APPLICATION NOTE

RESILIENT AND RELIABLE POWER SUPPLY IN A MODERN OFFICE BUILDING: CASE STUDY

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1	June 2008	Initial publication
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Disclaimer

CONTENTS

SUMMARY

This Application Note describes the design of the electrical infrastructure for a modern 10-story head-office building in Milan, Italy, housing 500 employees using IT intensively. It demonstrates how concern for resilience and reliability at design stage can save high maintenance and renovation costs at later stage. Two design approaches are discussed and compared, including a cost comparison. Attention goes to the choice of the electrical distribution scheme, the choice of the earthing configuration, how to cope with harmonic currents, the coordination of many different protection devices, and how to ensure power supply for mission critical loads.

Introduction

This paper presents a design approach to assure resilient and reliable power supply in an electronics-intensive office building. The document is a case study of a 10-floor office in Milan, Italy (hereafter referred to as “the building” for confidentiality reasons). The building is the head office of a major financial institution and is occupied by 500 employees using information technology equipment intensively.

After a description of the current status of the electrical installation in the building, accompanied by the results of power quality measurements, two design proposals are presented that assure a resilient and reliable power supply. A cost analysis completes this report.

Description of existing situation

Distribution scheme

The building is connected to the 23 kV MV public grid. The medium voltage main power supply consists of two 800 kVA transformers, 23/0.4 kV, 50 Hz. The low voltage side of the installation is designed as a TN-S system.

The load is subdivided into standard, preferential, and privileged loads, according to requirements for continuity of supply (this is discussed in greater detail later in the text). There is a second point of common coupling (PCC) to feed a small portion of the standard load. The two PCCs are fed from the same grid point and so are not independent.

To assure continuity of the power supply, two UPSs (80 + 200 kVA) and a motor generator (250 kVA) are installed according to the scheme in Fig 1. Note that in such a scheme, it is imperative that the neutral conductor is connected to the earth only once, at the main earthing terminal, and not at each transformer. Otherwise, the benefits of the TN-S wiring configuration – improved EMC and power quality – are lost.

The primary distribution is a compromise between radial and shunt schemes[1]. The installation has grown in a haphazard way, without a consistent structure. This is a direct result of the many changes in power requirements experienced during the building’s lifetime. Two distribution panels feed each floor. Each panel has two sections (standard and privileged) corresponding to the standard and privileged sections of the main LV power panel (Fig. 2). Final distribution uses a single radial scheme.

Lines

The 3-phase distribution is made with multi-core copper cables. Where the phase conductor cross sections were greater than 35 mm^2, half-sized neutral conductors had been used.

[1] Shunt scheme: a rising bus bar or power line is shared for all floors; at each floor, a connection is made to the LV panel at the floor. Radial scheme: each LV panel at each floor has a dedicated connection with its corresponding switchgear at the main LV distribution panel in the basement.

