.49	4,486,932	3,579,132	735,800	172,000	55
7.36	1,000,000	91.77	92.49	11,109,132	3,579,132	7,358,000	172,000	207

Table 9.1: Summarized results, Maximum Nominal Power Reliability approach.

System 1: Intel(R) Core (TM) i3CPU M350_2.27GHz, 64-bit, 4 GB ram.

Deficit sum (Mw)	Deficit Unit Cost (€)	Reliability Index	OFV (€)	Fuel Cost	Deficit Cost (€)	Maintenance Cost (€)	Solution Time system 2 (sec)
30.70	1	56.25	3,617,285	3,445,255	31	172,000	16
25.04	10	56.25	3,617,531	3,445,281	250	172,000	16
20.34	100	62.50	3,619,447	3,445,413	2,034	172,000	16
16.34	1000	68.75	3,635,852	3,447,515	16,337	172,000	22
8.89	10,000	84.73	3,758,398	3,497,493	88,904	172,000	278
3.78	100,000	94.64	4,128,152	3,578,344	377,808	172,000	169
3.78	1,000,000	94.64	7,528,427	3,578,344	3,778,083	172,000	75

Table 9.2: Summarized results, Maximum Run Power Reliability approach. System 2: AMD A10-6800K APU with Radeon(tm) HD Graphics_4.10 GHz, 64-bit, 8 GB ram.

The usefulness of the whole approach is illustrated in Figure 9-21 where, Parreto optimal frontiers are depicted for maxRP and maxNP reliability approaches.

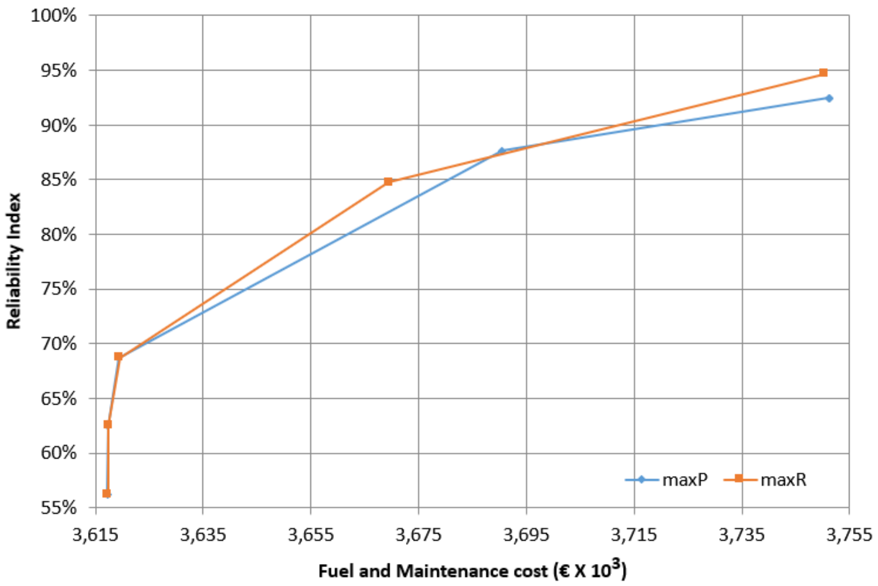
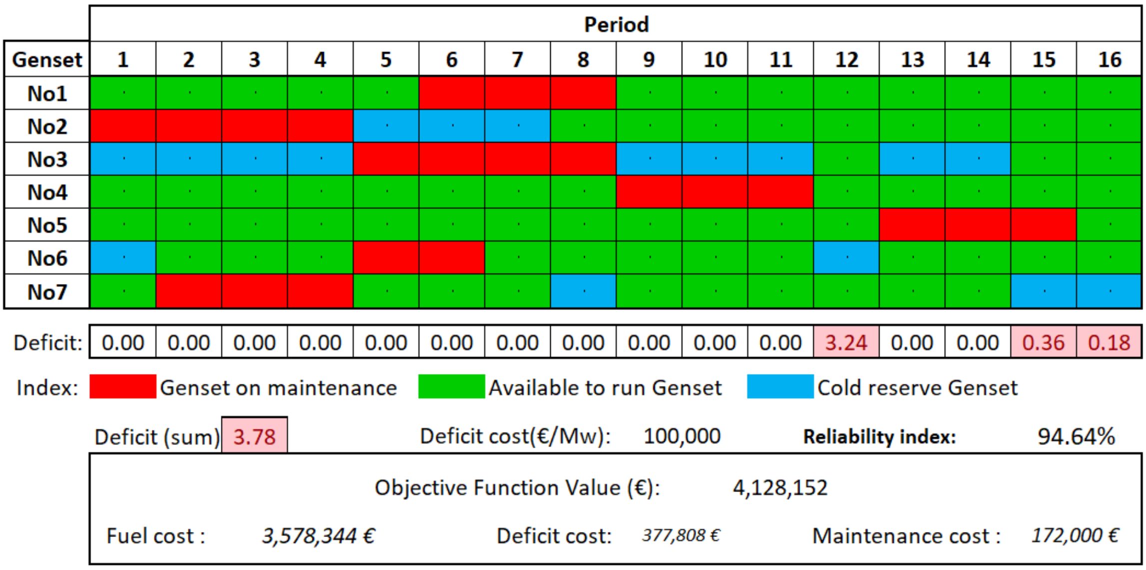


Figure 9-21: Parreto optimal frontiers

As expected, when system was pushed to the limits in concern to reliability cost, the maxRP approach yielded higher Reliability Index for less fuel and maintenance cost. The more than 2% increase in reliability with the maxRP approach is evident for roughly the same total cost since the difference is just 0.02%.

Since higher system reliability refers to maxRP, deficit cost 100.000€/Mw, this schedule is presented in Figure 9-22, below.



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No2	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟦	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟦	🟦	🟩	🟩
No4	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩
No6	🟦	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟩
No7	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟦
Deficit:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.24	0.00	0.00	0.36	0.18

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

Deficit (sum) 3.78 Deficit cost(€/Mw): 100,000 **Reliability index:** 94.64%

Objective Function Value (€): 4,128,152

Fuel cost : *3,578,344 €* Deficit cost: *377,808 €* Maintenance cost : *172,000 €*

Figure 9-22: Optimal schedule for maxRP approach, 100.000 €/Mw deficit cost.

We notice that reserves are leveled except period 12 (see Figure 9-23) where not enough capacity is present, revealing a systems weak point. A problem also exists during week 15 and 16.

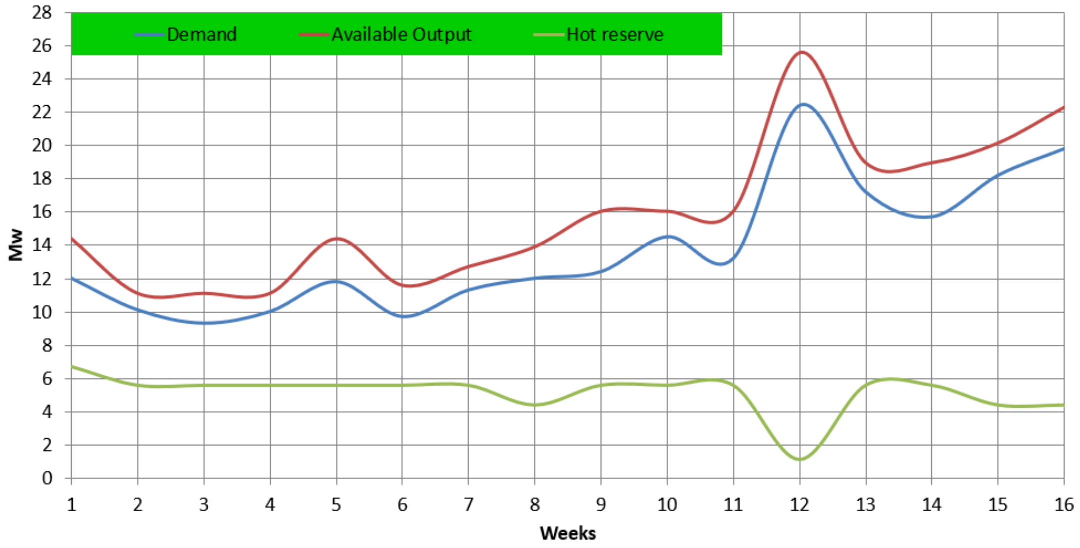


Figure 9-23: System demand, spinning reserve and reserve power

Managerial decisions have to alleviate the problem since reliability capacity of the system is exhausted. And when considering alternatives, optimal schedules of different deficit costs are yet valuable.

The importance of our approach is already revealed. We know exactly what it takes to achieve desired level of reliability. Further on, comparisons are possible among different states of reliability as presented in

Figure 9-24. It is evident that this approach is valid for all different systems; but actual findings depend on each one in particular.

For example, let’s consider a 10% increase in reliability. To mitigate from 84.73% reliability state A to 94.64% state B the additional cost is 81.000€.

A part of that 81.000€ cost may well serve as an upper bound in our attempt to consider alternatives. Since state A (figure 5) needs maximum 3.24Mw in reserves (max deficit) to reach 100% reliability we might consider relocation of three (3) mobile Gensets not actually needed elsewhere. Or even consider renting some power for some period.

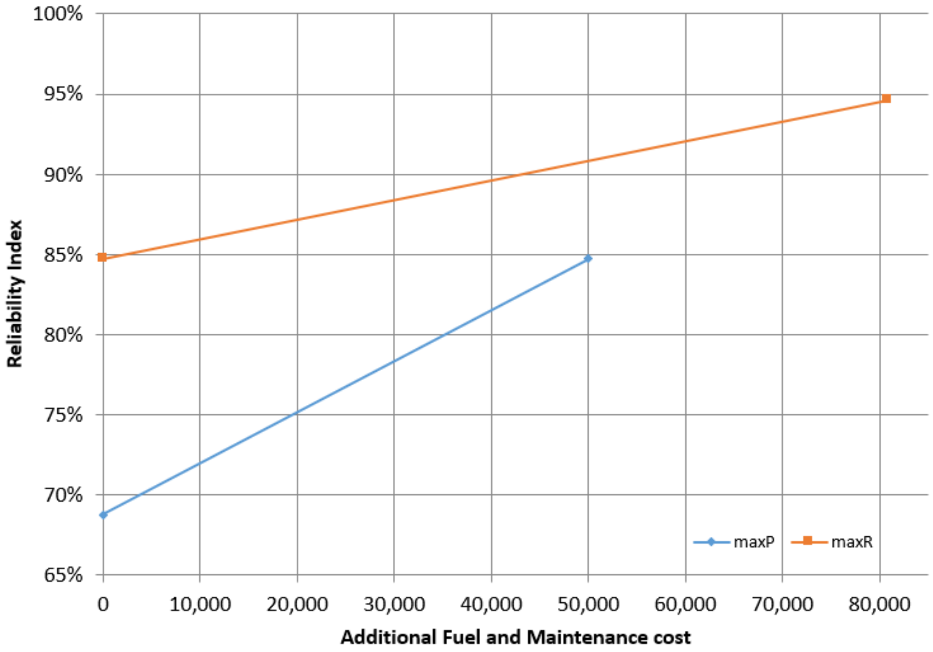


Figure 9-24: Cost of mitigating to some higher reliability status

Actual comparisons are also possible when considering a different production equipment portfolio. In any case, further considerations about how to utilize the wealth of information presented deviates from our scope. Table 9.3 suggests the power dispatch among weekly peak system demand.

Genset	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1.552	2.267	1.552	2.167	1.552				2.288	2.794	2.794	2.794	2.794	2.674	2.794	2.794
2								4.400	2.940	4.534	3.234	4.365	4.320	2.940	4.760	4.578
3												4.365			4.760	4.578
4	4.918	5.061	5.061	5.061	4.718	4.170	5.061	4.400				4.365	5.061	5.061	4.760	4.578
5	1.130	2.147	2.062	2.147	1.130	1.130	1.214	2.147	2.147	2.147	2.147	2.147				2.147
6		0.625	0.625	0.625			0.625	1.053	0.625	0.625	0.625		0.625	0.625	1.125	1.125

7	4.400				4.400	4.400	4.400		4.400	4.400	4.400	4.365	4.400	4.400		

Table 9.3: Gensets power output for weekly peak system demand

Table 9.4 suggests the power dispatch of each Genset for each class of week 1 and is consistent to table 6:

	1	2	3	4	5	6	7	8	9	10
1	2,000							1,552	1,552	1,552
2										
3										
4		2,664	3,300	3,900	3,370	3,970	4,570	4,848	4,318	4,918
5					1,130	1,130	1,130		1,130	1,130
6										
7	4,400	4,336	4,400	4,400	4,400	4,400	4,400	4,400	4,400	4,400

Table 9.4: Gensets power output for 1st week classes (dispatch per class upper limit).

First of all, we notice the smooth operation we anticipated: Genset 7 serves as base load and Genset 4 is in close contact. The other 2 Gensets provide when necessary.

Secondly, we notice that during week 12, 15 and 16 peak system demand, many Gensets within each week share same output. This is due to the maxRP approach. As a result, a detailed Economic Dispatch during actual operation, provided the fixed allocation of Gensets to run (output of this study), can cause further fuel consumption reduction for certain amount of time. And that comes without compromising reliability. The logic is simple and a simple example is useful.

Suppose we possess 2 Gensets with different fuel efficiency and our study states that at some point Genset 1 has to run at 75%NP output say 5 Mw and Genset 2 at 80%NP output say 3Mw. If during actual run it is more economic to run Genset 1 at 80%NP output (higher loading) this is certainly more than welcomed. In that case Genset 2 consequently has to run at lower rating to meet system demand.

It is evident that in case of Genset 1 malfunction, Genset 2 can always restore operation to 80% NP output practically yielding again a 5Mw power loss, as counter measured by our current study. Reliability as framed initially is not compromised since we still need 5 Mw to compensate for the malfunction.

Bottom line is that for a malfunction not to occur, if it is cost effective to follow what real time Economic Dispatch dictates, we can certainly do harvesting (in a safe and opportunistic way) additional cost savings.

Scheduled spinning reserves for all classes among weeks are found more or less, higher than set minimum requirements. But spinning reserves above set requirement, incur undesired extra fuel cost. What they really represent is the additional fuel cost optimal allocation among time units, in order to retrieve some optimal solution, as shown in Figure 9-25.

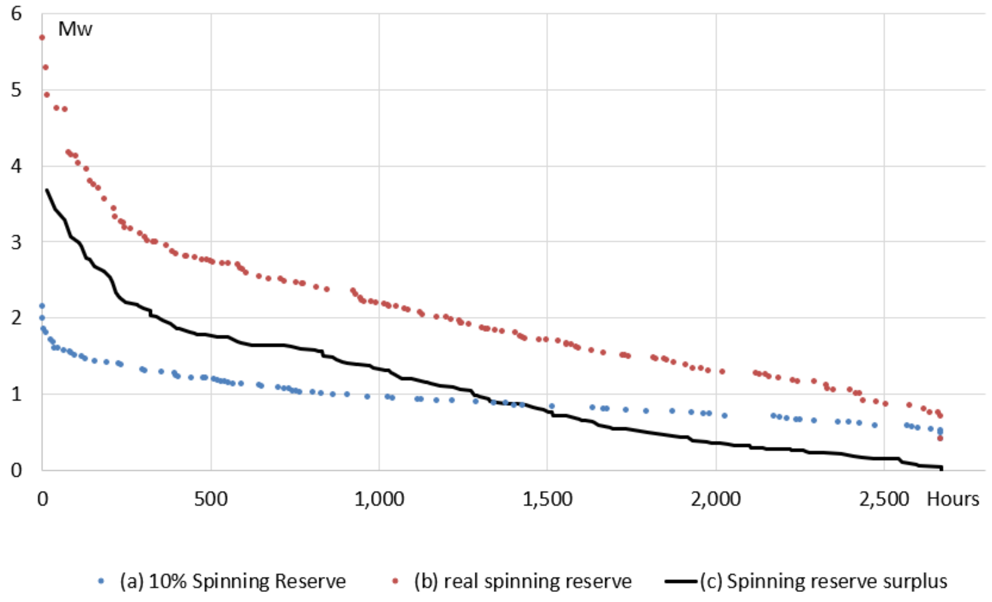


Figure 9-25: Spinning Reserves Duration, maxRP approach, 100.000€ deficit cost.

In the above figure, line (c) represent the surplus spinning reserves duration and as an example can be easily seen that for 1,500 hours surplus is more than 1 Mw. In the same logic, plots (a) and (b) correspond to set (10%) spinning reserves and actual (model output) spinning reserves respectively.

Some final remarks. Interestingly, when it comes to incorporate renewable energy sources, surplus spinning reserves in conjunction to energy storage technologies or other approaches, could represent a potential that might not otherwise be exploited. In current system we didn't explicitly regard any renewable energy participation despite this could be done in some ways. Typically, by simply allocating a fixed amount of power in addition to existing spinning reserve requirements and either compensate system demand or not. Since out of our scope we shall simply state that in such a case and for even comparably small contribution of renewables, scheduled spinning reserves would possibly give unnecessary rise to additional fuel costs.

9.11 Comments

The maxRP approach compared to maxNP exhibits more economical results in respect to reliability. But, further cost reduction and especially fuel cost optimization can be obtained for a single reason.

We must recall that in maxRP approach, when deficit cost (€/Mw) is high enough, during some periods it is preferable to sacrifice some fuel cost efficiency in order to lower maxRP but altogether we effectively minimize deficit cost. In the over all this proves to be cost effective for the entire horizon.

But during actual run, a detailed Economic Dispach algorithm, provided a fixed allocation of Gensets to run (output of this study), can effectively reduce fuel consumption. The logic is simple and a simple example is useful.

Suppose we possess 2 Gensets with different fuel efficiency and our study states that at some point Genset 1 has to run at 75%NP output say 5 Mw and Genset 2 at 80%NP output say 3Mw. If during actual run it is more economic to run Genset 1 at 80%NP output (higher loading) this is certainly more than welcomed. In that case Genset 2 consequently has to run at lower rating to meet system demand.

The interesting thing is that in case of Genset 1 malfunction, Genset 2 can always restore operation to 80% NP output practically yielding a power loss of 5Mw, as counter measured by our current study. Reliability as framed initially is not compromised since we still need 5 Mw to compensate for the malfunction.

In contrast, by utilizing the maxNP approach we constantly allocate valuable amount of power for redundancy reasons. As a result, any model is deprived of many cost-effective run combinations yielding higher operation cost. By letting the model to decide maxRP we enlarge the domain of feasible solutions by enabling many more cost-effective run combinations.

A side effect is that computational time increases dramatically but within acceptable limits. For example, in the critical 10.000€Mw zone of deficit cost the maxRP model took almost 38 minutes to provide an outcome. In contrast, maxNP required a couple of minutes.

The bottom line is that if not for a malfunction to occur, if it is cost effective to follow what real time Economic Dispatch dictates, we can certainly do harvesting (in a safe opportunistic way) additional cost savings.

Chapter 10

Conclusions

10.1 Summary

A realistic system has to be modeled in quite enough detail if reliable information is to be acquired. In our study we used real Genset and system demand data forming a system with characteristics commonly found around the world.

The incorporation of the Economic Dispatch problem in the model yielded no significant problems in terms of realistic solving times.

The output of the model represents a valuable aid in the managerial decision process of deciding upon the tradeoff between overall cost and system reliability. The marginal cost of reliability is extremely handy. Any power deficit concerning system reliability is realized soon enough and decisions upon further actions (investments, rental Gensets etc.) have a solid foundation

At the end, results are also reliable and accurate enough so as to fix next seasons maintenance schedule with an eye on overall cost.

10.2 Contributions

A realistic system commonly found around the world was modeled in sufficient enough detail and reliable information were acquired, serving as a valuable decision aid for many planning activities. The optimal Generator Maintenance schedule can be retrieved in conjunction to desired reliability status. If maximum system reliability is exhausted, optimal schedule is considered in conjunction to cost of alternatives. The holistic approach presented, allows for any power deficit concerning system reliability to be accurately realized and decisions upon further actions (investments, rental Gensets etc.) have hence a solid foundation based on actual and reliable cost data.

The newly introduced maxRP reliability approach compared to the established maxNP approach, exhibits greater potential in respect to reliability when cost reduction is on the table. The inherent to any system higher reliability status is revealed.

The Parreto optimal frontier derived for each approach, reveals the true tradeoffs and in particular the change in overall system cost when shifting to a different reliability status. As a result, marginal costs of reliability status are known and thus extremely important. When treated in conjunction to various ways of alleviating power deficit, constitute a best practice in an attempt to reach any desired reliability status. Schedules derived from maxRP and maxNP approaches can be respected in parallel, offering even more alternatives.

The classification of hourly system demand in classes and the notion of the weekly available Genset pool, constitute a solid framework for optimizing power systems. The afore mentioned approaches, greatly reduce dimensionality and search space domain yielding quick solving times. As a result, the incorporation of the Economic Dispatch problem in the model yields no significant problems in terms of realistic solving times.

10.3 Future work

Something worth investigating is under what circumstances is realized the validity of the concept that beyond a percentage of injected energy in the model, maintenance schedule is practically un-changed or sufficiently un important.

The reasoning is simple. With 100% of energy demand injected in the model, what is not under maintenance each time is either put in service or set as reserve. And for sure, more energy should be produced by the more efficient Gensets and vice versa.

As a result, as the % of injected energy increases, the rest of the un-injected energy could possibly not produce a fuel cost difference that can force a major scheduling change. This can be extremely useful taking under consideration the dimensionality reduction that can be realized.

In Figure 10-1 below we basically represent a neat Economic Dispatch problem and the concept remains the same.

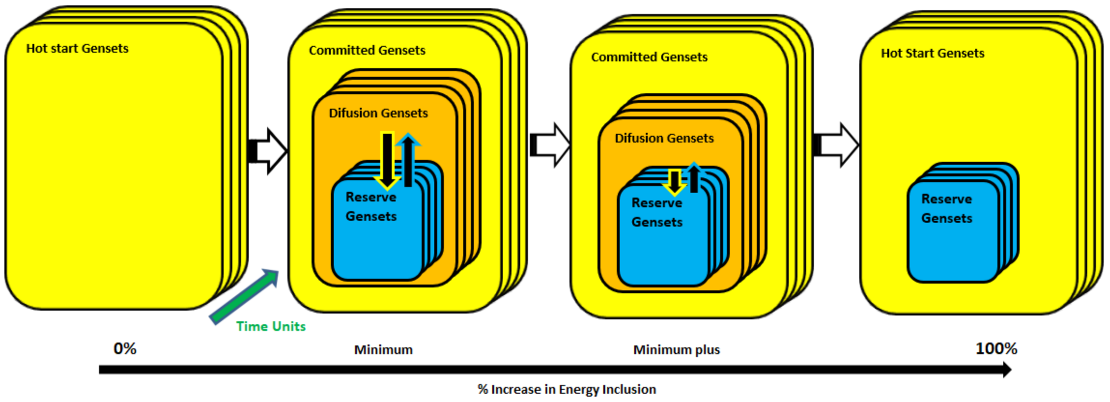


Figure 10-1: Economic Dispatch problem and energy injection

With increasing energy injection, the diffusion between committed and reserved Gensets is reduced until Gensets form two distinct pools, the hot start and the reserve Gensets pool. The question is if there exist a % of energy injection that can trigger no significant scheduling change beyond that point.

Taking under consideration the dimensionality aspect, something worth investigating is the optimal number of classes such that beyond them, maintenance schedules are practically un-changed or differences are sufficiently un-important.

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APPENDIX A: Model Inputs

10.4 Model Inputs

System weekly peak loads (Mw)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
12,0	10,1	9,3	10,0	11,8	9,7	11,3	12,0	12,4	14,5	13,2	22,4	17,2	15,7	18,2	19,8

System weekly spinning reserve (as % of peak load)

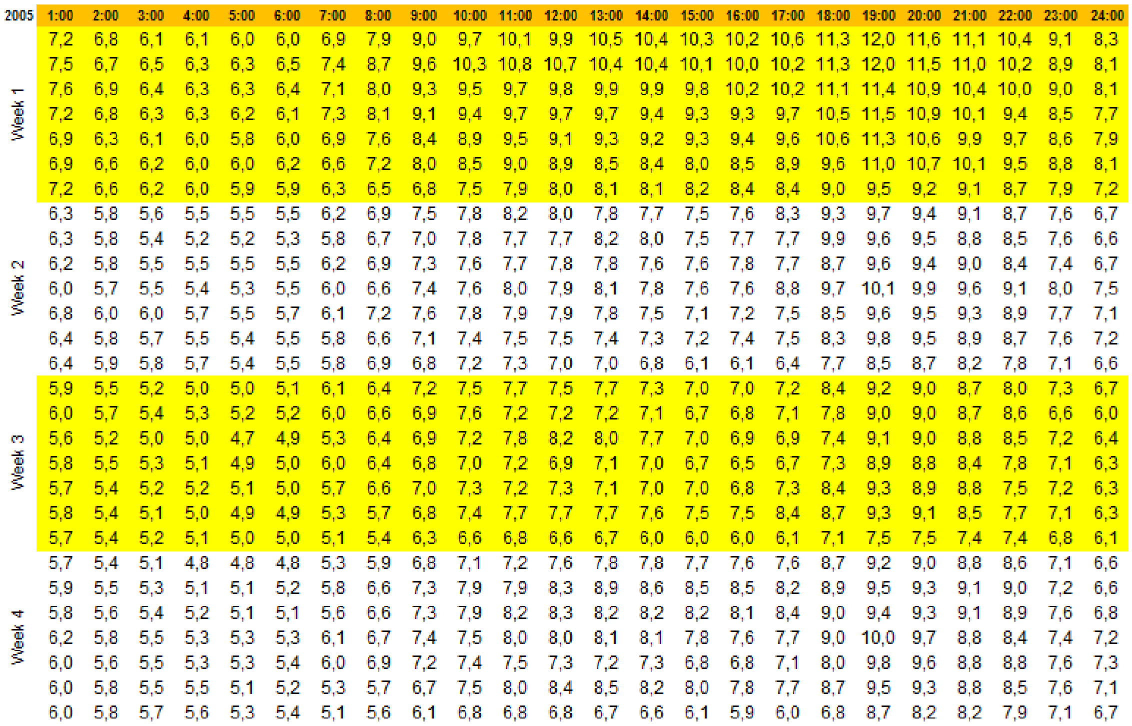
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%

Genset data

Genset	1	2	3	4	5	6	7
Nom. Power (Mw)	3.104	5.880	5.880	5.327	2.260	1.250	5.500
Max. Power (Mw)	2.794	5.586	5.586	5.061	2.147	1.125	4.400
Max. Power (Mw) (% of Nominal P.)	90%	95%	95%	95%	95%	90%	80%
Min. Power (Mw)	1.552	2.940	2.940	2.664	1.130	0.625	2.750
Maintenance Duration (Weeks)	3	4	4	3	3	2	3
Fuel type	Heavy Fuel Oil	Diesel Oil	Diesel Oil	Heavy Fuel Oil	Heavy Fuel Oil	Diesel Oil	Heavy Fuel Oil
Fuel cost (€/tn)	650	1000	1000	650	650	1000	650

10.5 Hourly load data

Each entry represents higher system demand during each hour.



2005	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
Week 1	7,2	6,8	6,1	6,1	6,0	6,0	6,9	7,9	9,0	9,7	10,1	9,9	10,5	10,4	10,3	10,2	10,6	11,3	12,0	11,6	11,1	10,4	9,1	8,3
	7,5	6,7	6,5	6,3	6,3	6,5	7,4	8,7	9,6	10,3	10,8	10,7	10,4	10,4	10,1	10,0	10,2	11,3	12,0	11,5	11,0	10,2	8,9	8,1
	7,6	6,9	6,4	6,3	6,3	6,4	7,1	8,0	9,3	9,5	9,7	9,8	9,9	9,9	9,8	10,2	10,2	11,1	11,4	10,9	10,4	10,0	9,0	8,1
	7,2	6,8	6,3	6,3	6,2	6,1	7,3	8,1	9,1	9,4	9,7	9,7	9,7	9,4	9,3	9,3	9,7	10,5	11,5	10,9	10,1	9,4	8,5	7,7
	6,9	6,3	6,1	6,0	5,8	6,0	6,9	7,6	8,4	8,9	9,5	9,1	9,3	9,2	9,3	9,4	9,6	10,6	11,3	10,6	9,9	9,7	8,6	7,9
	6,9	6,6	6,2	6,0	6,0	6,2	6,6	7,2	8,0	8,5	9,0	8,9	8,5	8,4	8,0	8,5	8,9	9,6	11,0	10,7	10,1	9,5	8,8	8,1
	7,2	6,6	6,2	6,0	5,9	5,9	6,3	6,5	6,8	7,5	7,9	8,0	8,1	8,1	8,2	8,4	8,4	9,0	9,5	9,2	9,1	8,7	7,9	7,2
Week 2	6,3	5,8	5,6	5,5	5,5	5,5	6,2	6,9	7,5	7,8	8,2	8,0	7,8	7,7	7,5	7,6	8,3	9,3	9,7	9,4	9,1	8,7	7,6	6,7
	6,3	5,8	5,4	5,2	5,2	5,3	5,8	6,7	7,0	7,8	7,7	7,7	8,2	8,0	7,5	7,7	7,7	9,9	9,6	9,5	8,8	8,5	7,6	6,6
	6,2	5,8	5,5	5,5	5,5	5,5	6,2	6,9	7,3	7,6	7,7	7,8	7,8	7,6	7,6	7,8	7,7	8,7	9,6	9,4	9,0	8,4	7,4	6,7
	6,0	5,7	5,5	5,4	5,3	5,5	6,0	6,6	7,4	7,6	8,0	7,9	8,1	7,8	7,6	7,6	8,8	9,7	10,1	9,9	9,6	9,1	8,0	7,5
	6,8	6,0	6,0	5,7	5,5	5,7	6,1	7,2	7,6	7,8	7,9	7,9	7,8	7,5	7,1	7,2	7,5	8,5	9,6	9,5	9,3	8,9	7,7	7,1
	6,4	5,8	5,7	5,5	5,4	5,5	5,8	6,6	7,1	7,4	7,5	7,5	7,4	7,3	7,2	7,4	7,5	8,3	9,8	9,5	8,9	8,7	7,6	7,2
	6,4	5,9	5,8	5,7	5,4	5,5	5,8	6,9	6,8	7,2	7,3	7,0	7,0	6,8	6,1	6,1	6,4	7,7	8,5	8,7	8,2	7,8	7,1	6,6
Week 3	5,9	5,5	5,2	5,0	5,0	5,1	6,1	6,4	7,2	7,5	7,7	7,5	7,7	7,3	7,0	7,0	7,2	8,4	9,2	9,0	8,7	8,0	7,3	6,7
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	5,8	5,5	5,3	5,1	4,9	5,0	6,0	6,4	6,8	7,0	7,2	6,9	7,1	7,0	6,7	6,5	6,7	7,3	8,9	8,8	8,4	7,8	7,1	6,3
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	5,8	5,4	5,1	5,0	4,9	4,9	5,3	5,7	6,8	7,4	7,7	7,7	7,7	7,6	7,5	7,5	8,4	8,7	9,3	9,1	8,5	7,7	7,1	6,3
	5,7	5,4	5,2	5,1	5,0	5,0	5,1	5,4	6,3	6,6	6,8	6,6	6,7	6,0	6,0	6,0	6,1	7,1	7,5	7,5	7,4	7,4	6,8	6,1
Week 4	5,7	5,4	5,1	4,8	4,8	4,8	5,3	5,9	6,8	7,1	7,2	7,6	7,8	7,8	7,7	7,6	7,6	8,7	9,2	9,0	8,8	8,6	7,1	6,6
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	5,8	5,6	5,4	5,2	5,1	5,1	5,6	6,6	7,3	7,9	8,2	8,3	8,2	8,2	8,2	8,1	8,4	9,0	9,4	9,3	9,1	8,9	7,6	6,8
	6,2	5,8	5,5	5,3	5,3	5,3	6,1	6,7	7,4	7,5	8,0	8,0	8,1	8,1	7,8	7,6	7,7	9,0	10,0	9,7	8,8	8,4	7,4	7,2
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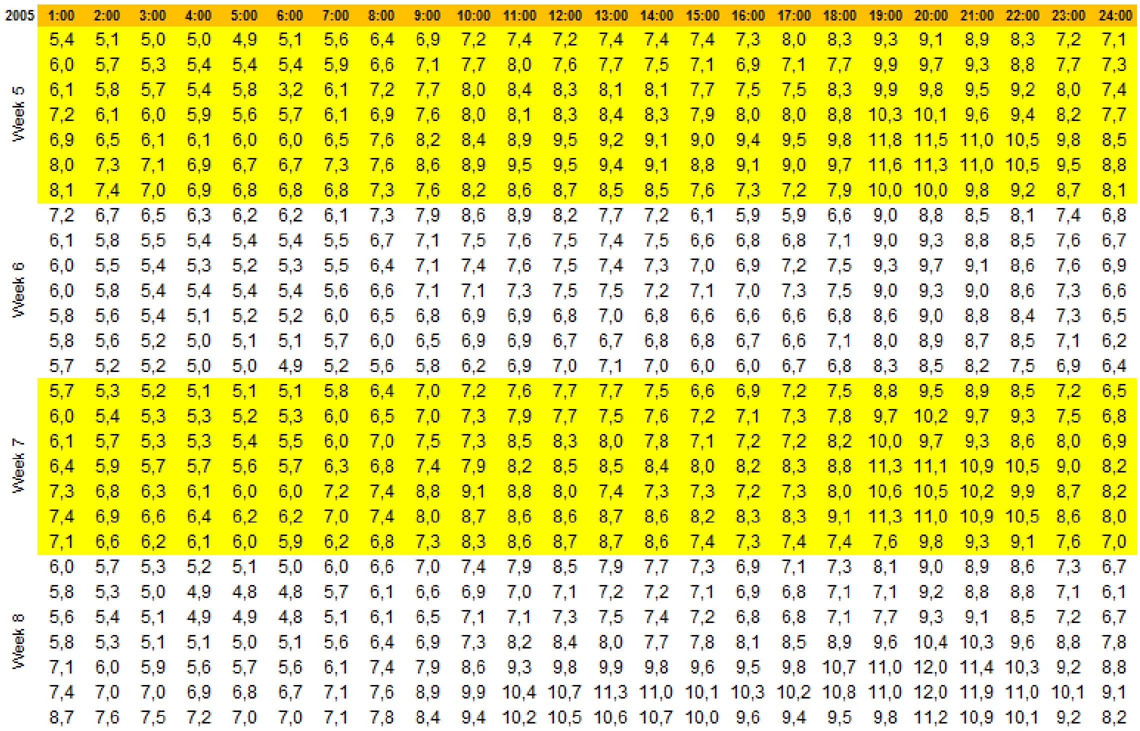
	6,0	5,8	5,7	5,6	5,3	5,4	5,1	5,6	6,1	6,8	6,8	6,8	6,7	6,6	6,1	5,9	6,0	6,8	8,7	8,2	8,2	7,9	7,1	6,7



2005	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
Week 5	5,4	5,1	5,0	5,0	4,9	5,1	5,6	6,4	6,9	7,2	7,4	7,2	7,4	7,4	7,4	7,3	8,0	8,3	9,3	9,1	8,9	8,3	7,2	7,1
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	8,1	7,4	7,0	6,9	6,8	6,8	6,8	7,3	7,6	8,2	8,6	8,7	8,5	8,5	7,6	7,3	7,2	7,9	10,0	10,0	9,8	9,2	8,7	8,1
Week 6	7,2	6,7	6,5	6,3	6,2	6,2	6,1	7,3	7,9	8,6	8,9	8,2	7,7	7,2	6,1	5,9	5,9	6,6	9,0	8,8	8,5	8,1	7,4	6,8
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Week 7	5,7	5,3	5,2	5,1	5,1	5,1	5,8	6,4	7,0	7,2	7,6	7,7	7,7	7,5	6,6	6,9	7,2	7,5	8,8	9,5	8,9	8,5	7,2	6,5
	6,0	5,4	5,3	5,3	5,2	5,3	6,0	6,5	7,0	7,3	7,9	7,7	7,5	7,6	7,2	7,1	7,3	7,8	9,7	10,2	9,7	9,3	7,5	6,8
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	7,1	6,6	6,2	6,1	6,0	5,9	6,2	6,8	7,3	8,3	8,6	8,7	8,7	8,6	7,4	7,3	7,4	7,4	7,6	9,8	9,3	9,1	7,6	7,0
Week 8	6,0	5,7	5,3	5,2	5,1	5,0	6,0	6,6	7,0	7,4	7,9	8,5	7,9	7,7	7,3	6,9	7,1	7,3	8,1	9,0	8,9	8,6	7,3	6,7
	5,8	5,3	5,0	4,9	4,8	4,8	5,7	6,1	6,6	6,9	7,0	7,1	7,2	7,2	7,1	6,9	6,8	7,1	7,1	9,2	8,8	8,8	7,1	6,1
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	7,4	7,0	7,0	6,9	6,8	6,7	7,1	7,6	8,9	9,9	10,4	10,7	11,3	11,0	10,1	10,3	10,2	10,8	11,0	12,0	11,9	11,0	10,1	9,1
	8,7	7,6	7,5	7,2	7,0	7,0	7,1	7,8	8,4	9,4	10,2	10,5	10,6	10,7	10,0	9,6	9,4	9,5	9,8	11,2	10,9	10,1	9,2	8,2

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Week 9	7,9	6,8	6,2	6,2	6,2	6,2	6,5	7,7	8,4	8,9	9,3	9,0	9,2	9,4	9,0	8,6	8,9	9,4	9,6	12,1	12,0	11,5	10,0	9,0
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	7,0	6,2	6,1	6,0	5,7	5,8	6,3	6,5	7,4	7,9	8,1	8,3	8,5	8,2	7,9	7,4	7,4	7,6	7,7	9,6	9,3	8,4	7,4	6,7
Week 10	5,8	5,5	5,3	5,0	5,0	5,2	5,5	6,6	7,4	7,9	8,5	8,7	8,7	8,3	7,7	8,0	8,2	8,3	8,7	10,0	9,9	9,6	7,6	6,6
	5,7	5,5	5,3	5,2	5,0	5,0	5,8	6,7	7,5	7,8	8,6	8,5	8,5	8,4	8,1	7,9	8,0	8,1	8,2	10,5	10,2	9,7	7,5	6,8
	5,8	5,3	5,2	5,1	5,1	5,0	5,7	6,8	7,5	8,1	8,7	8,8	8,3	8,3	8,3	8,2	8,3	8,4	8,5	10,2	10,1	9,2	8,1	7,0
	6,2	5,7	5,4	5,3	5,2	5,4	6,0	7,0	8,0	8,4	8,7	8,6	8,7	8,5	8,5	8,4	8,4	8,8	8,8	11,0	10,7	9,9	8,4	7,7
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	6,9	6,2	5,7	5,6	5,4	5,5	6,0	7,0	8,3	8,6	9,0	9,1	9,1	8,8	8,7	8,6	8,7	8,7	9,7	11,5	11,2	10,5	9,0	8,3
	7,0	6,3	5,9	5,6	5,5	5,7	5,9	7,1	8,4	8,4	9,1	9,2	9,2	9,1	8,7	8,7	9,0	8,2	9,0	10,2	10,0	9,3	8,2	7,4
Week 11	6,7	5,8	5,6	5,5	5,5	5,7	6,5	7,5	8,1	8,4	8,6	8,6	8,9	8,7	8,6	8,5	8,5	8,6	8,9	10,5	10,3	9,6	8,5	7,7
	6,8	6,3	5,7	5,5	5,6	5,7	6,2	6,9	7,8	8,6	8,9	9,5	9,0	8,8	8,7	8,5	8,6	8,9	9,2	11,0	11,0	10,3	9,5	7,9
	6,9	6,1	5,9	5,7	5,8	5,8	6,4	7,3	8,0	8,7	8,9	9,1	8,1	8,8	9,0	9,0	8,7	8,6	9,0	11,6	11,2	10,4	9,0	7,8
	6,8	6,2	5,9	5,7	5,7	5,8	6,5	7,3	8,3	8,8	9,5	9,3	9,1	9,4	9,1	9,0	8,5	9,0	9,5	11,7	11,4	11,0	8,9	8,0
	6,9	6,1	6,0	5,9	5,8	5,9	6,4	7,6	8,5	9,0	9,2	9,4	9,5	9,3	9,0	9,3	9,3	9,4	9,5	12,7	12,5	11,7	9,7	8,5
	7,5	7,0	6,8	6,8	6,7	6,5	6,8	7,5	9,0	9,5	10,2	10,1	10,4	10,2	9,7	9,8	9,5	9,8	9,8	11,1	13,2	12,4	9,0	9,4
	8,2	7,5	6,9	6,9	6,6	6,7	7,1	8,9	9,4	8,9	10,3	10,4	10,2	9,9	9,8	9,7	9,9	10,3	10,9	13,0	12,7	12,2	10,6	9,4
Week 12	8,4	7,5	7,0	6,8	6,7	6,8	7,8	8,3	10,0	10,6	11,0	11,2	11,1	11,1	10,9	10,6	10,3	10,8	11,1	14,0	13,9	13,0	11,3	9,6
	8,7	7,5	7,3	7,1	7,1	7,2	7,5	8,5	9,8	10,5	10,7	11,3	11,4	11,5	11,6	11,7	11,8	12,5	12,5	14,6	13,3	14,5	10,8	10,7
	9,4	8,3	8,0	7,7	7,6	7,7	8,1	9,6	10,6	12,0	12,3	12,4	13,1	12,4	11,7	11,4	11,1	11,4	12,4	15,5	15,3	15,0	11,9	11,8
	10,2	9,2	8,7	8,1	7,9	8,1	8,6	10,2	11,7	12,4	12,7	12,9	13,1	12,8	12,5	12,1	12,2	12,4	17,1	14,6	16,9	16,4	14,5	12,7
	11,3	10,0	9,4	8,8	8,6	8,7	8,6	9,8	10,8	12,4	13,1	13,1	12,9	13,0	13,0	12,6	12,5	13,0	13,8	18,2	18,0	16,5	14,8	13,9
	12,5	11,5	10,6	9,9	9,8	9,6	10,0	10,9	12,3	13,2	14,0	14,8	14,9	14,9	14,5	14,3	14,5	14,8	15,5	22,4	15,7	21,4	19,1	15,3
	13,5	13,9	13,0	11,7	10,6	10,3	9,8	10,9	12,4	13,3	14,2	14,3	14,0	13,5	13,0	12,5	11,7	11,8	12,5	17,9	17,6	10,9	16,2	14,9

2005	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
Week 13	12,7	11,4	10,4	10,2	9,7	9,3	9,6	10,6	11,7	12,7	13,4	13,8	13,7	13,5	13,0	12,7	12,5	12,2	13,1	17,2	17,0	16,2	14,3	13,8
	11,2	10,0	9,7	8,6	8,4	8,3	9,3	10,4	11,6	12,2	13,3	13,2	13,5	13,3	12,6	12,1	11,2	11,5	12,8	16,0	15,6	14,6	12,9	11,7
	9,8	8,7	8,1	7,5	7,4	7,5	8,0	9,5	11,5	11,9	12,6	12,8	12,5	12,1	11,8	11,4	11,6	11,8	12,7	15,2	14,9	14,4	12,2	10,8
	9,4	8,4	8,1	7,6	7,4	7,5	7,7	9,0	10,5	11,2	11,7	12,3	12,0	12,1	11,8	11,5	11,2	11,4	12,6	15,2	14,8	14,2	12,3	10,9
	9,2	8,3	7,6	7,4	7,3	7,2	7,8	9,0	10,3	11,1	11,7	12,1	12,1	12,2	11,8	11,3	11,3	11,9	12,2	14,9	14,6	14,5	12,5	11,3
	9,5	8,6	8,1	8,0	7,8	7,5	7,7	9,1	10,2	10,7	12,3	12,4	12,2	12,1	11,9	11,6	11,5	11,5	11,8	15,2	14,9	14,2	12,7	10,7
	9,7	8,6	8,1	7,9	7,7	7,8	7,8	8,7	10,3	10,6	11,4	12,0	12,0	11,9	11,5	10,8	10,3	10,5	10,7	14,2	14,0	13,5	12,1	10,3
Week 14	9,0	8,0	7,8	7,4	7,2	7,2	7,8	8,6	10,4	10,8	11,6	11,9	11,9	11,9	11,4	11,1	10,9	10,9	11,6	14,5	14,3	13,5	12,3	10,4
	9,0	8,4	7,8	7,4	7,1	7,2	7,9	9,0	10,3	10,9	11,7	11,5	12,0	12,0	11,3	10,9	10,7	11,0	11,2	12,2	14,1	13,4	11,5	9,8
	9,0	7,8	7,6	7,2	7,0	7,0	7,4	8,9	10,1	10,8	11,1	11,4	11,6	11,4	11,2	10,8	10,9	11,1	11,4	13,9	13,6	13,5	11,6	10,1
	8,8	8,0	7,6	7,3	7,3	7,0	7,6	9,0	10,6	10,9	12,1	12,2	12,0	12,0	12,0	11,4	11,2	11,6	12,3	14,6	14,5	14,0	12,2	10,3
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Week 15	9,5	8,7	8,0	7,8	7,4	7,5	7,5	8,7	10,3	10,7	11,7	12,1	12,0	12,2	11,9	11,6	11,3	11,9	12,5	13,1	15,1	14,4	12,7	11,3
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	11,5	10,2	9,3	8,6	8,6	8,5	9,4	10,2	11,5	12,6	13,2	14,2	14,9	14,7	14,4	14,0	13,7	13,3	14,3	15,4	18,2	16,5	14,5	13,2
	11,8	11,1	5,8	9,2	9,0	8,8	8,8	10,5	11,4	12,8	14,5	14,4	14,3	14,3	12,9	13,0	12,6	12,6	12,9	13,3	16,7	16,6	14,3	12,5
Week 16	11,1	10,1	9,1	8,6	8,6	8,4	9,0	10,3	11,8	12,7	13,3	13,7	13,9	13,8	13,2	13,3	13,0	13,1	13,4	14,5	17,2	15,8	13,9	12,4
	10,5	9,7	8,8	8,3	8,1	8,0	9,0	10,5	12,0	12,9	13,4	14,0	14,1	13,4	13,0	12,8	12,3	12,5	13,1	13,6	16,5	16,0	13,2	11,5
	10,0	9,1	8,6	8,1	7,9	7,9	9,1	10,3	12,0	12,8	13,7	13,7	13,7	13,5	13,1	12,7	12,3	12,0	12,8	14,3	15,0	14,4	12,8	11,3
	9,8	8,7	8,1	8,0	7,8	7,7	9,1	10,3	11,9	13,0	13,9	14,1	13,9	13,6	12,6	12,1	11,8	12,0	12,6	14,4	15,8	15,3	13,4	11,7
	9,8	8,9	8,7	8,5	8,3	7,9	8,9	9,7	11,5	12,5	13,0	13,7	14,2	13,5	12,9	12,6	12,5	13,0	13,3	15,0	17,6	16,9	14,4	12,8
	11,2	10,3	9,3	8,9	8,6	8,4	9,2	10,6	11,7	12,4	13,1	14,1	14,5	14,5	14,0	14,9	14,6	14,4	16,2	17,0	19,8	18,0	16,6	13,8
	12,4	11,3	10,3	9,8	9,6	9,6	9,8	11,1	12,6	14,2	15,0	15,6	16,1	15,8	14,9	14,5	13,2	13,8	14,8	15,2	18,0	17,0	15,6	14,3

10.6 Fuel Consumption

Arguably, among the most important aspects of any Genset is the Specific Fuel Oil consumption (gr/Kwh). This is the reason that detailed measurement tests according to ISO standards are carried out during the delivery phase. If not for a Genset to meet manufacturers guaranteed consumption, penalties incur. Usually, Fuel consumption is measured at 3 operating points namely 50%, 75% and 100% of nominal output and a quadratic curve is realized. This curve is the single most important item for a reliable solution to the Economic Dispatch problem. But, generally it is not that simple.

First of all we must state that even for ultimately the same kind of brand new Gensets, fuel consumption differences do exist in practice (in some instances deviation escalates up to 3%). This deviation may also be false, resulting from poor implementation of measurement procedures, faults in measurement equipment or other reasons. In any case and whatever the reason, the important point is that what we perceive as real (gr/Kwh curve) is not that real. But, since measurement tests in ISO conditions are laborious and costly (hence hardly ever are repeated) we accept the curves as real and for the years to come serve as a reference point.

Having in our disposal a Specific Fuel Oil Consumption curve, what is just left to do is simply insert it the proper way in the model. But generally it is not that simple.

Any sfo curve refers to ideal situations where everything is brand new. Not to argue, after some thousands of operating hours, equipment deteriorates and as a result sfo naturally changes (worsens). The original sfo curve in that case is simply misleading and compensation is mandatory.

Someone could think that we should carry out new measurement tests, say every year after major overhauls. This approach is costly and impractical for many reasons and in practice is disregarded. A better approach could obviously be for a power plant to install state of the art real time fuel metering devices for each Genset. But still, the problem is not solved.

When we schedule maintenances, Gensets in respect realize current operating status and suppose we know the exact current Fuel Oil Consumption. But we must always have in mind that these Gensets run at best on some leftover running hours. And as a result of the overall degraded operation condition, fuel consumption is highly possible to even worsen during operation and what matters the most, upon maintenance outage. It is clear that sfo curve can only serve simply just as guidance for Fuel Oil Consumption comparison among Gensets. The latter is crucial since small deviations from sfo curve are hence allowed.

Finally, despite the best scenario involves small deviations big deviations can easily be introduced during actual operation, with high overall impact. In any case, deviations one way or another in practice are to be realized, describing an aspect of inherent difficulty.

10.6.1 Genset N°1

Case presented in chapter 9

10.6.2 Genset N°2

Genset No2 with 5.880 Mw nominal power runs on Diesel oil and the Specific Fuel Consumption curve is depicted in figure below. Genset is in good working condition and as a result output is set to 95% of NP, namely 5.586Mw.

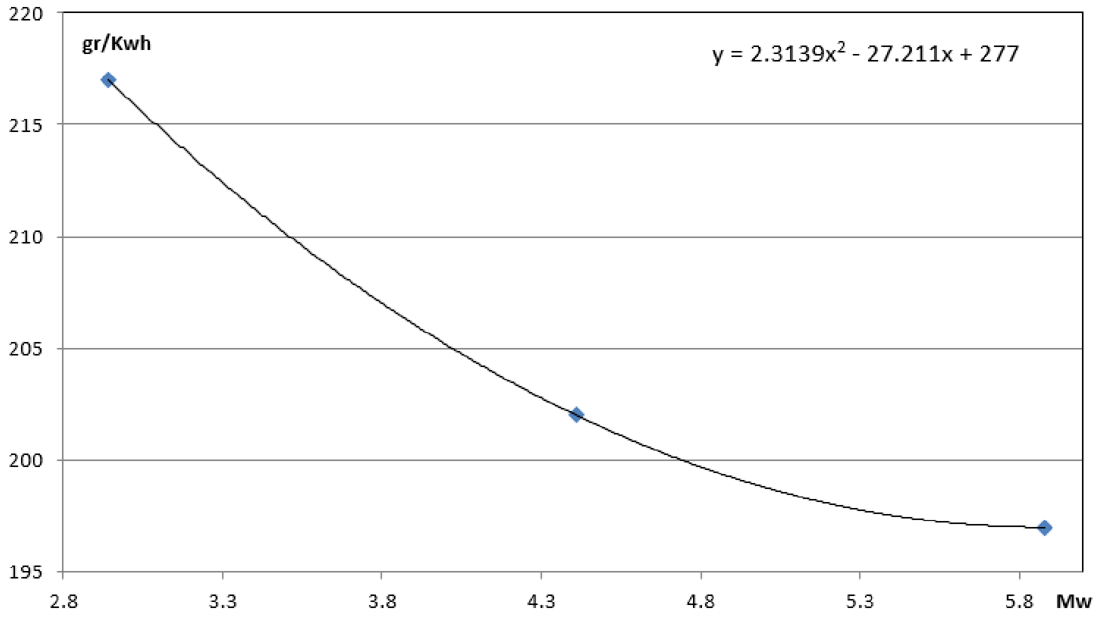


Figure 10-1: Genset N°2 Specific Fuel Consumption (Quadratic function)

Fuel consumption is depicted in figure below.

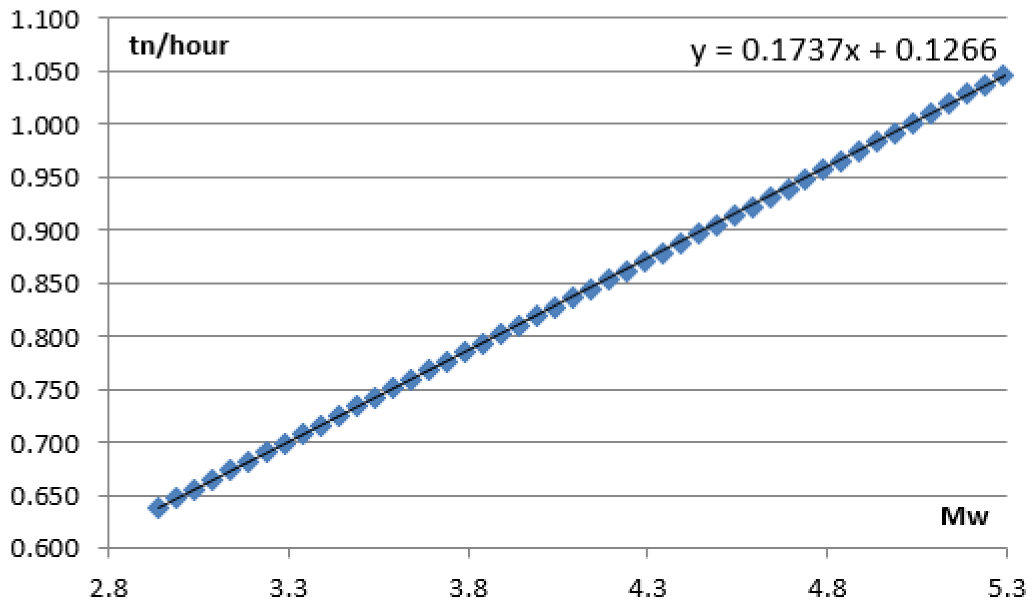


Figure 10-2: Genset N°2 Fuel Consumption (Linear Approximation)

Within the technical minimum and set maximum Output band, linear approximation in respect to real Specific Fuel Consumption deviates within acceptable limits (see figure below). Other than that, technical minimum is set to 50% of NP that is 2.940Mw.

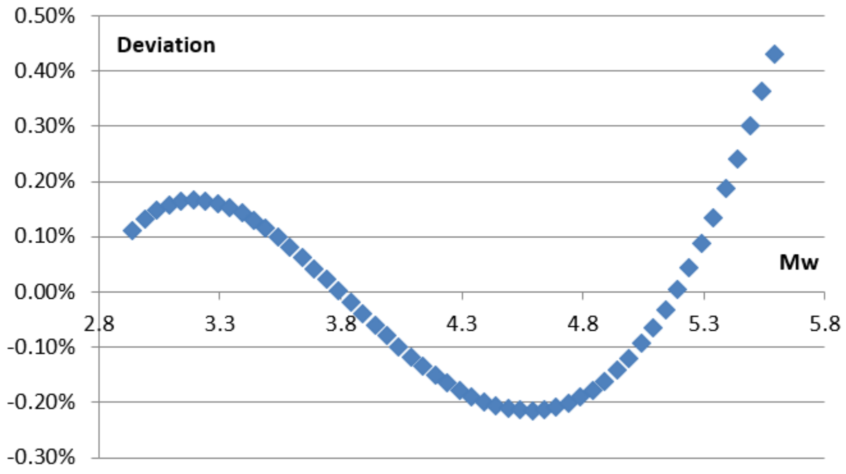


Figure 10-3: Genset N° 2 Linear model % deviation

10.6.3 Genset N°3

Genset N^{o}3 exhibits almost same characteristics with N^{o}2, since same models but there exists a slight difference in efficiency. Genset is in good working condition and as a result output is set to 95% of NP, namely 5.586Mw.

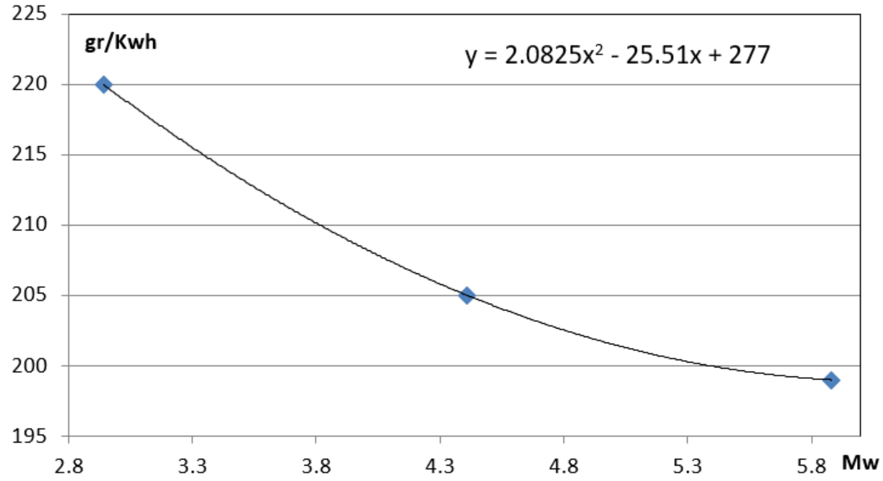


Figure 10-4: Genset N^{o}3 Specific Fuel Consumption (Quadratic function)

Fuel consumption is depicted in figure

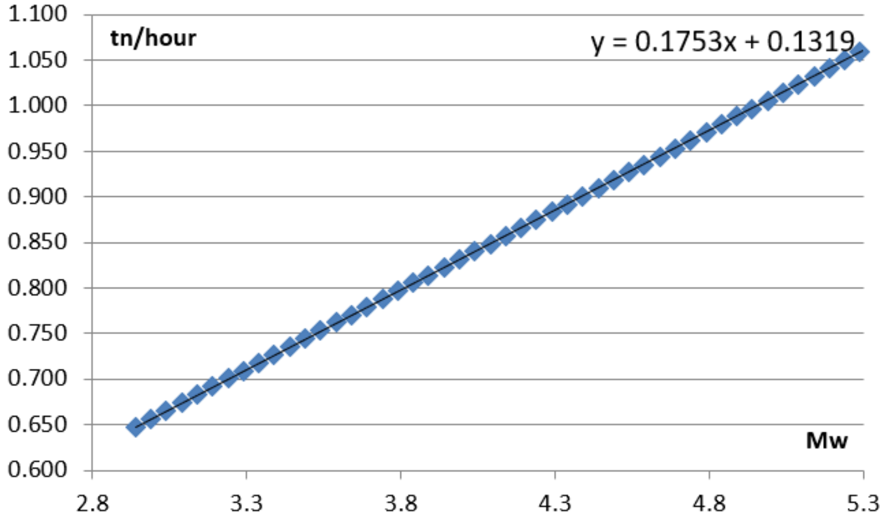


Figure 10-5: Genset N^{o}3 Fuel Consumption (Linear Approximation)

Within the technical minimum and set maximum Output band, linear approximation in respect to real Specific Fuel Consumption deviates within acceptable limits (see figure below). Other than that, technical minimum is set to 50% of NP that is 2.940Mw.

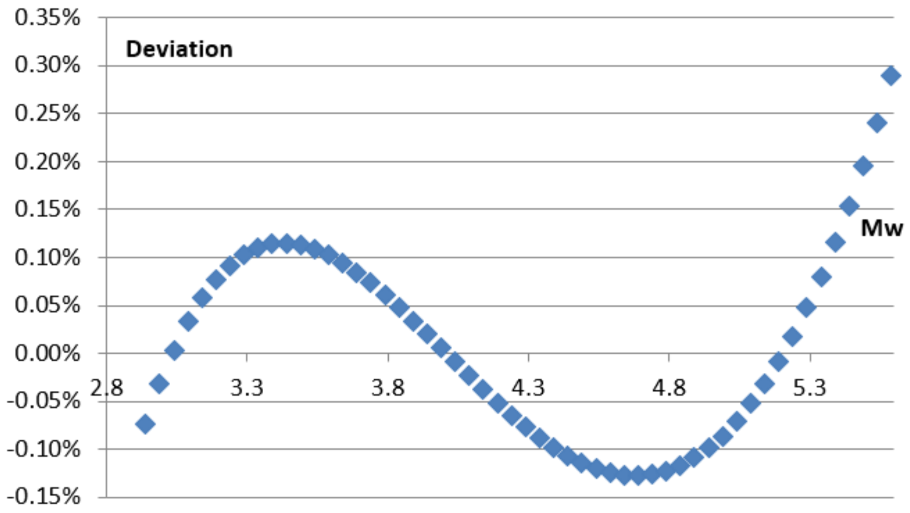


Figure 10-6: Genset N° 3 Linear model % deviation

10.6.4 Genset No4

Genset N°4 with 5.327 Mw nominal power runs on Diesel oil and the Specific Fuel Consumption curve is depicted in figure below. Genset is in good working condition and as a result output is set to 95% of NP, namely 5.061Mw.

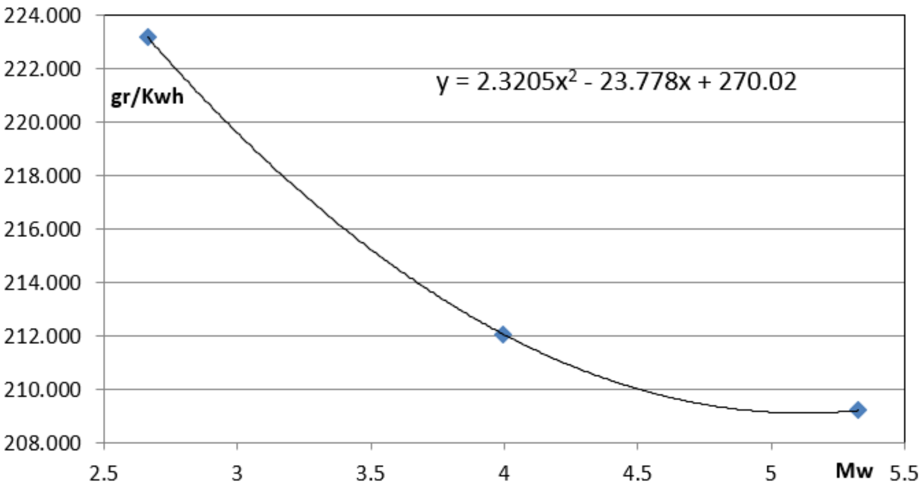


Figure 10-7: Genset N°4 Specific Fuel Consumption (Quadratic function)

Fuel consumption is depicted in figure below.

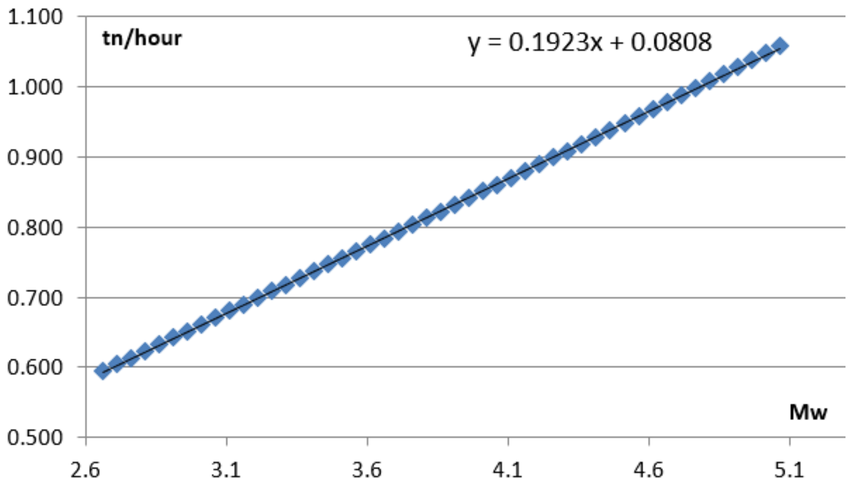


Figure 10-8: Genset N^{o}4 Fuel Consumption (Linear Approximation)

Within the technical minimum and set maximum Output band, linear approximation in respect to real Specific Fuel Consumption deviates within acceptable limits (see figure below). Other than that, technical minimum is set to 50% of NP that is 2.664Mw.

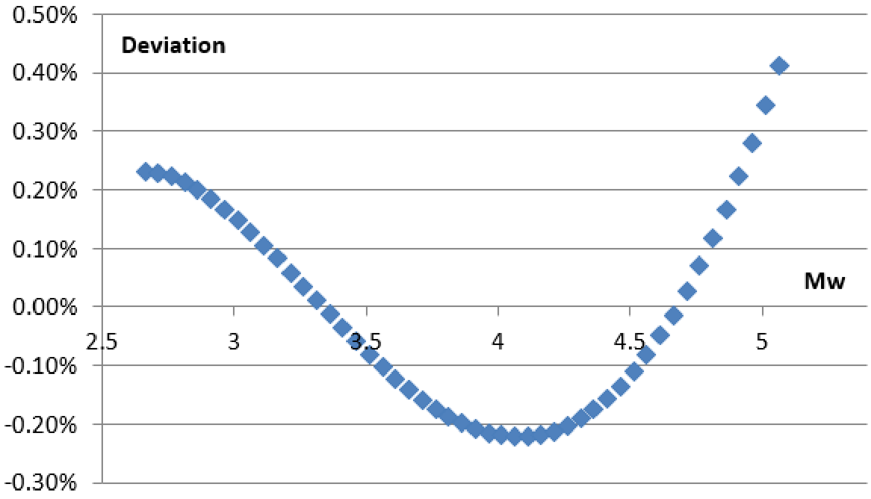


Figure 10-9: Genset N^o 4 Linear model % deviation

10.6.5 Genset No5

Genset N^{o}5 with 2.260 Mw nominal power runs on Heavy Fuel oil and the Specific Fuel Consumption curve is depicted in figure below. Genset is in good working condition and as a result output is set to 95% of NP, namely 2.147Mw.

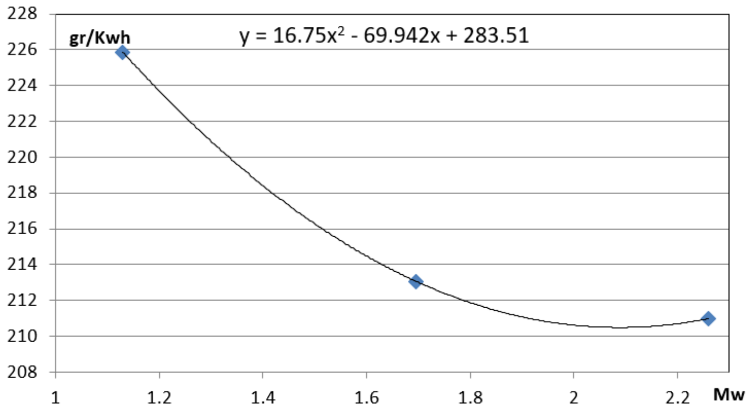


Figure 10-10: Genset N^{o}5 Specific Fuel Consumption (Quadratic function)

Same as Genset N^{o}1, thanks to the acute “hook shape” Specific Fuel Consumption curve, this Genset when linearly modeled (see figure below)

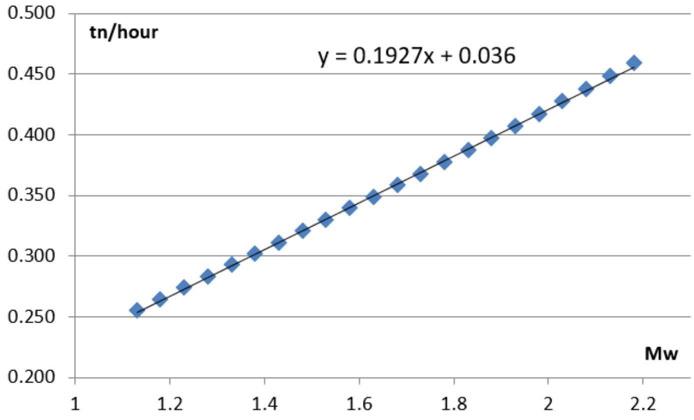


Figure 10-11: Genset N^{o}5 Fuel Consumption (Linear Approximation)

exhibits higher deviations in respect to other Gensets but within acceptable limits (see figure below).

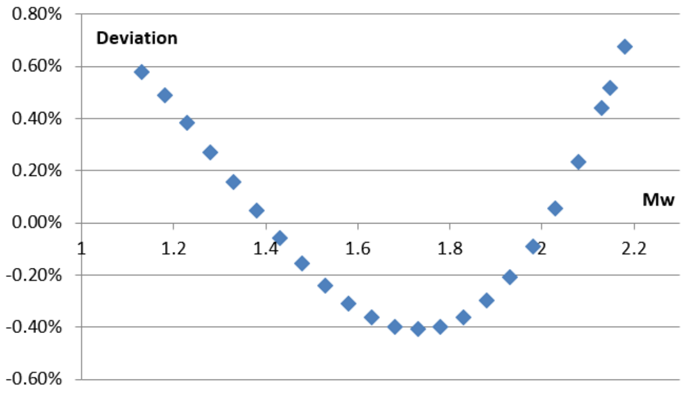


Figure 10-12: Genset N^{o} 5 Linear model % deviation

10.6.6 Genset No6

N^{o}6 is a high speed Genset with 1.250 Mw nominal power running on Diesel oil and the Specific Fuel Consumption curve is depicted in figure below. Genset is under acceptable working condition but there is concern about high exhaust gas temperatures near NP output. As a result, output is set to 90% of NP, namely 1.125Mw.

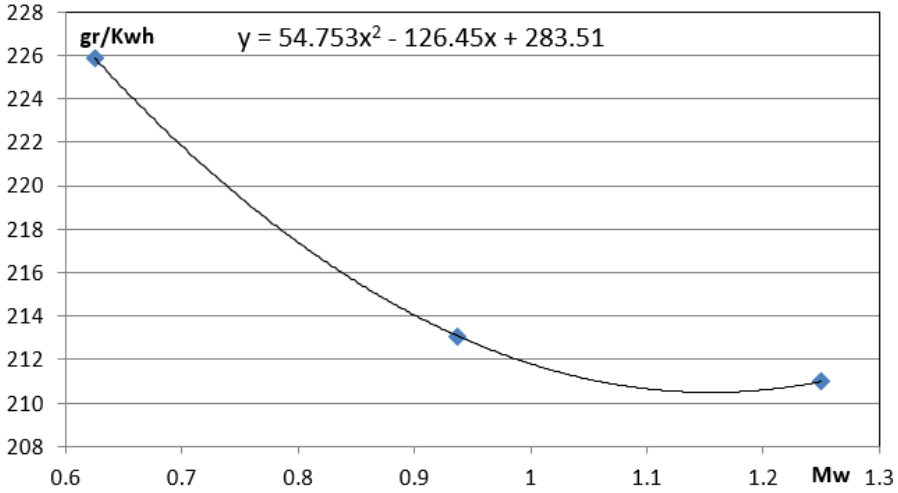


Figure 10-13: Genset N^{o}6 Specific Fuel Consumption (Quadratic function)

Fuel consumption is depicted in figure below.

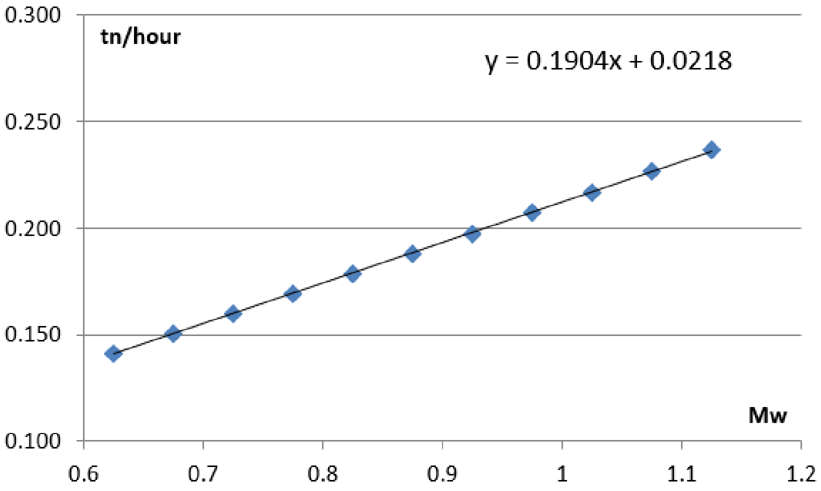


Figure 10-14: Genset N^{o}6 Fuel Consumption (Linear Approximation)

Within the technical minimum and set maximum Output band, linear approximation in respect to real Specific Fuel Consumption deviates within acceptable limits (see figure below). Other than that, technical minimum is set to 50% of NP that is 0.625Mw.

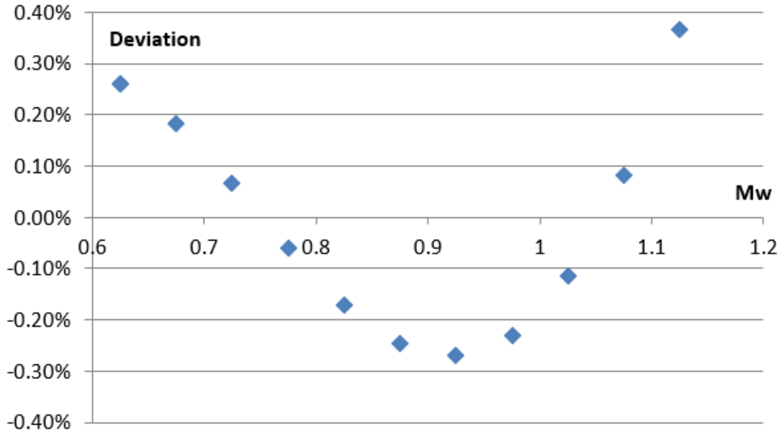


Figure 10-15: Genset N° 6 Linear model % deviation

10.6.7 Genset No7

Genset N°7 with 5.500 Mw nominal power runs on Heavy Fuel oil and the Specific Fuel Consumption curve is depicted in figure below. Genset is not in good working condition due to severe crankshaft damage and as a result output is empirically set to 80% of NP, namely 4.400Mw.

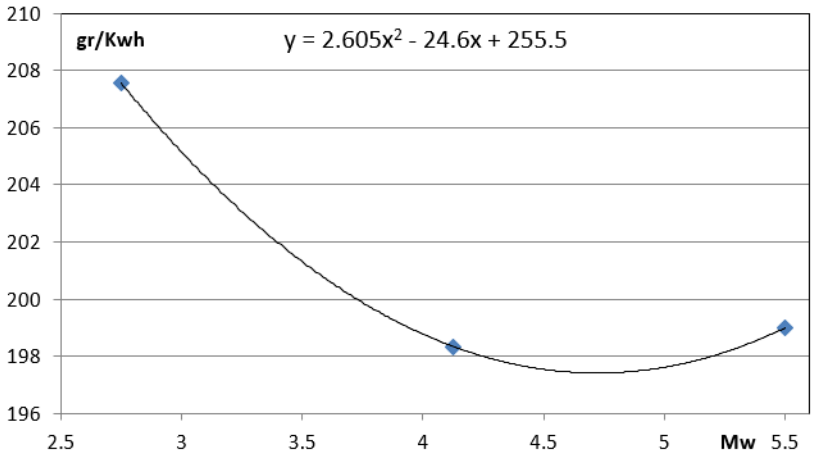


Figure 10-16: Genset N°7 Specific Fuel Consumption (Quadratic function)

Fuel consumption is depicted in figure below.

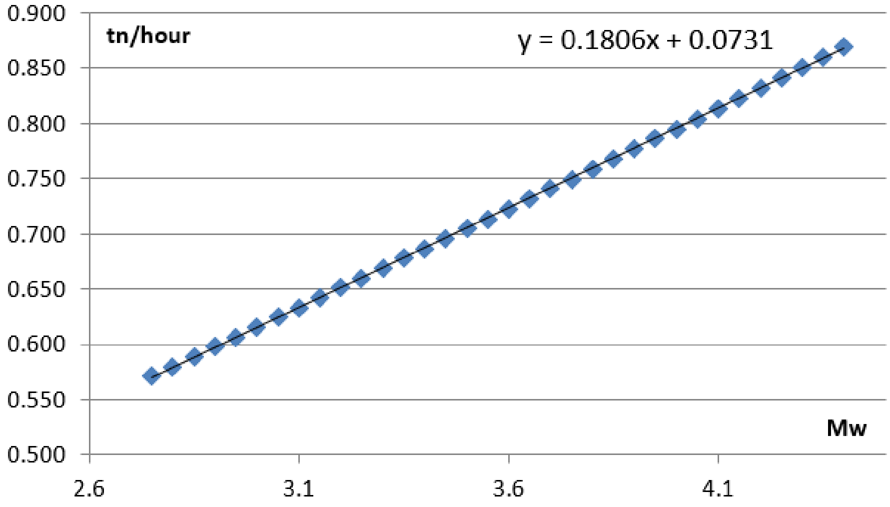


Figure 10-17: Genset N°7 Fuel Consumption (Linear Approximation)

Within the technical minimum and set maximum Output band, linear approximation in respect to real Specific Fuel Consumption deviates within acceptable limits (see figure below). Other than that, technical minimum is set to 50% of NP that is 2.750 Mw.

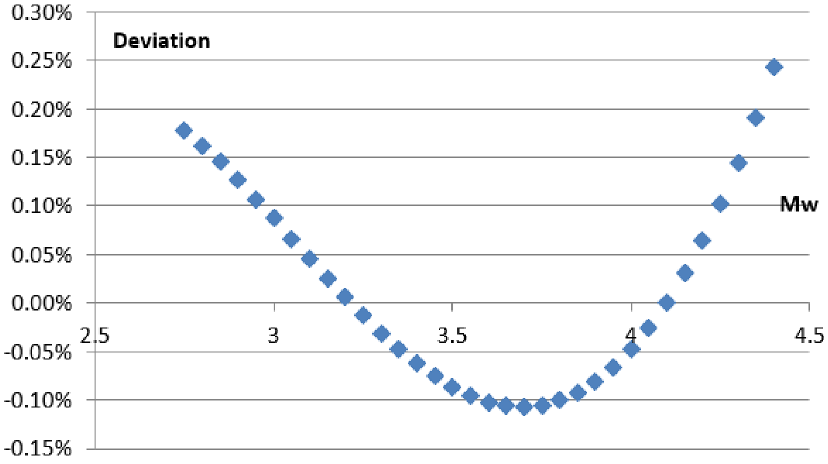


Figure 10-18: Genset N° 7 Linear model % deviation

10.7 Fuel calculating efficiency

10.7.1 50% test run

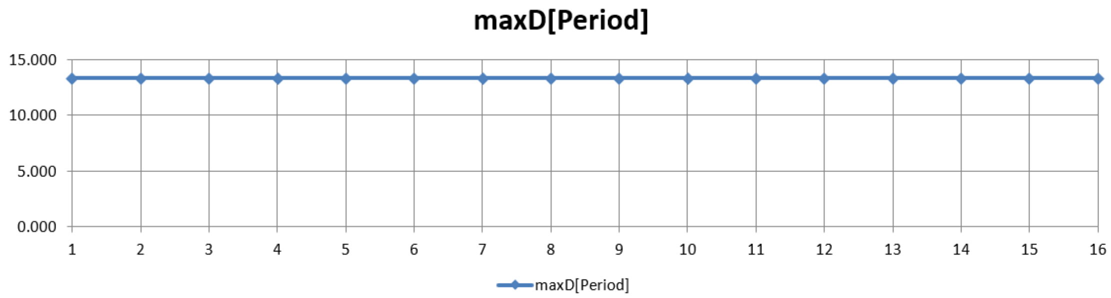
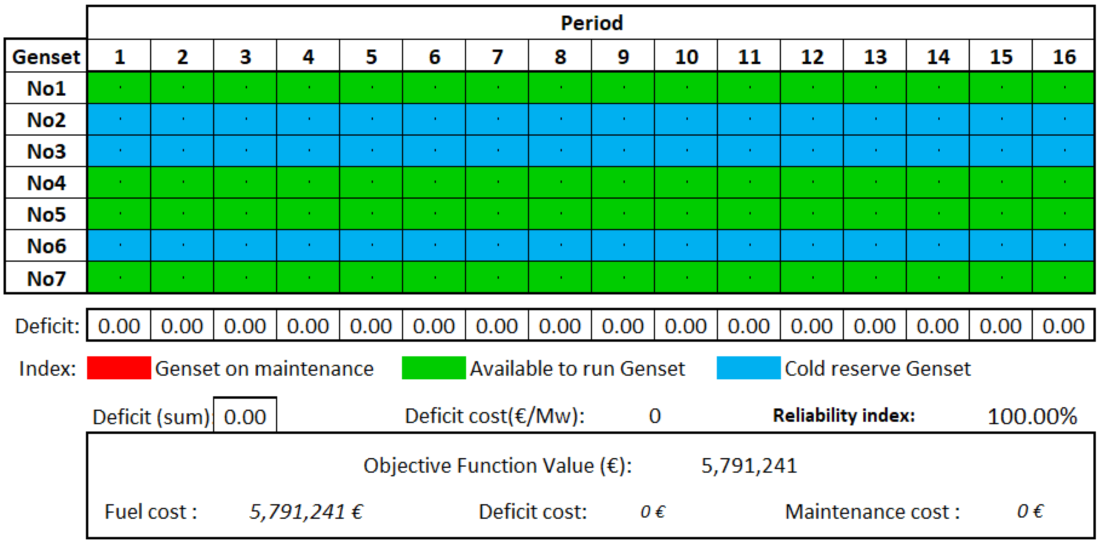


Figure 10-19: (50% run) Stable system demand



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No2	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
No3	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
No4	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No6	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
No7	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Deficit:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

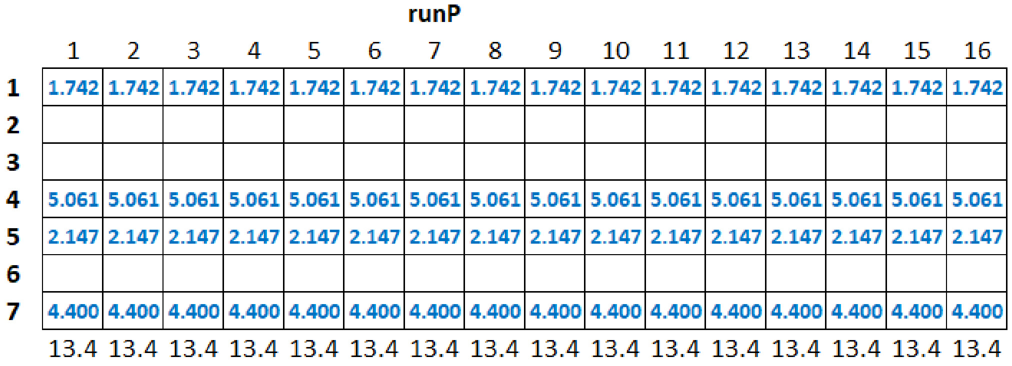
Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

Deficit (sum): 0.00 Deficit cost(€/Mw): 0 **Reliability index:** 100.00%

Objective Function Value (€): 5,791,241

Fuel cost : *5,791,241 €* Deficit cost: *0 €* Maintenance cost : *0 €*

Figure 10-20: (50% run) Scheduling output



runP

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1.742	1.742	1.742	1.742	1.742	1.742	1.742	1.742	1.742	1.742	1.742	1.742	1.742	1.742	1.742	1.742
2																
3																
4	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061
5	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147
6																
7	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400
	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4

Figure 10-21: (50% run) Weekly peak system Gensets loading (same with in classes)

10.7.2 75% run

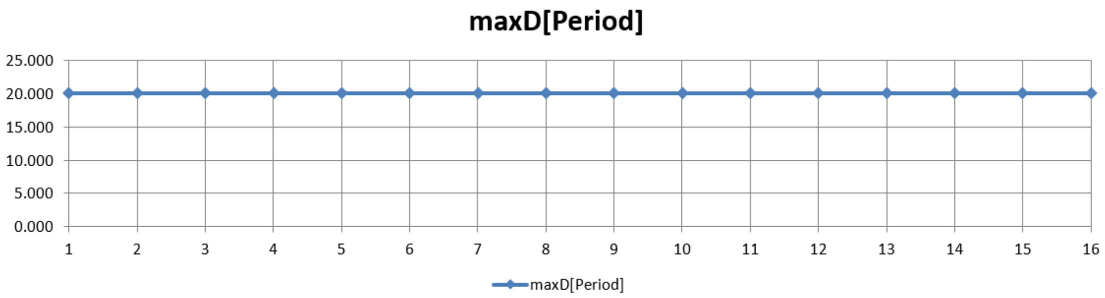
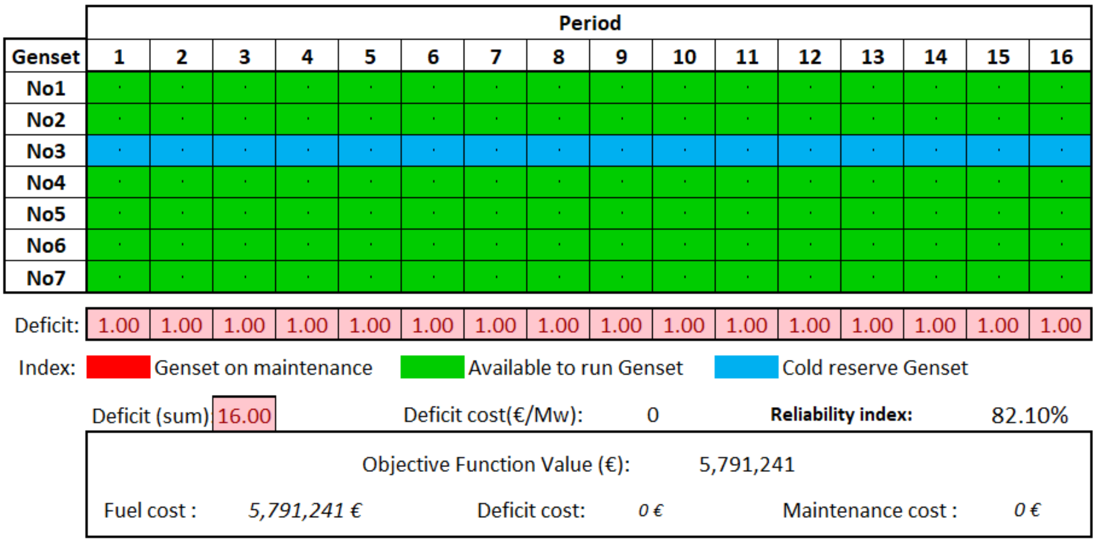


Figure 10-22: (75% run) Stable system demand



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No2	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
No4	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No6	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No7	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Deficit:	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

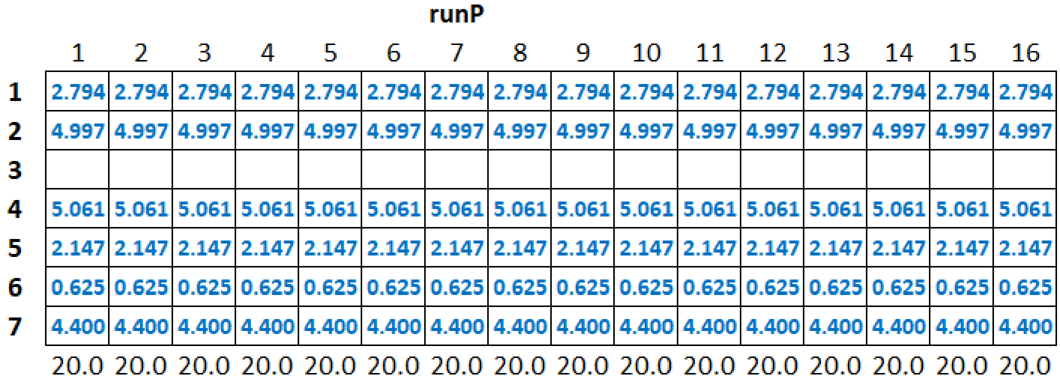
Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

Deficit (sum) 16.00 Deficit cost(€/Mw): 0 **Reliability index:** 82.10%

Objective Function Value (€): 5,791,241

Fuel cost : *5,791,241 €* Deficit cost: *0 €* Maintenance cost : *0 €*

Figure 10-23: (75% run) Scheduling output



runP

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	2.794	2.794	2.794	2.794	2.794	2.794	2.794	2.794	2.794	2.794	2.794	2.794	2.794	2.794	2.794	2.794
2	4.997	4.997	4.997	4.997	4.997	4.997	4.997	4.997	4.997	4.997	4.997	4.997	4.997	4.997	4.997	4.997
3																
4	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061
5	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147
6	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625
7	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400
	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0

Figure 10-24: (75% run) Weekly peak system Gensets loading (same with in classes)

10.7.3 100% run

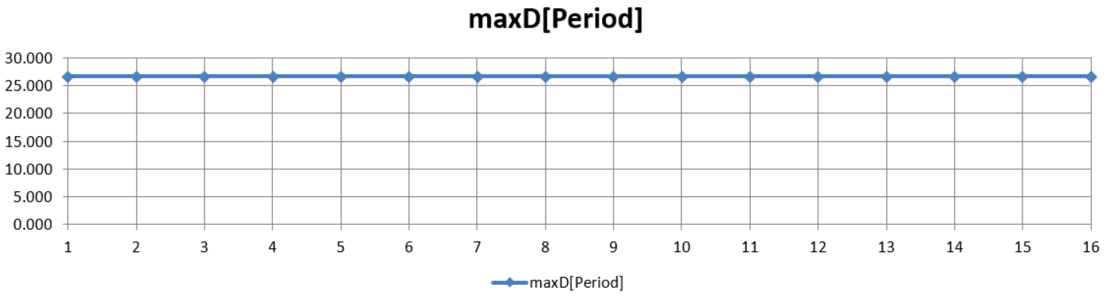
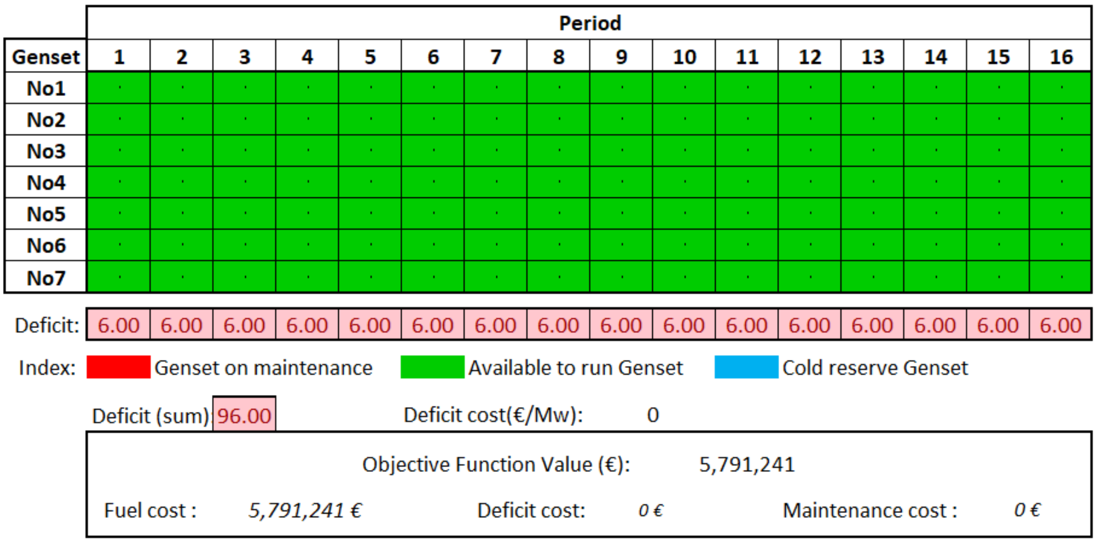


Figure 10-25: (100% run) Stable system demand



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No2	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No4	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No6	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No7	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Deficit:	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00

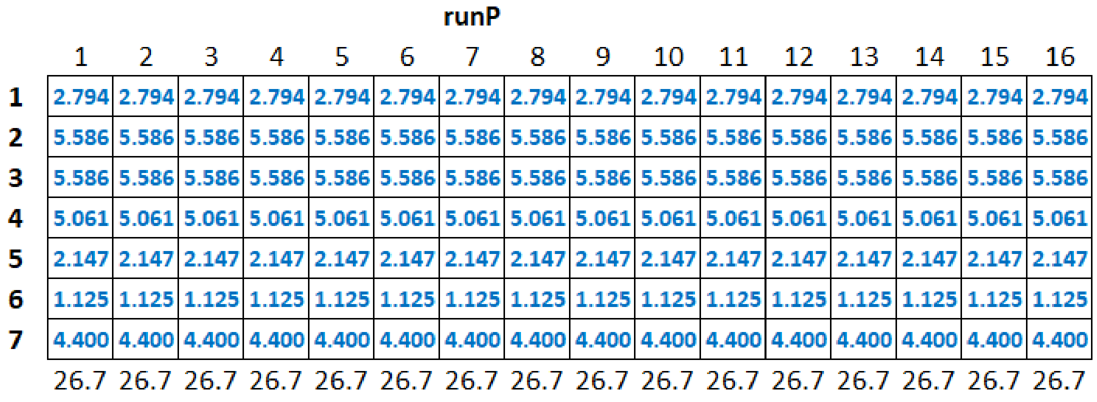
Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

Deficit (sum) 96.00 Deficit cost(€/Mw): 0

Objective Function Value (€): 5,791,241

Fuel cost : *5,791,241 €* Deficit cost: *0 €* Maintenance cost : *0 €*

Figure 10-26: (100% run) Scheduling output



runP

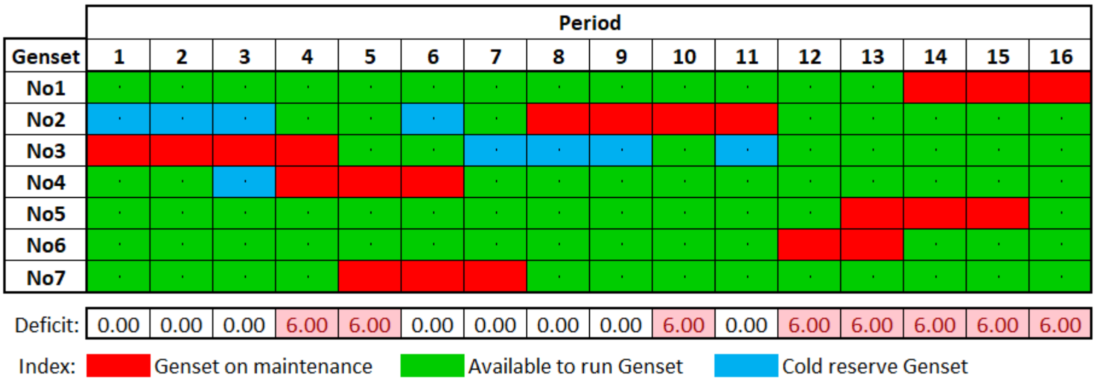
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	2.794	2.794	2.794	2.794	2.794	2.794	2.794	2.794	2.794	2.794	2.794	2.794	2.794	2.794	2.794	2.794
2	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586
3	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586
4	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061	5.061
5	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147	2.147
6	1.125	1.125	1.125	1.125	1.125	1.125	1.125	1.125	1.125	1.125	1.125	1.125	1.125	1.125	1.125	1.125
7	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400	4.400
	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7

Figure 10-27: (100% run) Weekly peak system Gensets loading (same with in classes)

APPENDIX B: GMS+UC

Maximum Nominal power reliability approach

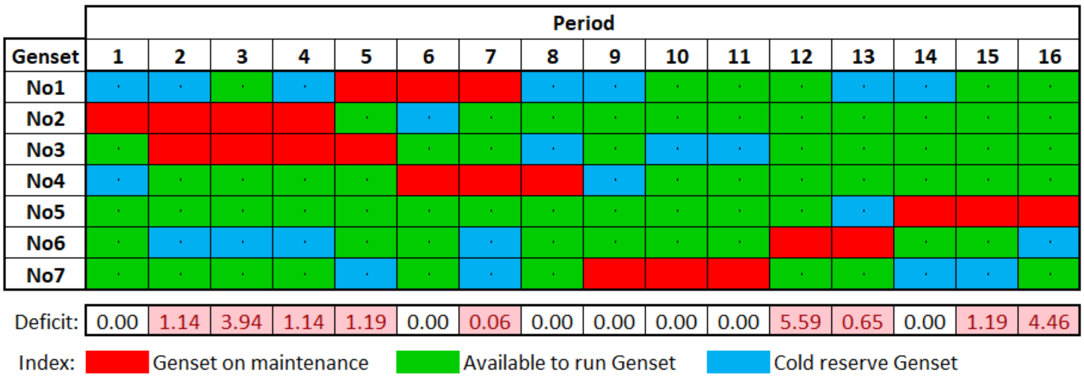
10.8 Scheduling results



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥
No2	🟦	🟦	🟦	🟩	🟩	🟦	🟩	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No3	🟥	🟥	🟥	🟥	🟩	🟩	🟦	🟦	🟦	🟩	🟦	🟩	🟩	🟩	🟩	🟩
No4	🟩	🟩	🟦	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩
No6	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩
No7	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Deficit:	0.00	0.00	0.00	6.00	6.00	0.00	0.00	0.00	0.00	6.00	0.00	6.00	6.00	6.00	6.00	6.00

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

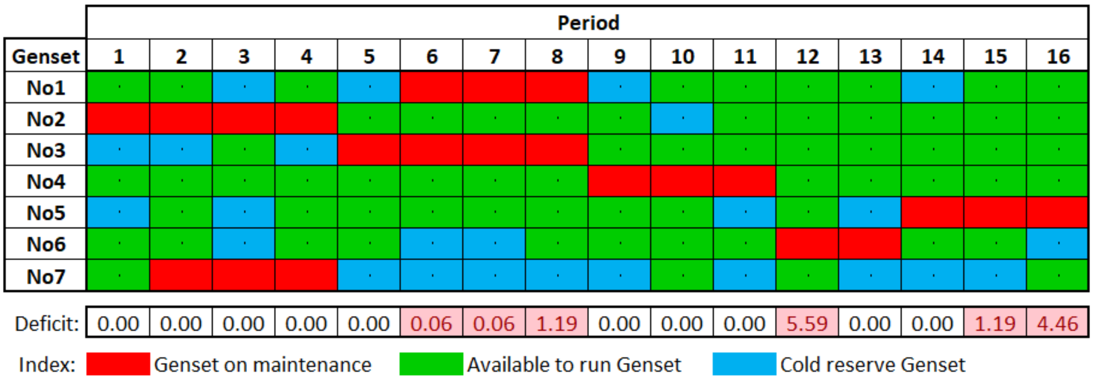
Figure 10-1: Deficit cost 0 €/Mw (Raw output)



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟦	🟦	🟩	🟦	🟥	🟥	🟥	🟦	🟦	🟩	🟩	🟩	🟦	🟦	🟩	🟩
No2	🟥	🟥	🟥	🟥	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟩	🟥	🟥	🟥	🟥	🟩	🟩	🟦	🟩	🟦	🟦	🟩	🟩	🟩	🟩	🟩
No4	🟦	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟥	🟥	🟥
No6	🟩	🟦	🟦	🟦	🟩	🟩	🟦	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟦
No7	🟩	🟩	🟩	🟩	🟦	🟩	🟦	🟩	🟥	🟥	🟥	🟩	🟩	🟦	🟦	🟩
Deficit:	0.00	1.14	3.94	1.14	1.19	0.00	0.06	0.00	0.00	0.00	0.00	5.59	0.65	0.00	1.19	4.46

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

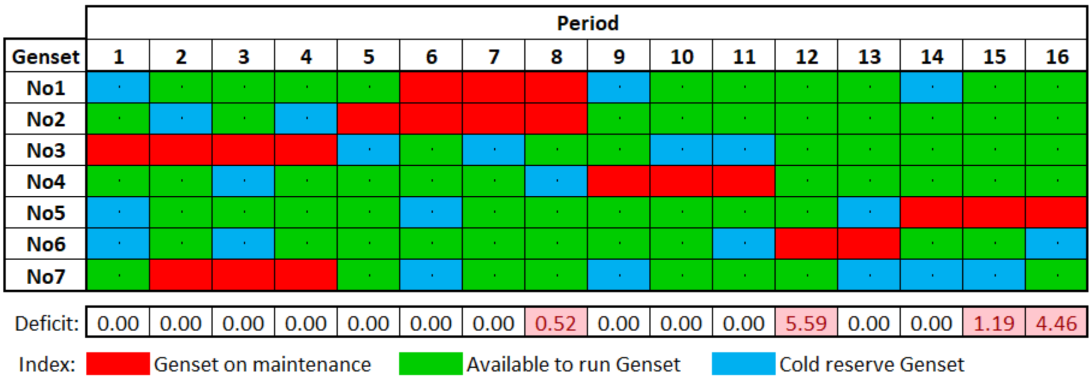
Figure 10-2: Deficit cost 1 €/Mw



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟦	🟩	🟦	🟥	🟥	🟥	🟦	🟩	🟩	🟩	🟩	🟦	🟩	🟩
No2	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟦	🟦	🟩	🟦	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No4	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No5	🟦	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟩	🟦	🟥	🟥	🟥
No6	🟩	🟩	🟦	🟩	🟩	🟦	🟦	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟦
No7	🟩	🟥	🟥	🟥	🟦	🟦	🟦	🟦	🟦	🟩	🟦	🟩	🟦	🟦	🟦	🟩
Deficit:	0.00	0.00	0.00	0.00	0.00	0.06	0.06	1.19	0.00	0.00	0.00	5.59	0.00	0.00	1.19	4.46

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

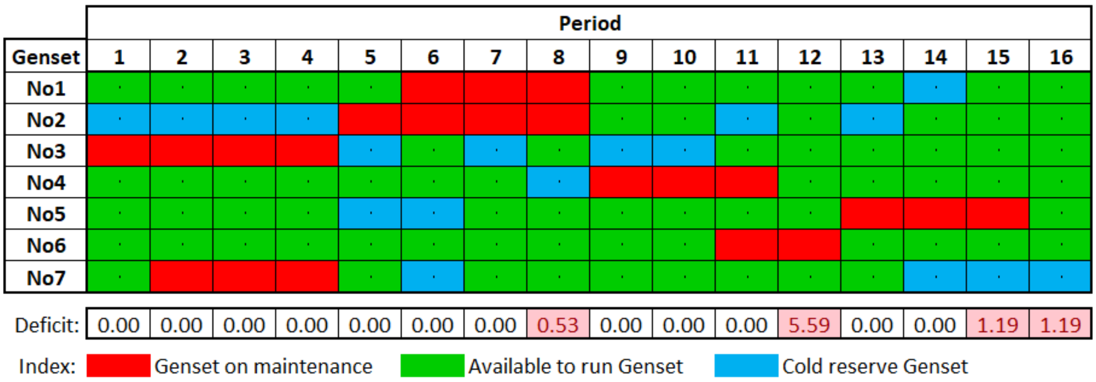
Figure 10-3: Deficit cost 10 €/Mw



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟦	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟦	🟩	🟩	🟩	🟩	🟦	🟩	🟩
No2	🟩	🟦	🟩	🟦	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟥	🟥	🟥	🟥	🟦	🟩	🟦	🟩	🟩	🟦	🟦	🟩	🟩	🟩	🟩	🟩
No4	🟩	🟩	🟦	🟩	🟩	🟩	🟩	🟦	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No5	🟦	🟩	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟥	🟥	🟥
No6	🟦	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟥	🟥	🟩	🟩	🟦
No7	🟩	🟥	🟥	🟥	🟩	🟦	🟩	🟩	🟦	🟩	🟩	🟩	🟦	🟦	🟦	🟩
Deficit:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.52	0.00	0.00	0.00	5.59	0.00	0.00	1.19	4.46

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

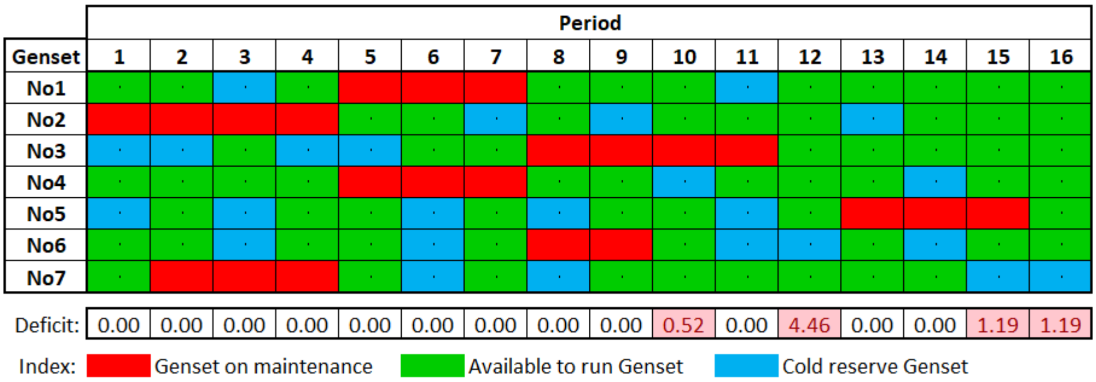
Figure 10-4: Deficit cost 100 €/Mw



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟦	🟩	🟩
No2	🟦	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟩	🟩	🟦	🟩	🟦	🟩	🟩	🟩
No3	🟥	🟥	🟥	🟥	🟦	🟩	🟦	🟩	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟩
No4	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩
No6	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩
No7	🟩	🟥	🟥	🟥	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟦
Deficit:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.00	0.00	0.00	5.59	0.00	0.00	1.19	1.19

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

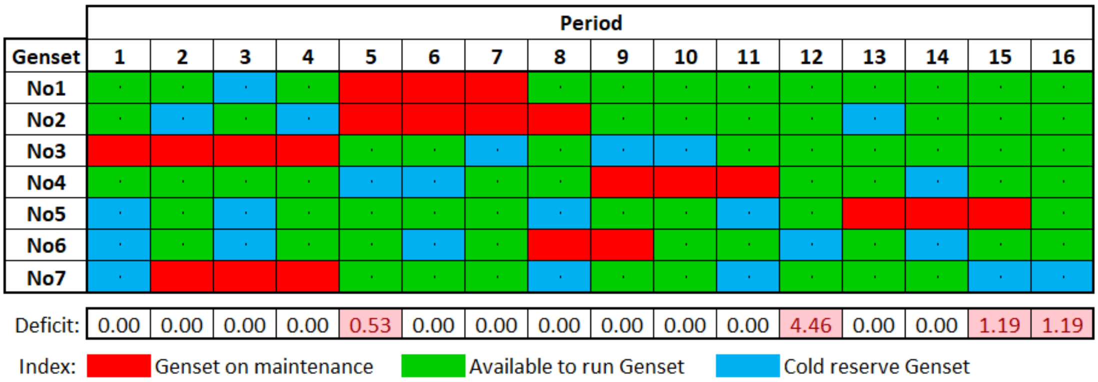
Figure 10-5: Deficit cost 1.000 €/Mw



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟦	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟩	🟩
No2	🟥	🟥	🟥	🟥	🟩	🟩	🟦	🟩	🟦	🟩	🟩	🟩	🟦	🟩	🟩	🟩
No3	🟦	🟦	🟩	🟦	🟦	🟩	🟩	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No4	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟦	🟩	🟩	🟩	🟦	🟩	🟩
No5	🟦	🟩	🟦	🟩	🟩	🟦	🟩	🟦	🟩	🟩	🟦	🟩	🟥	🟥	🟥	🟩
No6	🟩	🟩	🟦	🟩	🟩	🟦	🟩	🟥	🟥	🟩	🟦	🟦	🟩	🟦	🟩	🟩
No7	🟩	🟥	🟥	🟥	🟩	🟦	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟦
Deficit:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.52	0.00	4.46	0.00	0.00	1.19	1.19

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

Figure 10-6: Deficit cost 10.000 €/Mw



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟦	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No2	🟩	🟦	🟩	🟦	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟦	🟩	🟩	🟩
No3	🟥	🟥	🟥	🟥	🟩	🟩	🟦	🟩	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟩
No4	🟩	🟩	🟩	🟩	🟦	🟦	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟦	🟩	🟩
No5	🟦	🟩	🟦	🟩	🟩	🟩	🟩	🟦	🟩	🟩	🟦	🟩	🟥	🟥	🟥	🟩
No6	🟦	🟩	🟦	🟩	🟩	🟦	🟩	🟥	🟥	🟩	🟩	🟦	🟩	🟦	🟩	🟩
No7	🟦	🟥	🟥	🟥	🟩	🟩	🟩	🟦	🟩	🟩	🟦	🟩	🟩	🟩	🟦	🟦
Deficit:	0.00	0.00	0.00	0.00	0.53	0.00	0.00	0.00	0.00	0.00	0.00	4.46	0.00	0.00	1.19	1.19

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

Figure 10-7: Deficit cost 100.000 €/Mw

10.9 System Reserves

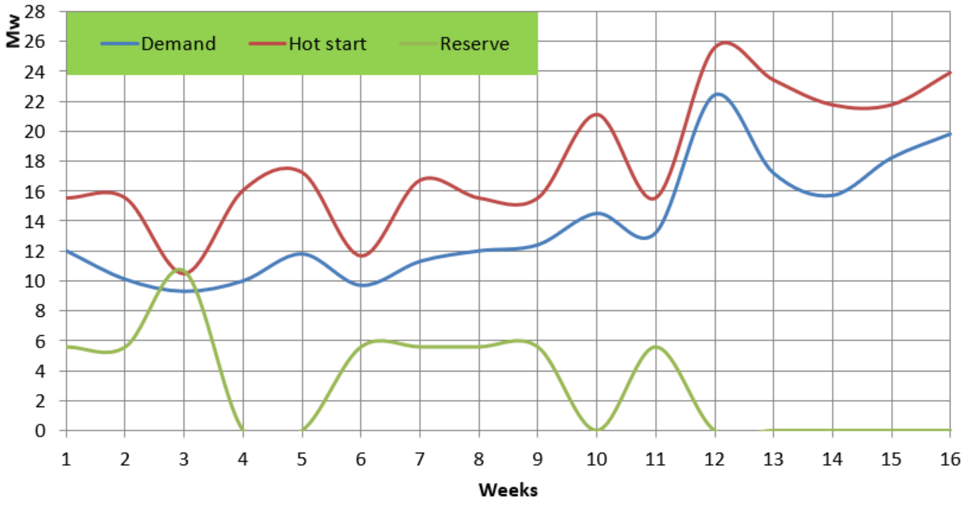


Figure 10-8: Deficit cost 0 €/Mw

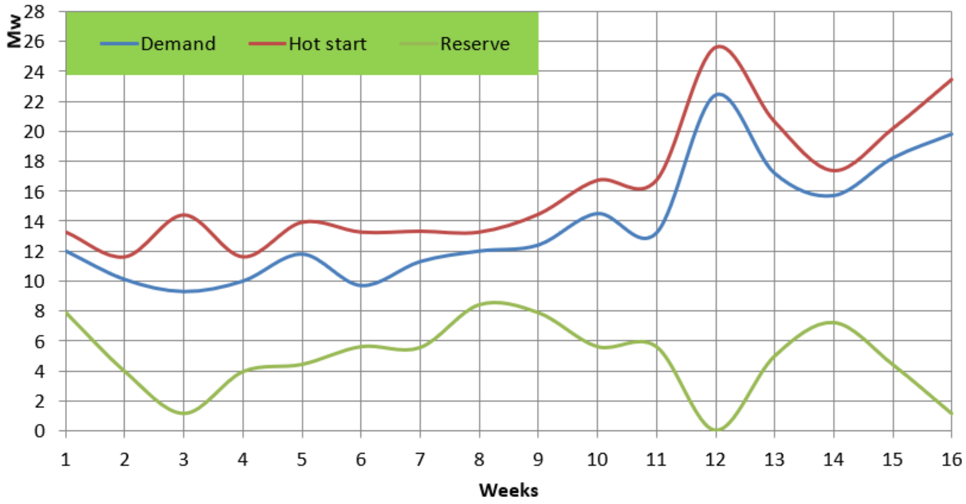


Figure 10-9: Deficit cost 1 €/Mw

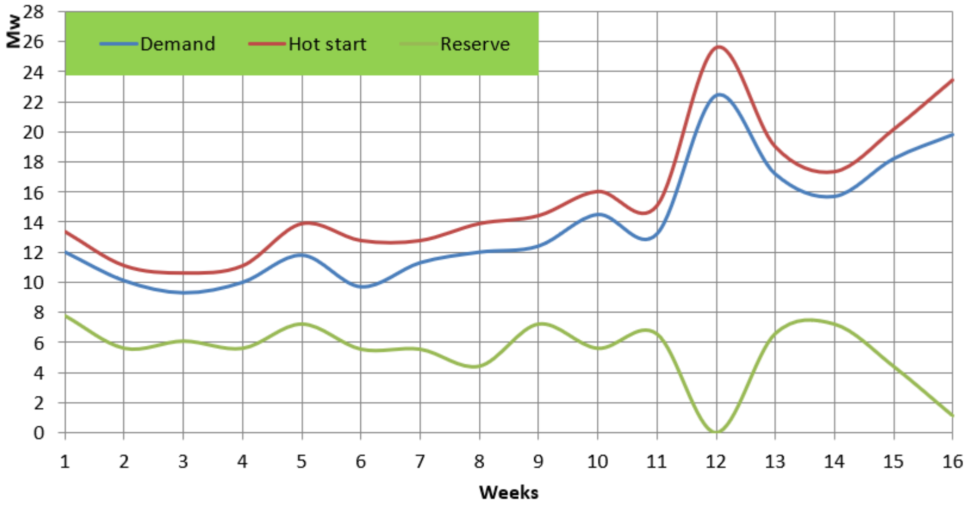


Figure 10-10: Deficit cost 10 €/Mw

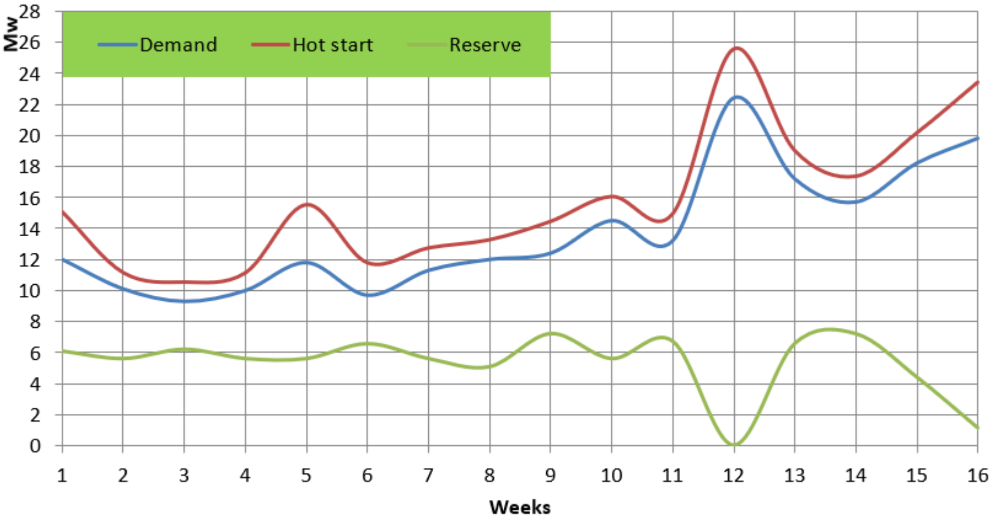


Figure 10-11: Deficit cost 100 €/Mw

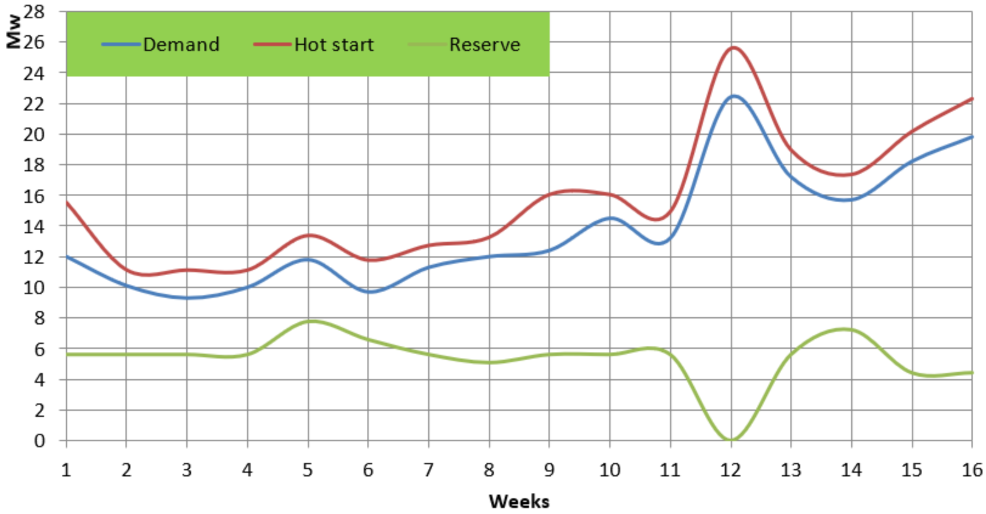


Figure 10-12: Deficit cost 1000 €/Mw

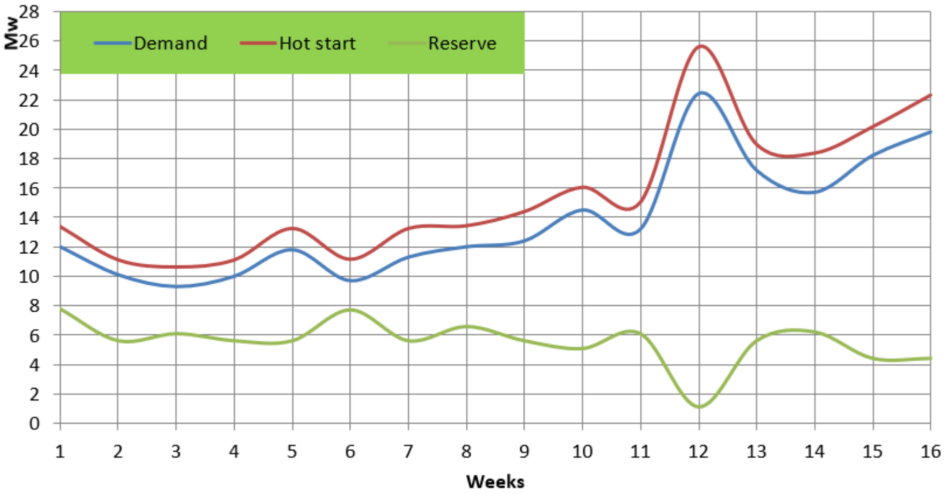


Figure 10-13: Deficit cost 10.000 €/Mw

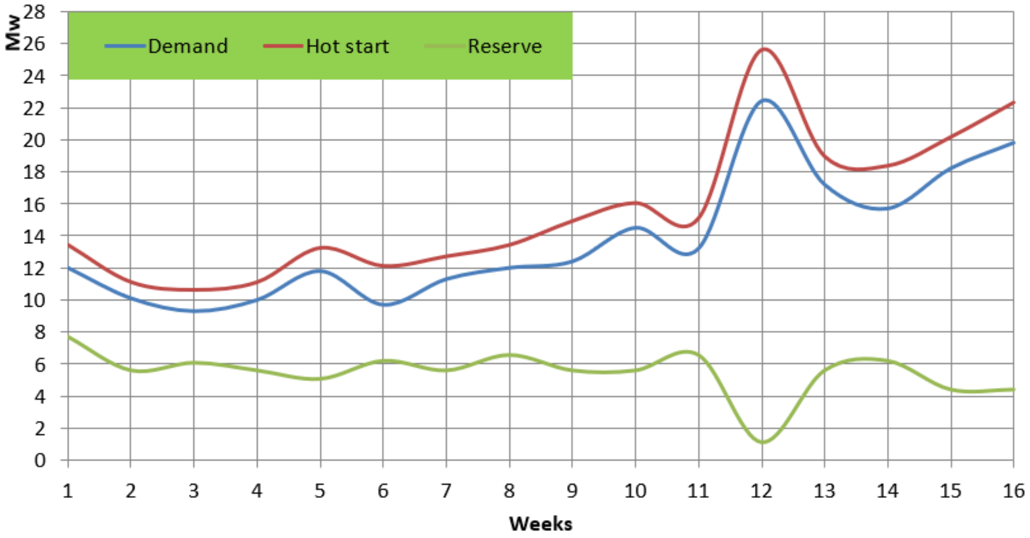
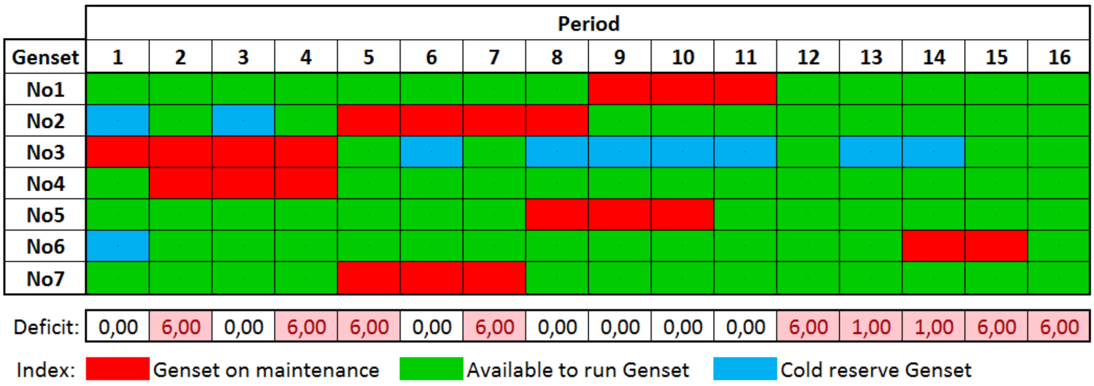


Figure 10-14: Deficit cost 100.000 €/Mw

APPENDIX C: GMS+UC+ED (maxNP)

Maximum Nominal power reliability approach

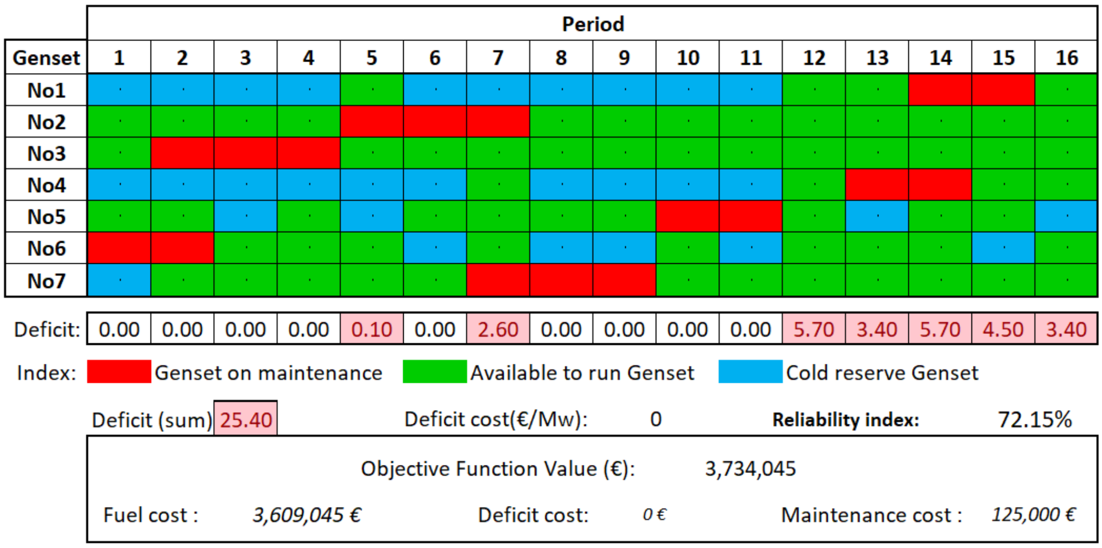
10.10 Scheduling results



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No2	🟦	🟩	🟦	🟩	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟥	🟥	🟥	🟥	🟩	🟦	🟩	🟦	🟦	🟦	🟦	🟩	🟦	🟦	🟩	🟩
No4	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
No6	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩
No7	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Deficit:	0,00	6,00	0,00	6,00	6,00	0,00	6,00	0,00	0,00	0,00	0,00	6,00	1,00	1,00	6,00	6,00

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

Figure 10-1: Deficit cost 0 €/Mw (Raw output)



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟦	🟦	🟦	🟦	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟩	🟩	🟥	🟥	🟩
No2	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No4	🟦	🟦	🟦	🟦	🟦	🟦	🟩	🟦	🟦	🟦	🟦	🟩	🟥	🟥	🟩	🟩
No5	🟩	🟩	🟦	🟩	🟦	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟦	🟩	🟩	🟦
No6	🟥	🟥	🟩	🟩	🟩	🟦	🟩	🟦	🟦	🟩	🟦	🟩	🟩	🟩	🟦	🟩
No7	🟦	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Deficit:	0.00	0.00	0.00	0.00	0.10	0.00	2.60	0.00	0.00	0.00	0.00	5.70	3.40	5.70	4.50	3.40

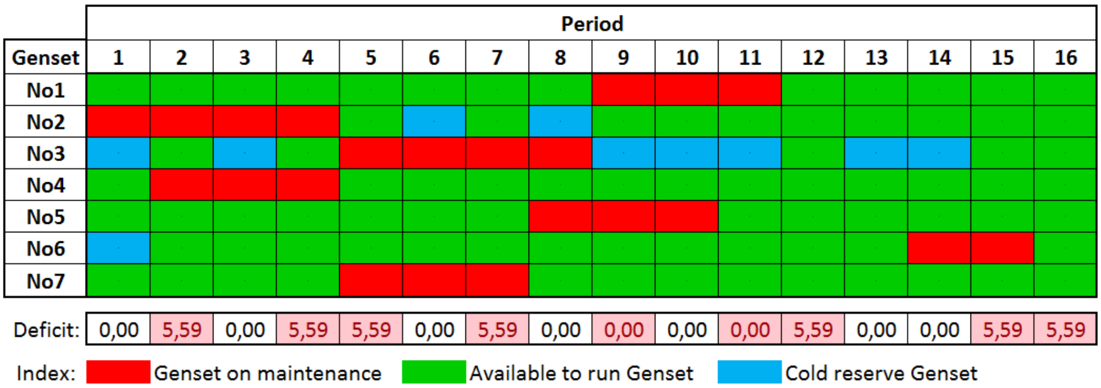
Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

Deficit (sum) 25.40 Deficit cost(€/Mw): 0 **Reliability index:** 72.15%

Objective Function Value (€): 3,734,045

Fuel cost : *3,609,045 €* Deficit cost: *0 €* Maintenance cost : *125,000 €*

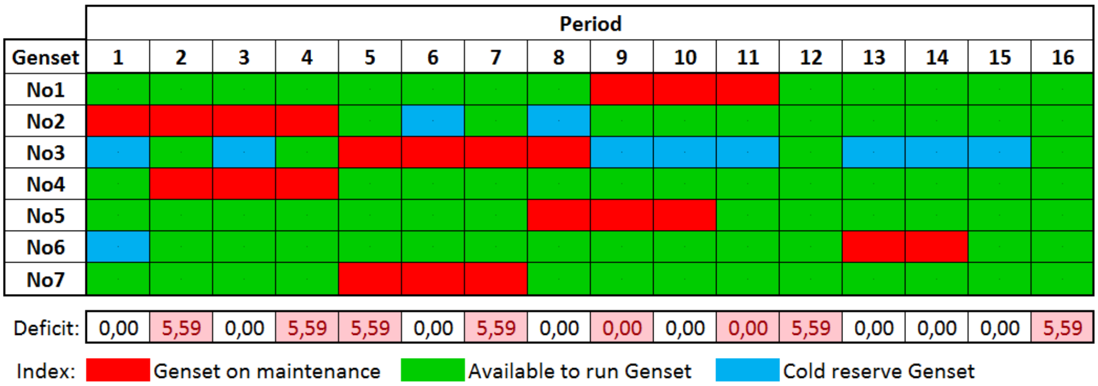
Figure 10-2: Deficit cost 0 €/Mw (Adjusted output)



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No2	🟥	🟥	🟥	🟥	🟩	🟦	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟦	🟩	🟦	🟩	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟦	🟦	🟩	🟩
No4	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
No6	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩
No7	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Deficit:	0,00	5,59	0,00	5,59	5,59	0,00	5,59	0,00	0,00	0,00	0,00	5,59	0,00	0,00	5,59	5,59

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

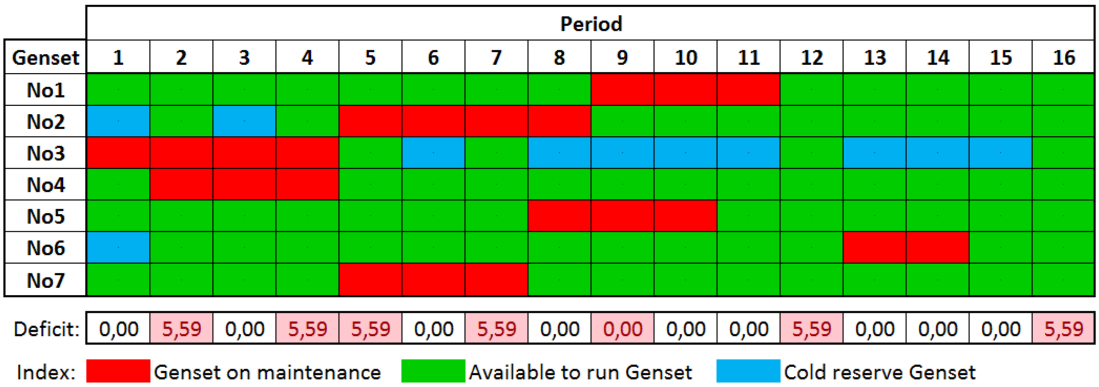
Figure 10-3: Deficit cost 1 €/Mw



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No2	🟥	🟥	🟥	🟥	🟩	🟦	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟦	🟩	🟦	🟩	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟦	🟦	🟦	🟩
No4	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
No6	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩
No7	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Deficit:	0,00	5,59	0,00	5,59	5,59	0,00	5,59	0,00	0,00	0,00	0,00	5,59	0,00	0,00	0,00	5,59

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

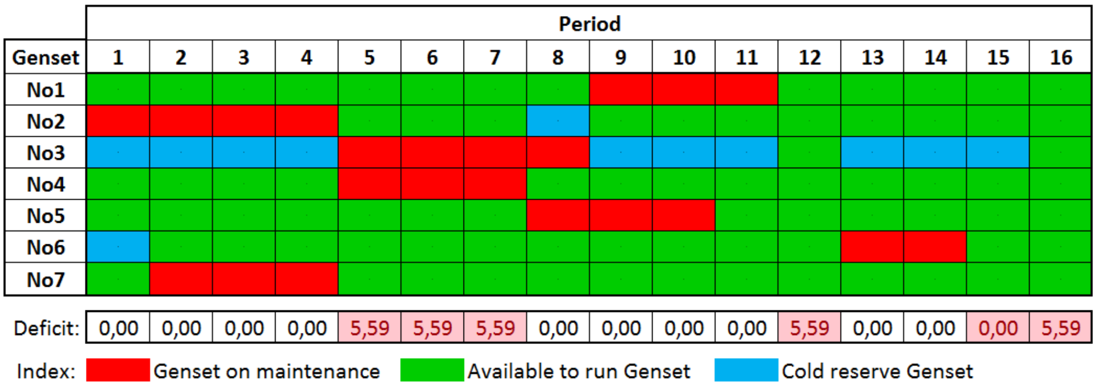
Figure 10-4: Deficit cost 10 €/Mw



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No2	🟦	🟩	🟦	🟩	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟥	🟥	🟥	🟥	🟩	🟦	🟩	🟦	🟦	🟦	🟦	🟩	🟦	🟦	🟦	🟩
No4	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
No6	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩
No7	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Deficit:	0,00	5,59	0,00	5,59	5,59	0,00	5,59	0,00	0,00	0,00	0,00	5,59	0,00	0,00	0,00	5,59

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

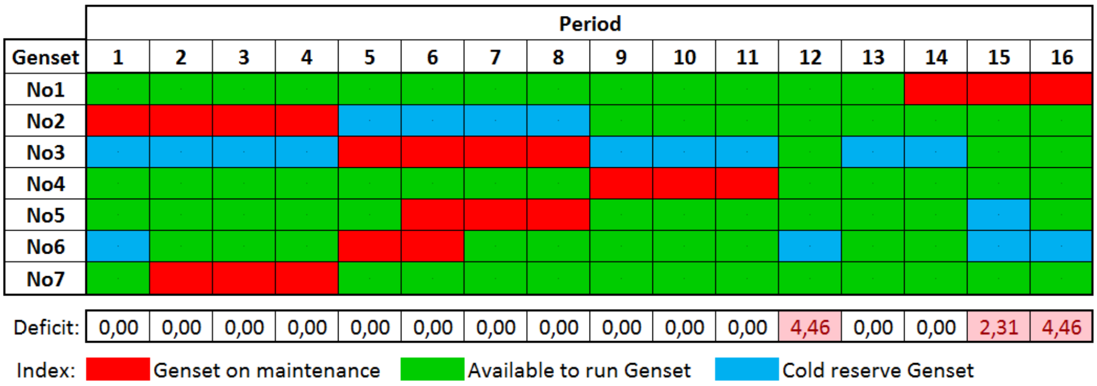
Figure 10-5: Deficit cost 100 €/Mw



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No2	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟦	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟦	🟦	🟦	🟩
No4	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
No6	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩
No7	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Deficit:	0,00	0,00	0,00	0,00	5,59	5,59	5,59	0,00	0,00	0,00	0,00	5,59	0,00	0,00	0,00	5,59

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

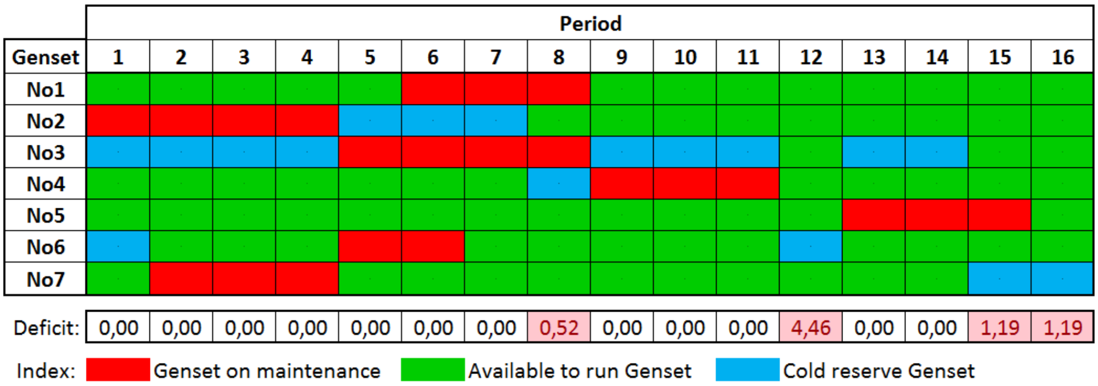
Figure 10-6: Deficit cost 1.000 €/Mw



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥
No2	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟦	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟦	🟦	🟩	🟩
No4	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟩
No6	🟦	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟦	🟩	🟩	🟦	🟦
No7	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Deficit:	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	4,46	0,00	0,00	2,31	4,46

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

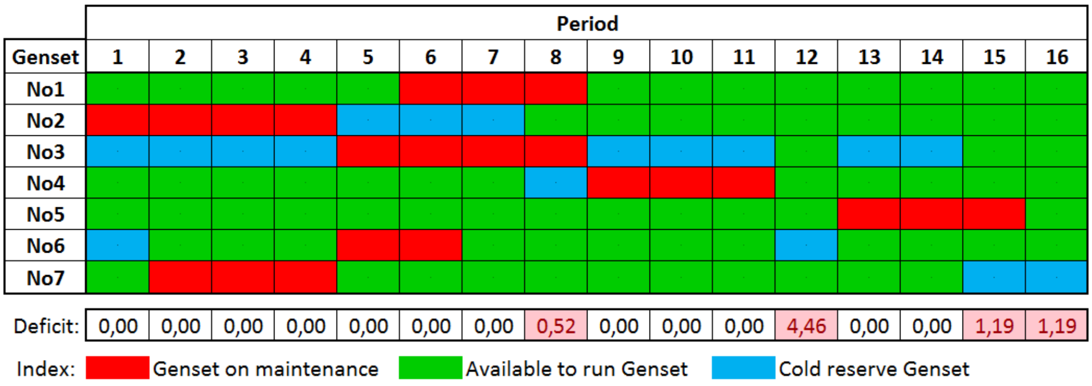
Figure 10-7: Deficit cost 10.000 €/Mw



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No2	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟦	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟦	🟦	🟩	🟩
No4	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩
No6	🟦	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟩
No7	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟦
Deficit:	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,52	0,00	0,00	0,00	4,46	0,00	0,00	1,19	1,19

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

Figure 10-8: Deficit cost 100.000 €/Mw



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No2	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟦	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟦	🟦	🟩	🟩
No4	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩
No6	🟦	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟩
No7	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟦
Deficit:	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,52	0,00	0,00	0,00	4,46	0,00	0,00	1,19	1,19

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

Figure 10-9: Deficit cost 1.000.000 €/Mw

10.11 System Reserves

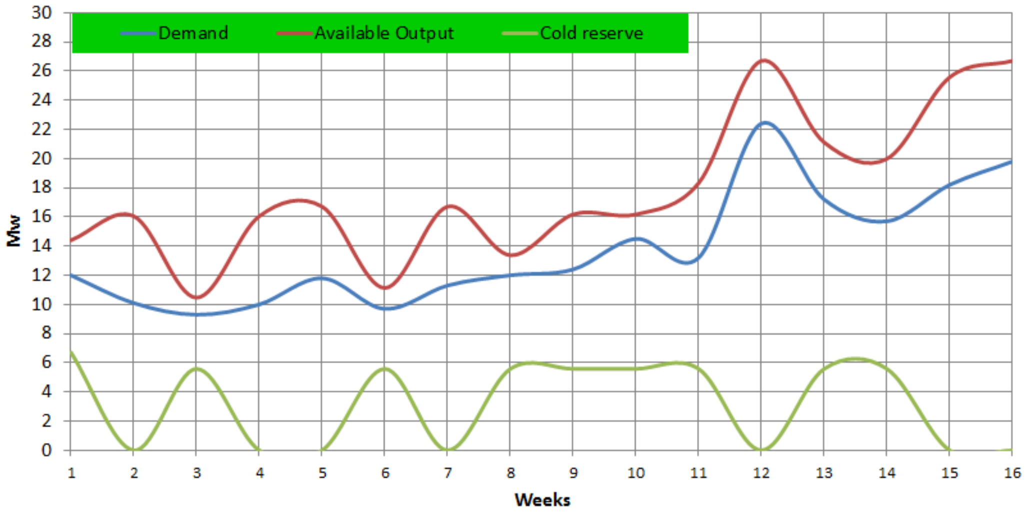


Figure 10-10: Deficit cost 0 €/Mw

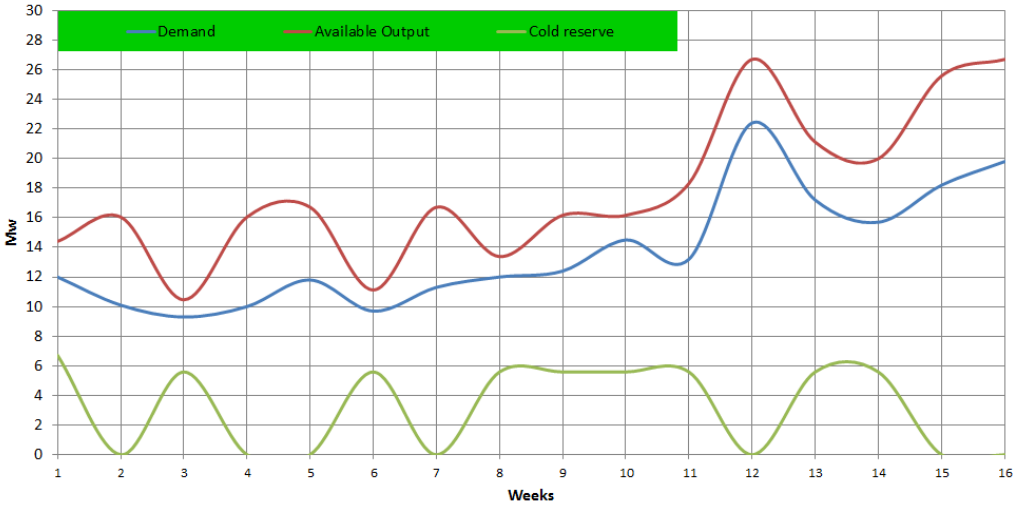


Figure 10-11: Deficit cost 1 €/Mw

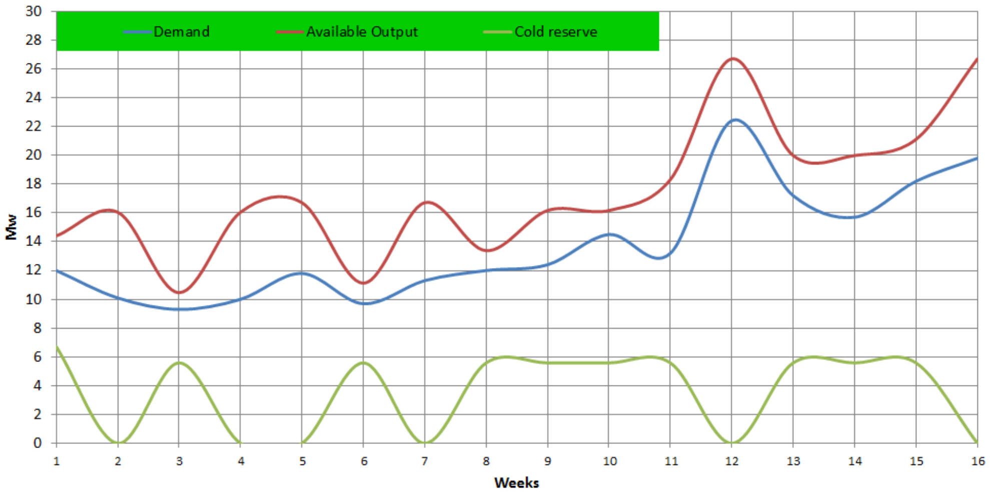


Figure 10-12: Deficit cost 10 €/Mw

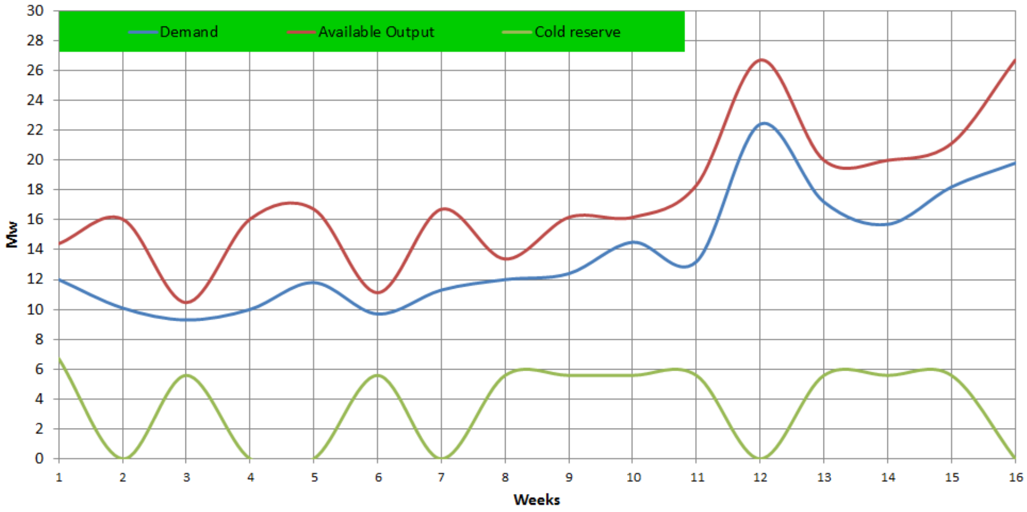


Figure 10-13: Deficit cost 100 €/Mw

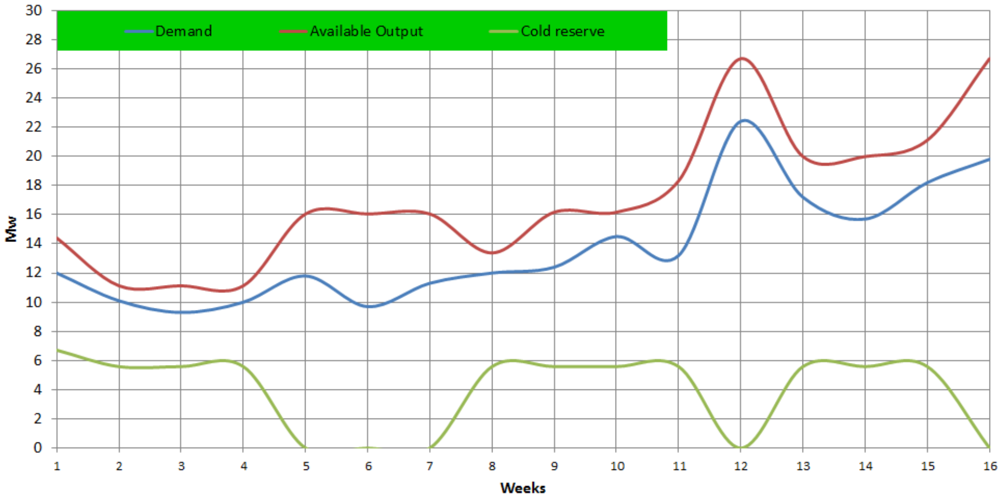


Figure 10-14: Deficit cost 1.000 €/Mw

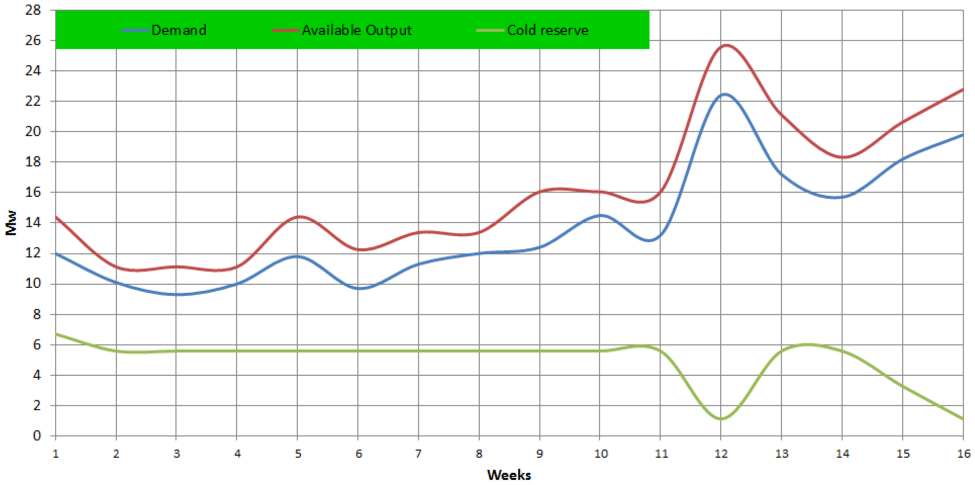


Figure 10-15: Deficit cost 10.000 €/Mw

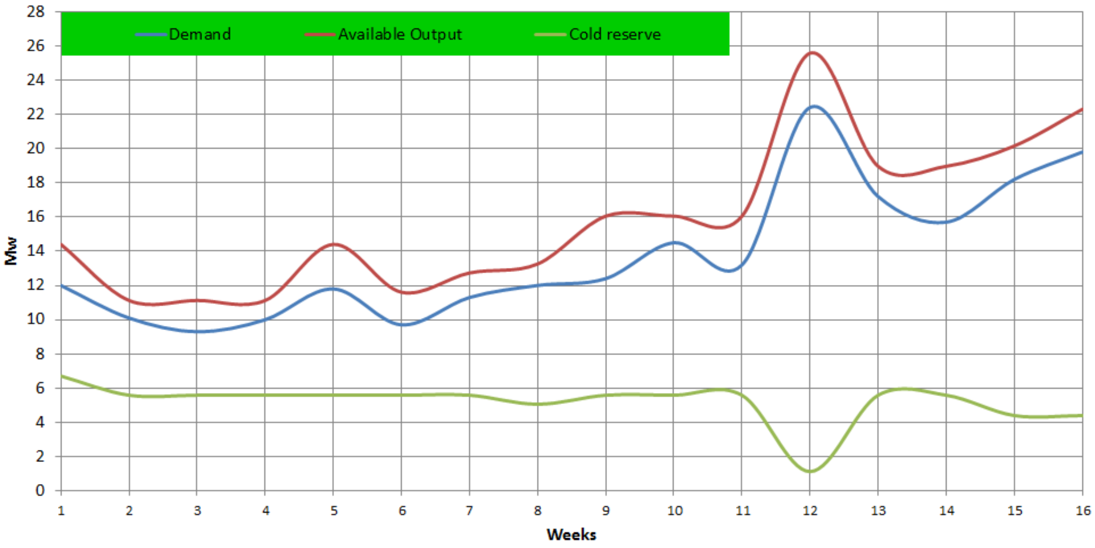


Figure 10-16: Deficit cost 100.000 €/Mw

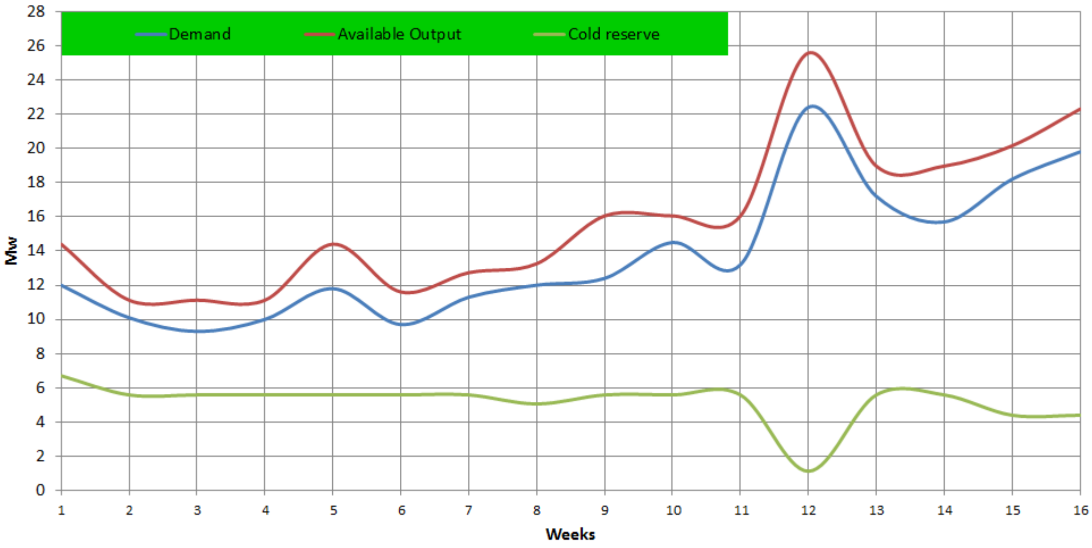
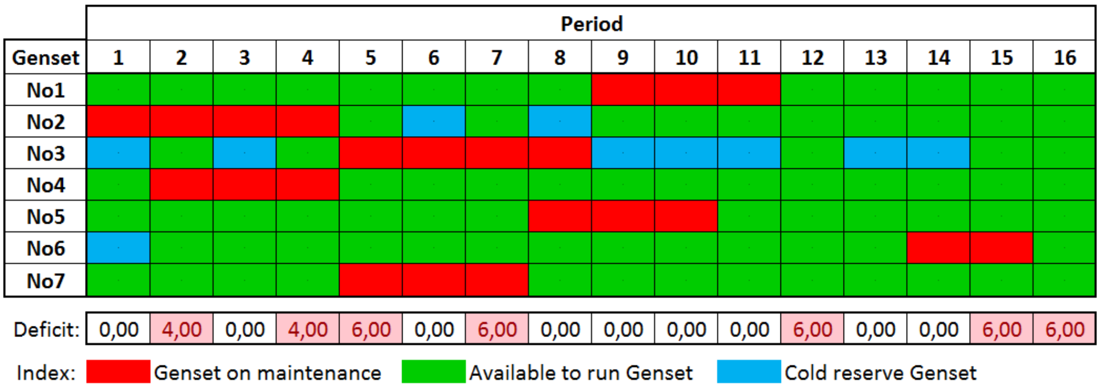


Figure 10-17: Deficit cost 1.000.000 €/Mw

APPENDIX D: GMS+UC+ED (maxRP)

Maximum Run power reliability approach

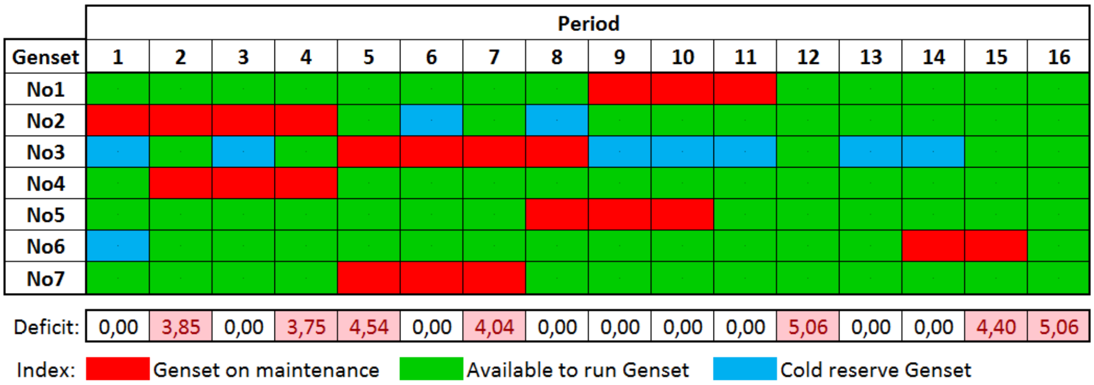
10.12 Scheduling results



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No2	🟥	🟥	🟥	🟥	🟩	🟦	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟦	🟩	🟦	🟩	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟦	🟦	🟩	🟩
No4	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
No6	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩
No7	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Deficit:	0,00	4,00	0,00	4,00	6,00	0,00	6,00	0,00	0,00	0,00	0,00	6,00	0,00	0,00	6,00	6,00

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

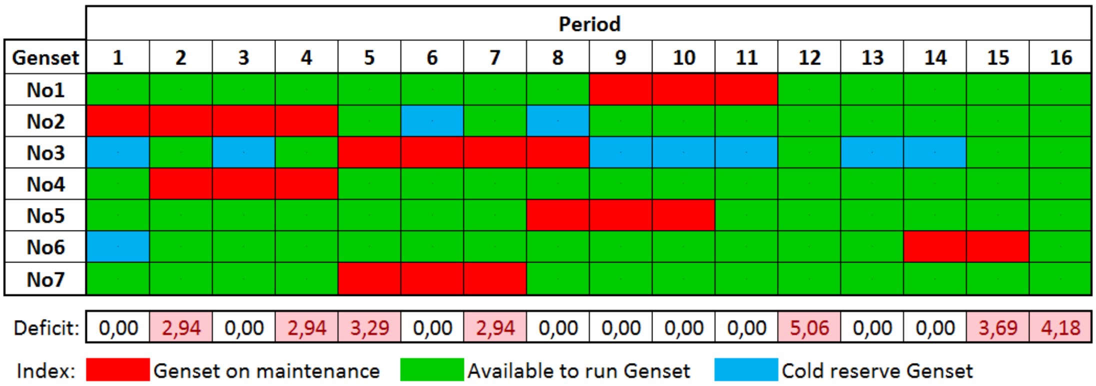
Figure 10-1: Deficit cost 0 €/Mw



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No2	🟥	🟥	🟥	🟥	🟩	🟦	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟦	🟩	🟦	🟩	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟦	🟦	🟩	🟩
No4	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
No6	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩
No7	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Deficit:	0,00	3,85	0,00	3,75	4,54	0,00	4,04	0,00	0,00	0,00	0,00	5,06	0,00	0,00	4,40	5,06

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

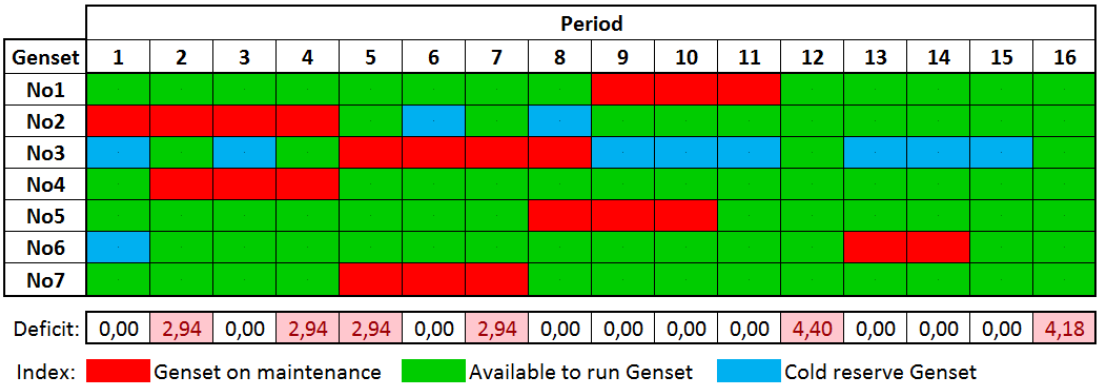
Figure 10-2: Deficit cost 1€/Mw



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No2	🟥	🟥	🟥	🟥	🟩	🟦	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟦	🟩	🟦	🟩	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟦	🟦	🟩	🟩
No4	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
No6	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩
No7	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Deficit:	0,00	2,94	0,00	2,94	3,29	0,00	2,94	0,00	0,00	0,00	0,00	5,06	0,00	0,00	3,69	4,18

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

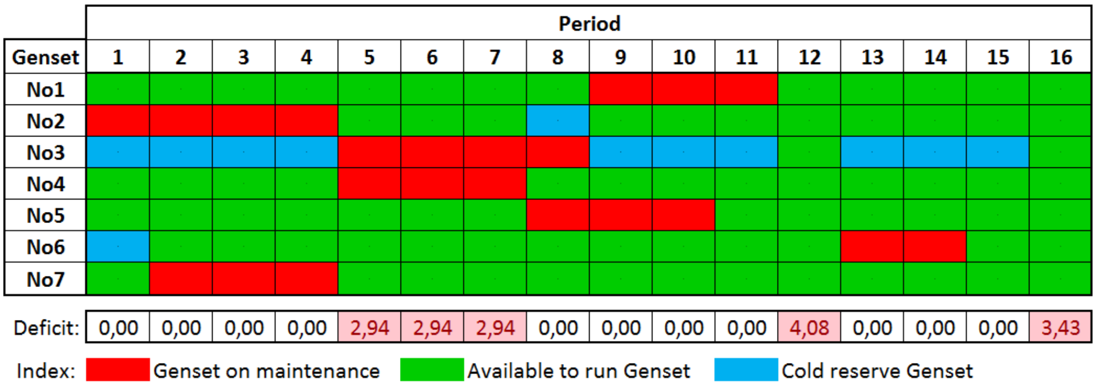
Figure 10-3: Deficit cost 10 €/Mw



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No2	🟥	🟥	🟥	🟥	🟩	🟦	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟦	🟩	🟦	🟩	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟦	🟦	🟦	🟩
No4	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
No6	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩
No7	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Deficit:	0,00	2,94	0,00	2,94	2,94	0,00	2,94	0,00	0,00	0,00	0,00	4,40	0,00	0,00	0,00	4,18

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

Figure 10-4: Deficit cost 100 €/Mw



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
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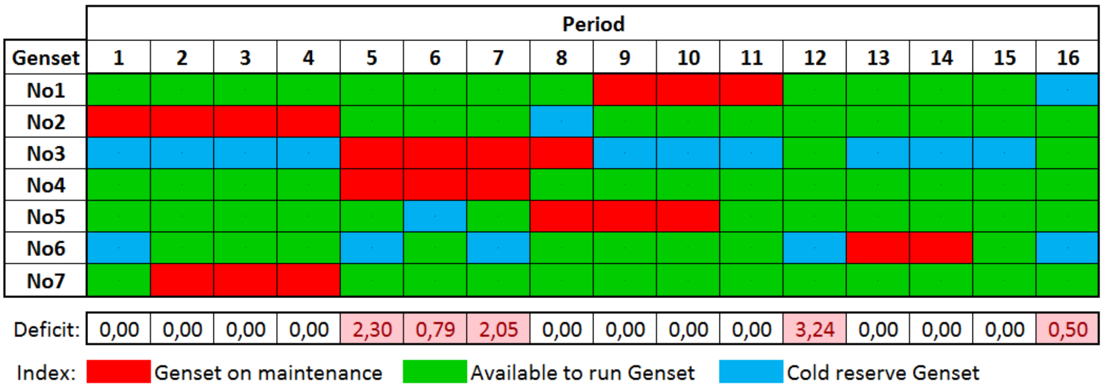
No3	🟦	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟦	🟦	🟦	🟩
No4	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
No6	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩
No7	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Deficit:	0,00	0,00	0,00	0,00	2,94	2,94	2,94	0,00	0,00	0,00	0,00	4,08	0,00	0,00	0,00	3,43

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

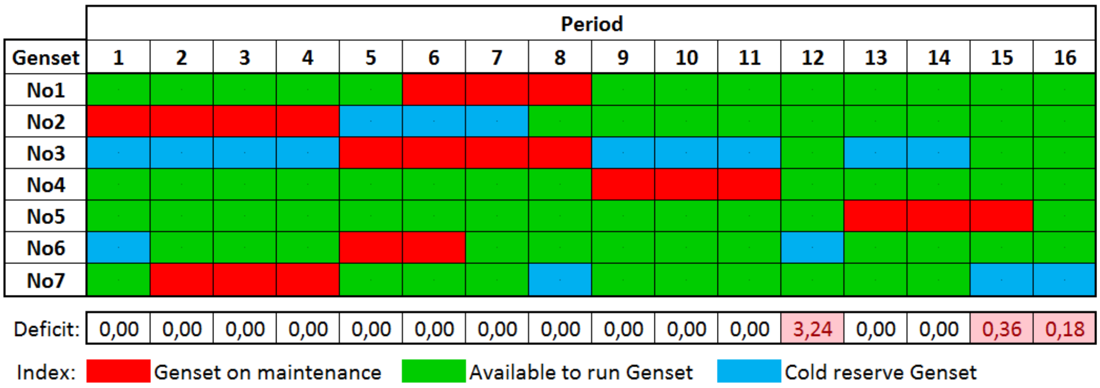
Figure 10-5: Deficit cost 1.000 €/Mw



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟦
No2	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟦	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟦	🟦	🟦	🟩
No4	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟦	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
No6	🟦	🟩	🟩	🟩	🟦	🟩	🟦	🟩	🟩	🟩	🟩	🟦	🟥	🟥	🟩	🟦
No7	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Deficit:	0,00	0,00	0,00	0,00	2,30	0,79	2,05	0,00	0,00	0,00	0,00	3,24	0,00	0,00	0,00	0,50

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

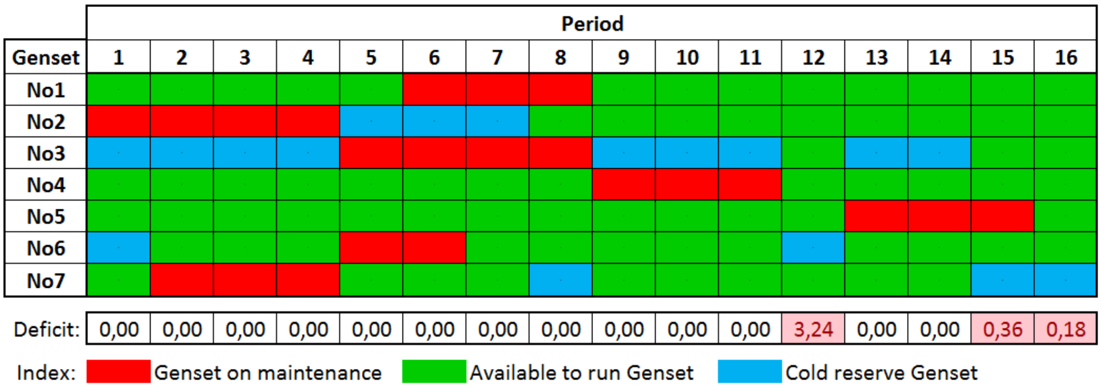
Figure 10-6: Deficit cost 10.000 €/Mw



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No2	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟦	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟦	🟦	🟩	🟩
No4	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩
No6	🟦	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟩
No7	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟦
Deficit:	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	3,24	0,00	0,00	0,36	0,18

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

Figure 10-7: Deficit cost 100.000 €/Mw



	Period															
Genset	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
No1	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No2	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
No3	🟦	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟩	🟦	🟦	🟩	🟩
No4	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
No5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩
No6	🟦	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟩
No7	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟦
Deficit:	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	3,24	0,00	0,00	0,36	0,18

Index: 🟥 Genset on maintenance 🟩 Available to run Genset 🟦 Cold reserve Genset

Figure 10-8: Deficit cost 1.000.000 €/Mw

10.13 System Reserves

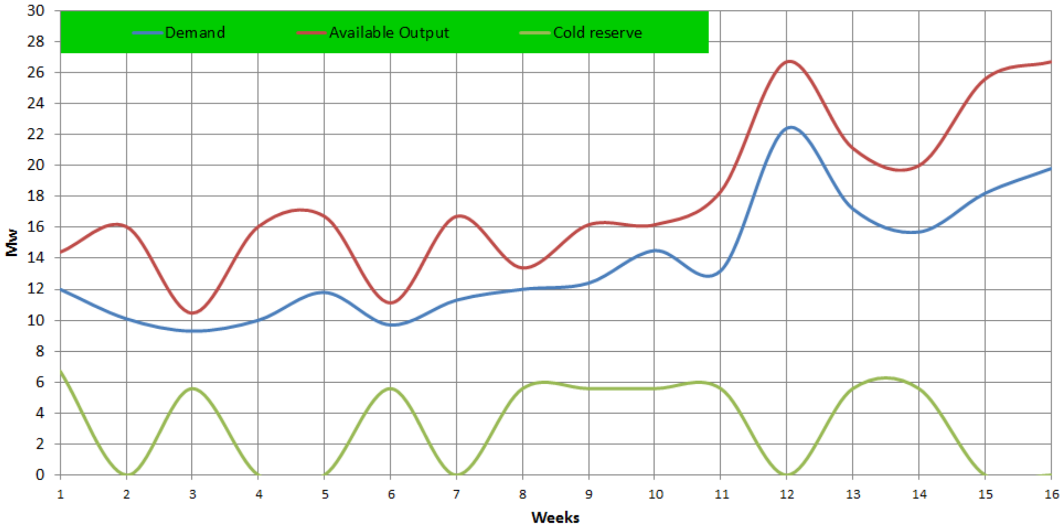


Figure 10-9: Deficit cost 0 €/Mw

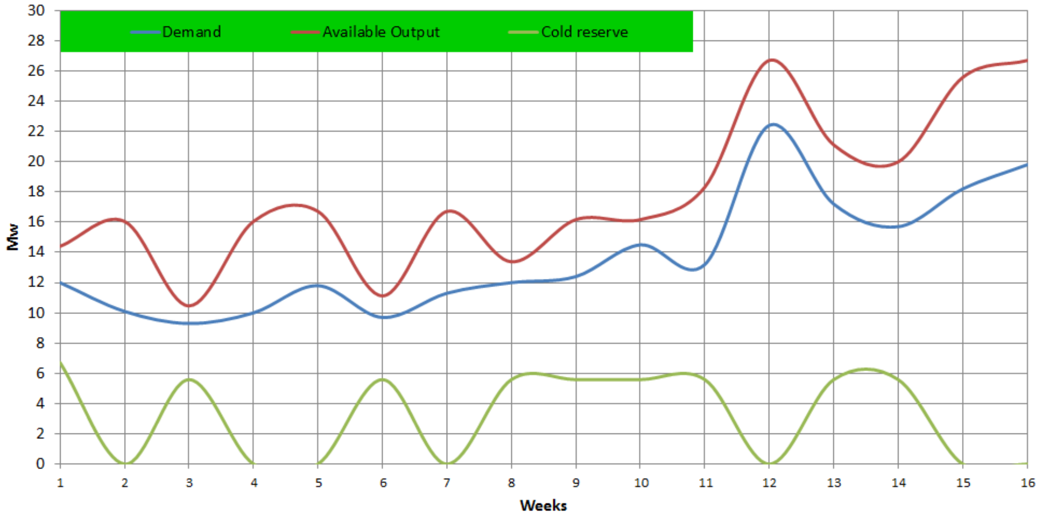


Figure 10-10: Deficit cost 1 €/Mw

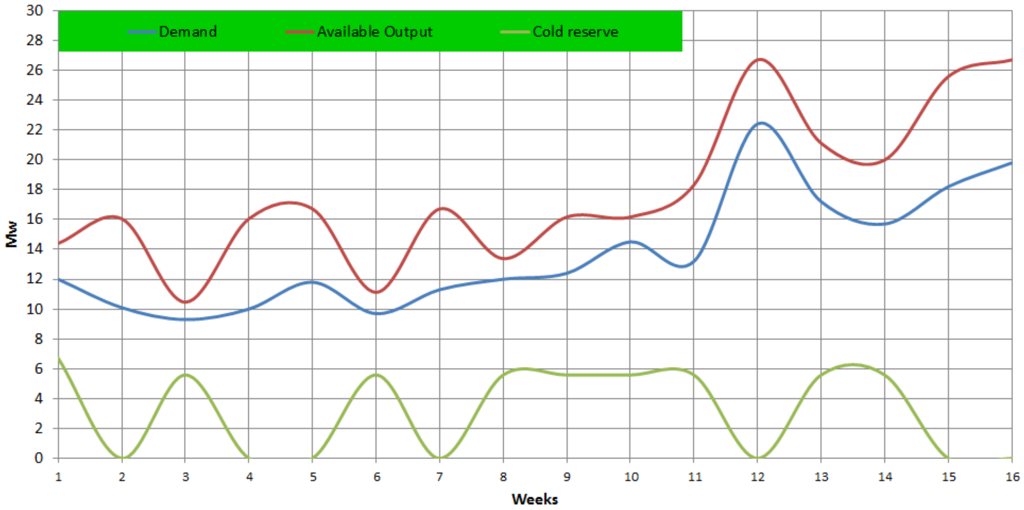


Figure 10-11: Deficit cost 10 €/Mw

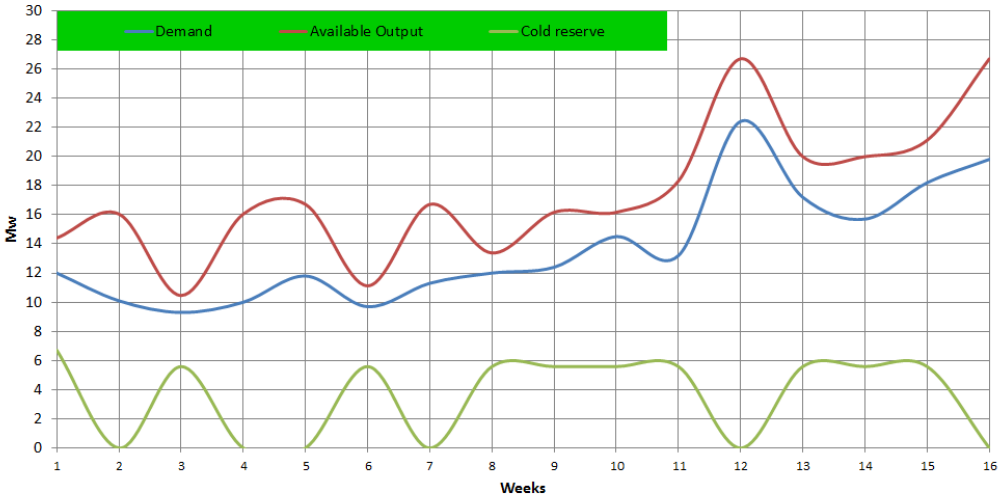


Figure 10-12: Deficit cost 100 €/Mw

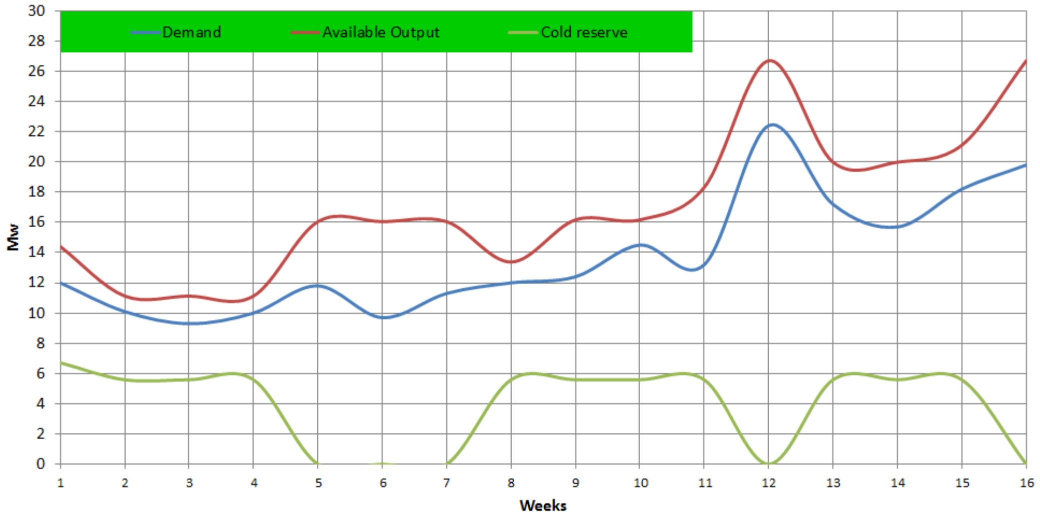


Figure 10-13: Deficit cost 1.000 €/Mw

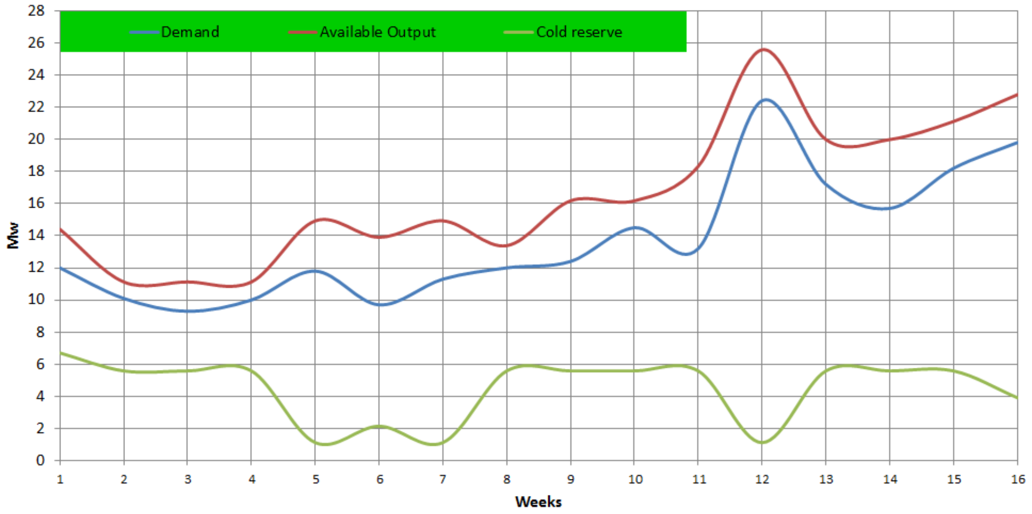


Figure 10-14: Deficit cost 10.000 €/Mw

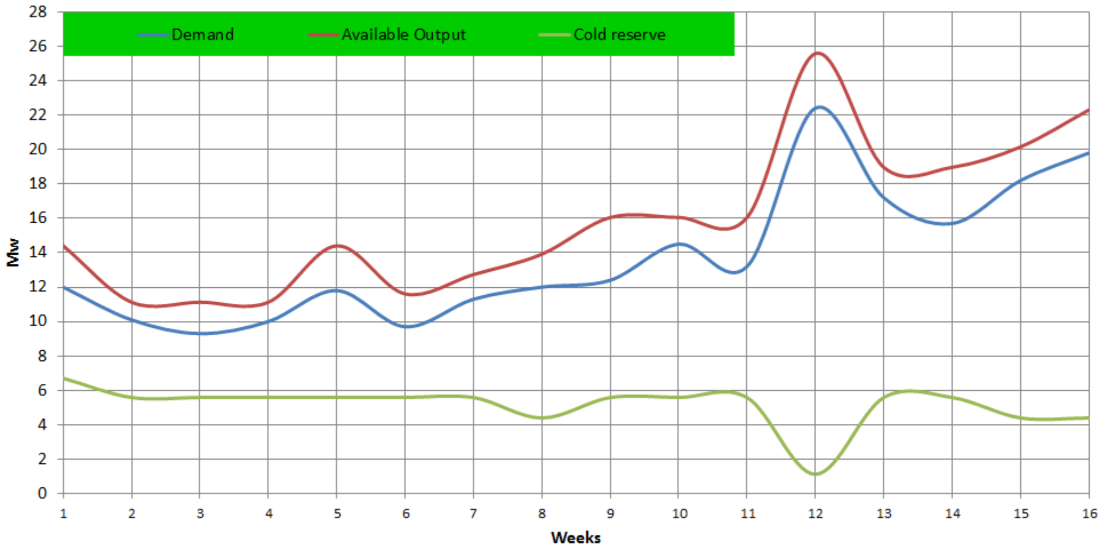


Figure 10-15: Deficit cost 100.000 €/Mw

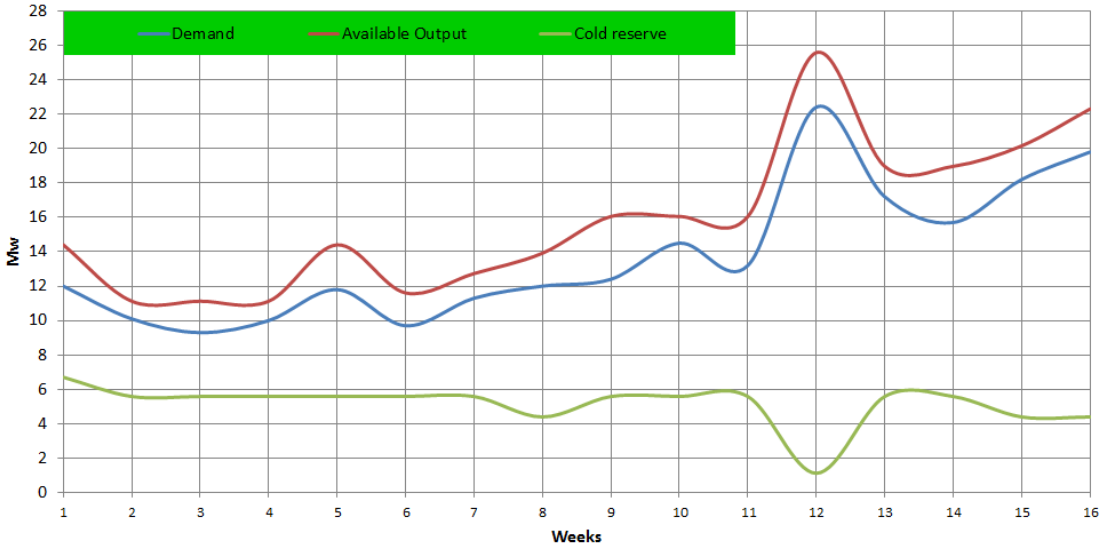
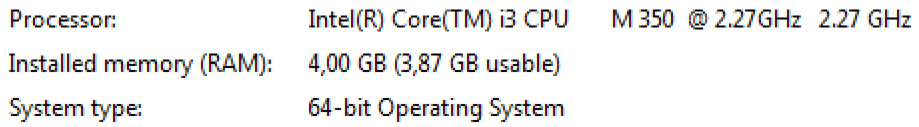


Figure 10-16: Deficit cost 1.000.000 €/Mw

APPENDIX E: COMPUTATION TIME

10.14 Hardware equipment

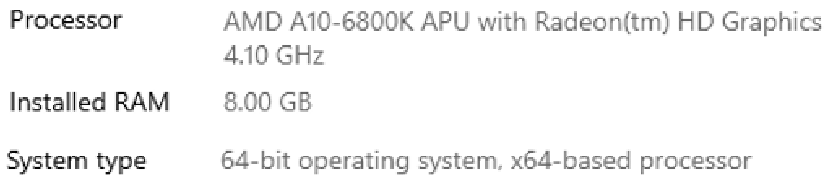
Models were run with the use of 2 systems for comparison reasons. One laptop (system A) with the following specifications



Processor:	Intel(R) Core(TM) i3 CPU M 350 @ 2.27GHz 2.27 GHz
Installed memory (RAM):	4,00 GB (3,87 GB usable)
System type:	64-bit Operating System

Figure 10-1: System A specifications

and one desktop (system B) with the following specifications



Processor	AMD A10-6800K APU with Radeon(tm) HD Graphics 4.10 GHz
Installed RAM	8.00 GB
System type	64-bit operating system, x64-based processor

Figure 10-2: System B specifications

In Figure 10-3 (below) we present for comparison reason, observed calculation times for the whole range of deficit cost (€/Mw) inserted.

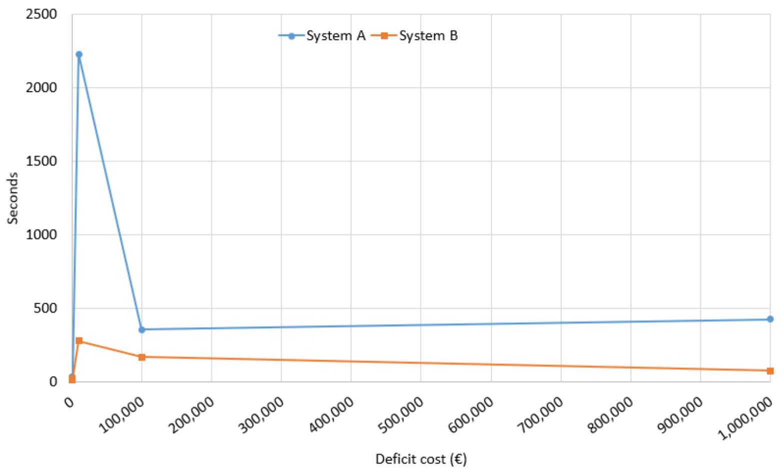


Figure 10-3: maxRP observed calculation times

It is evident that system B performed better

10.15 Computation times of system A

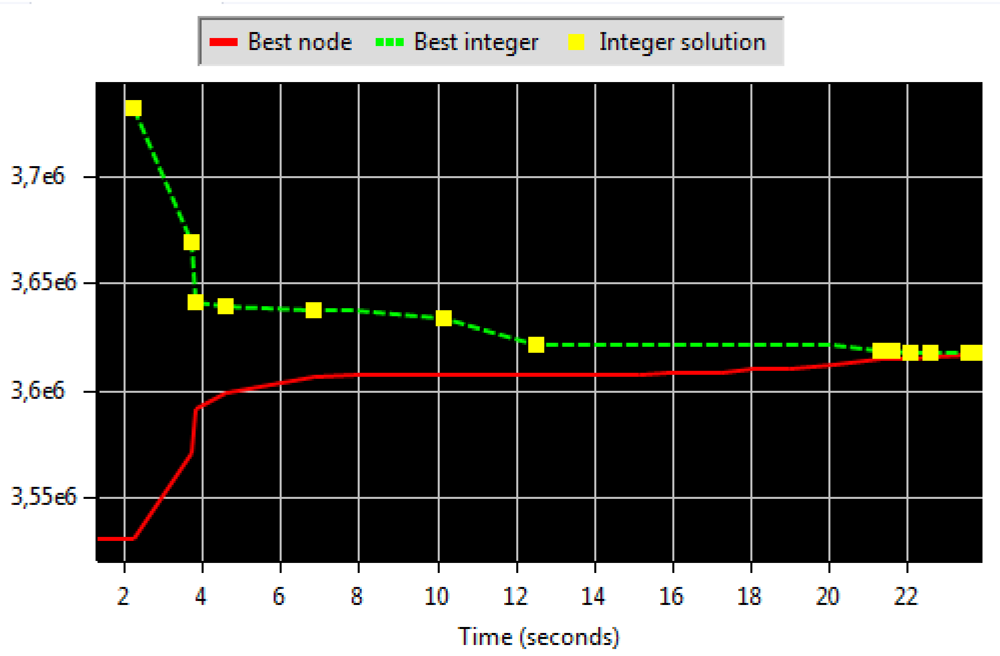


Figure 10-4: System A, Deficit cost:0

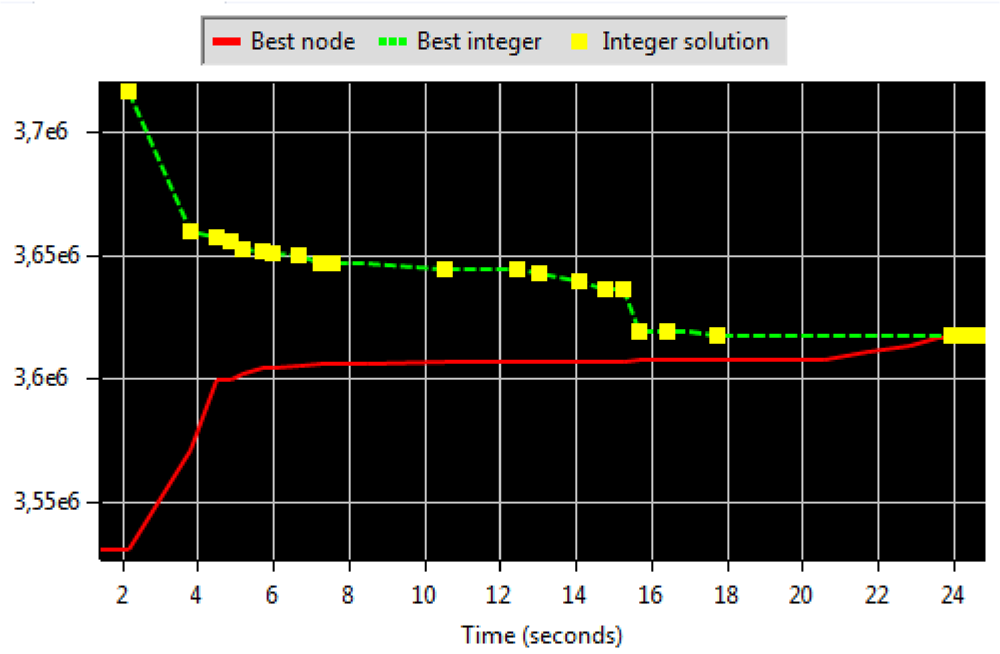


Figure 10-5: System A, Deficit cost:1

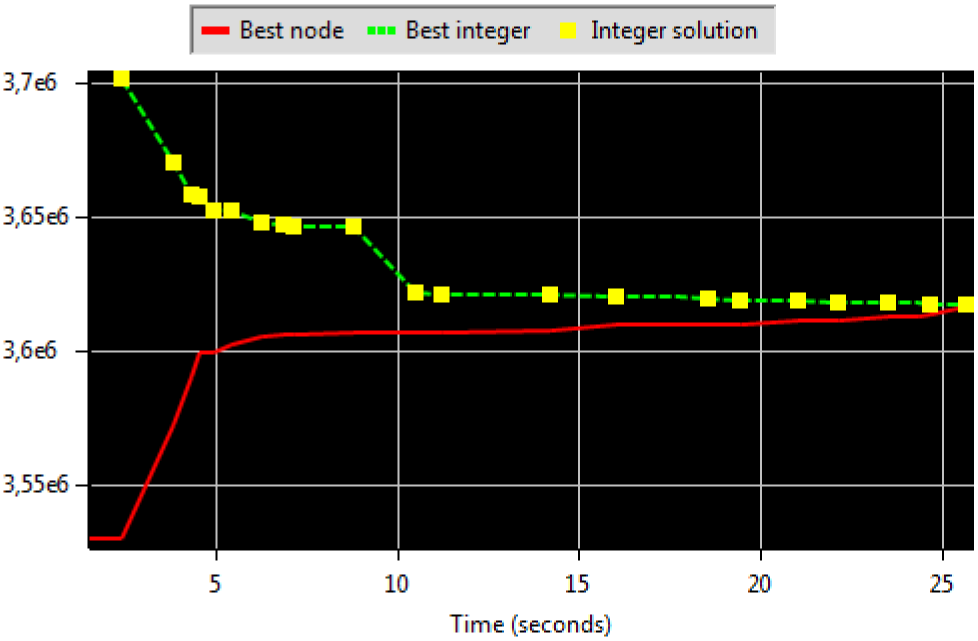


Figure 10-6: System A, Deficit cost:10

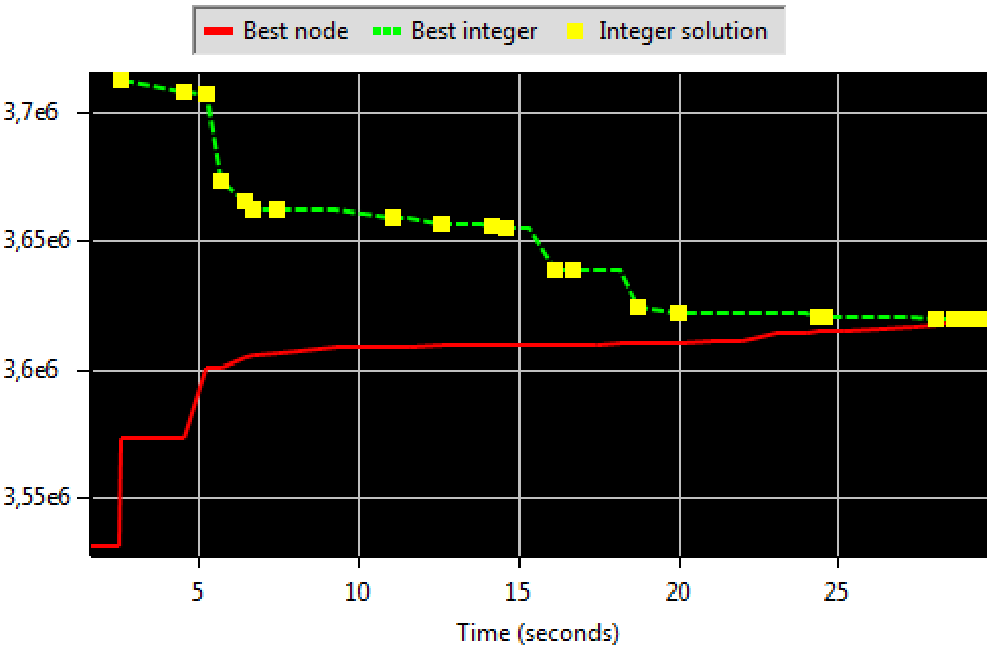


Figure 10-7: System A, Deficit cost:100

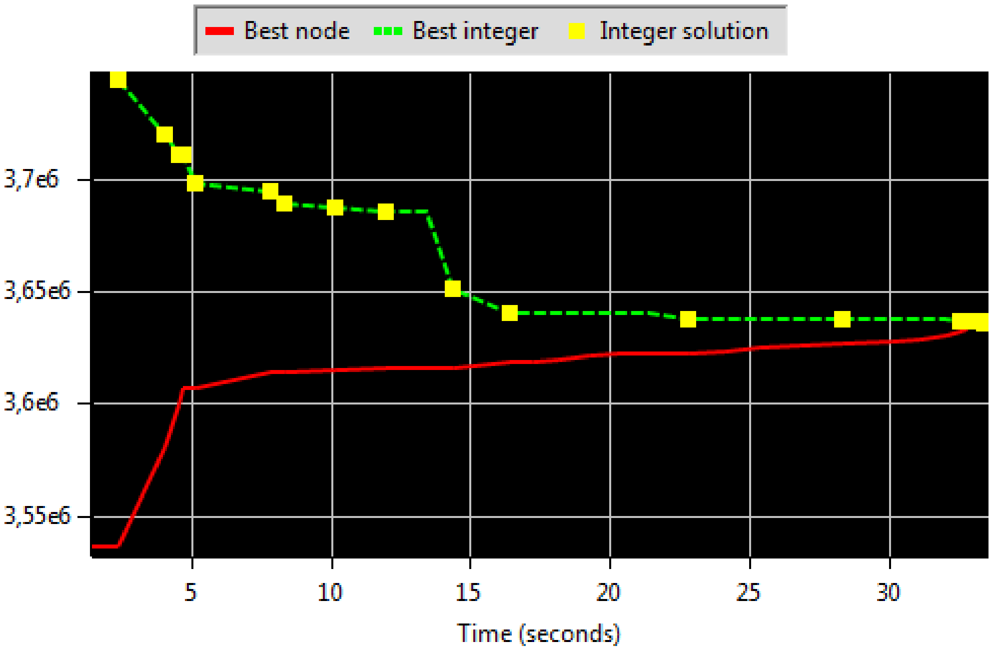


Figure 10-8: System A, Deficit cost:1.000

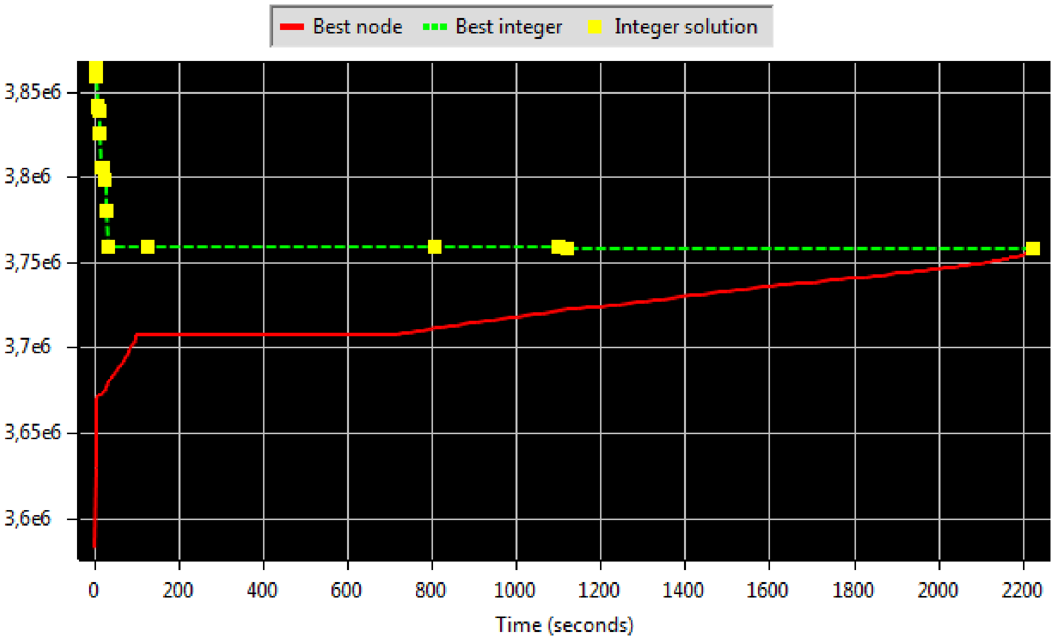


Figure 10-9: System A, Deficit cost:10.000

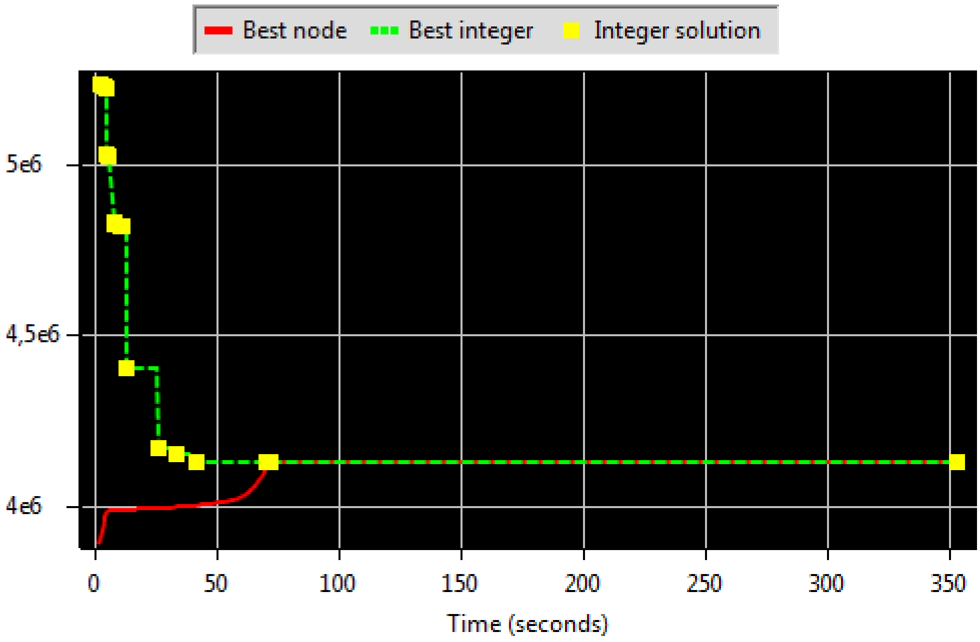


Figure 10-10: System A, Deficit cost:100.000

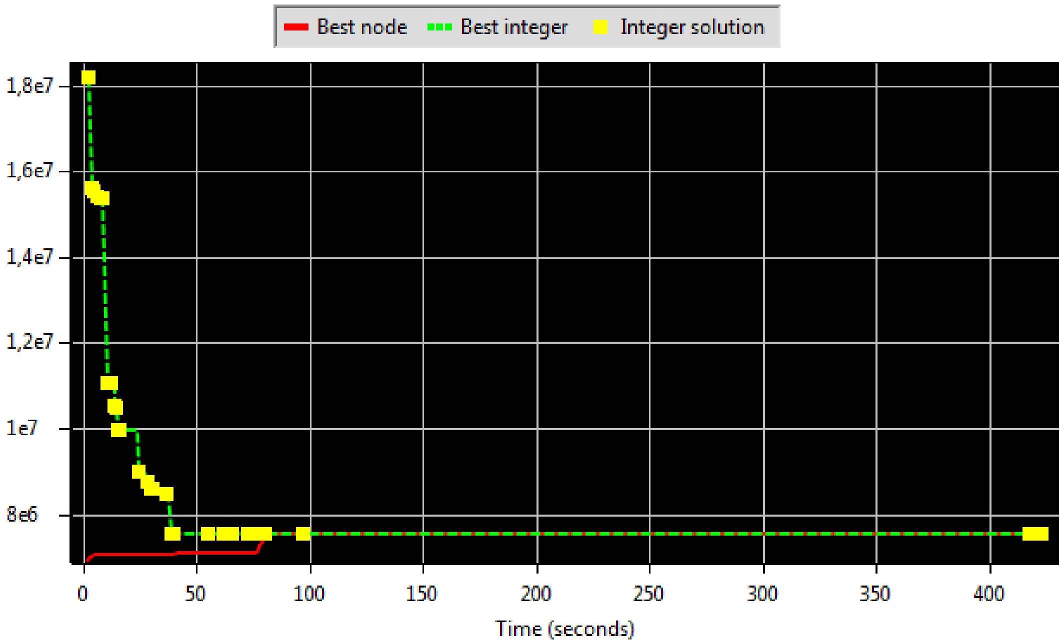


Figure 10-11: System A, Deficit cost:1.000.000