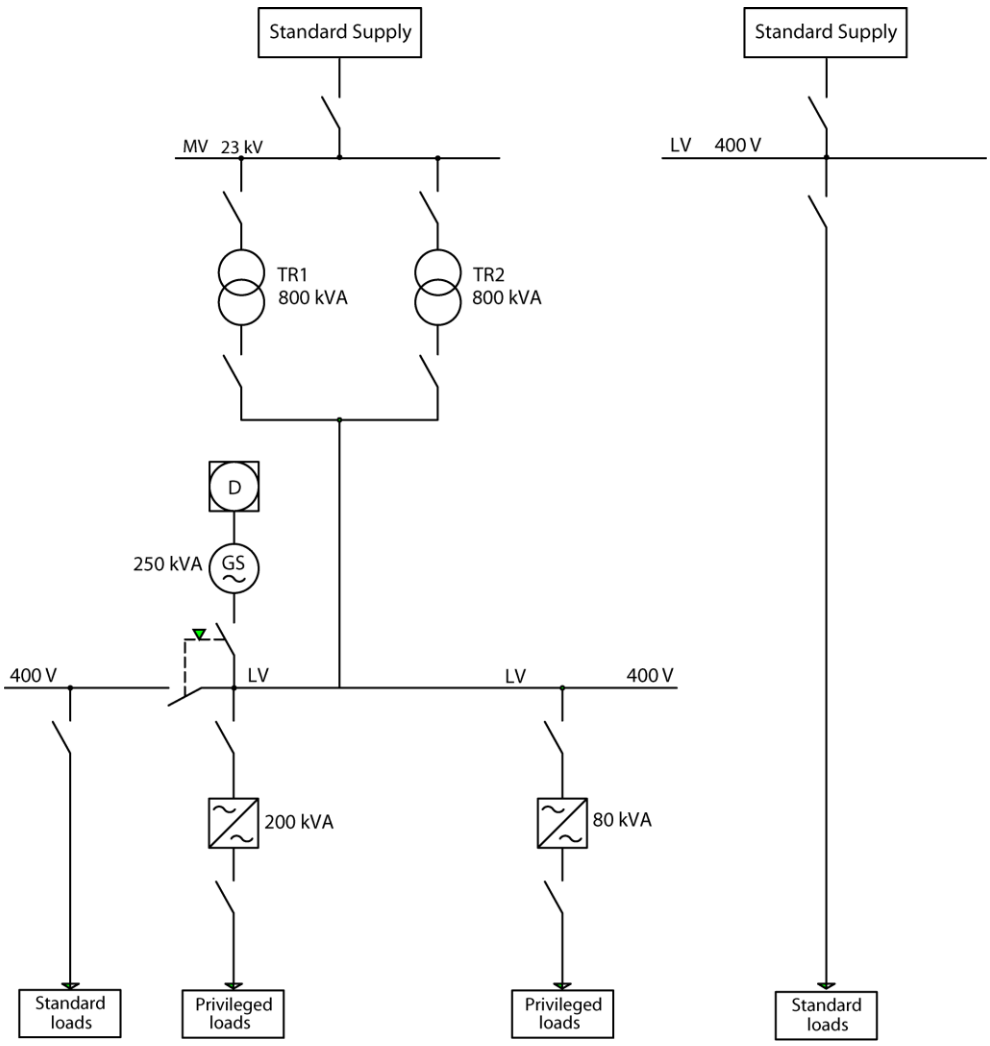

Figure 1 – Initial distribution scheme, before the modifications.

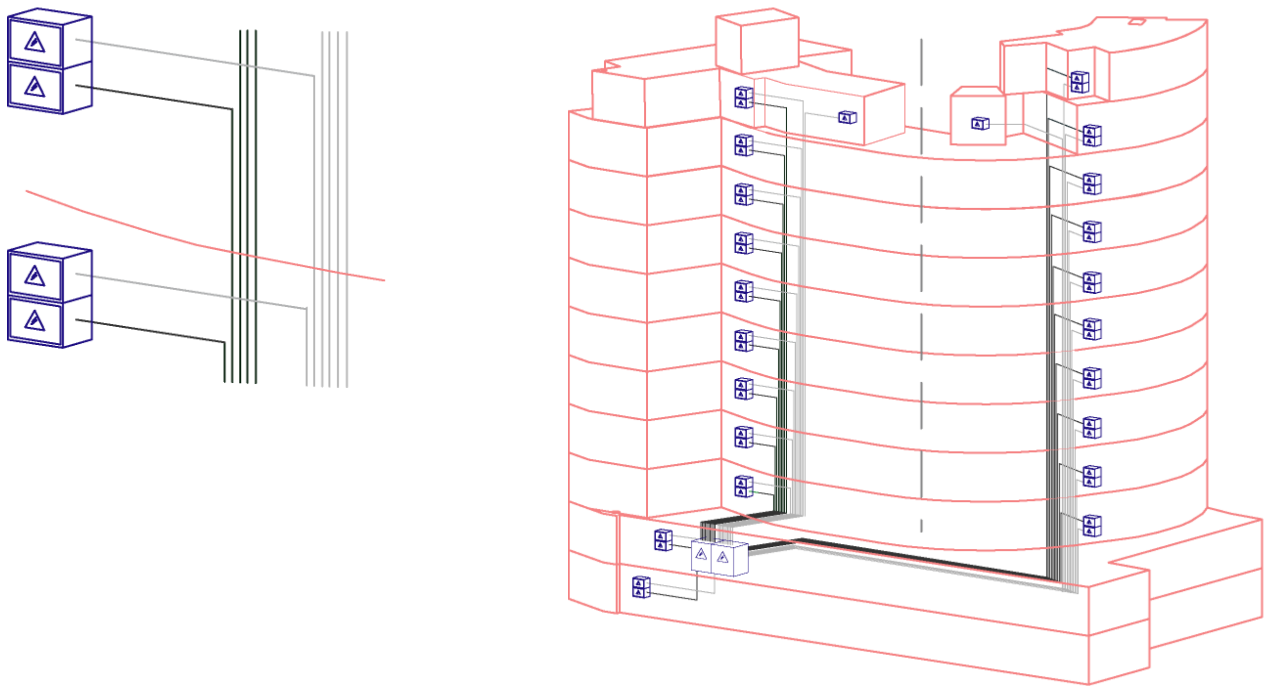

Figure 2 –Initial distribution flow chart, before the modifications. The dark lines indicate the standard distribution. The light lines indicate the privileged distribution.

LOAD

The rated load for the office building is typical and consists of:

- Elevators (approx. 80 kVA)
- Services (approx. 100 kVA)
- Air-conditioning (approx. 600 kVA)
- Horizontal distribution for lighting and power in the open office space (approx. 35 kVA per floor)

POWER QUALITY

To evaluate the quality of the power supply, current harmonic content was measured at the main electrical lines feeding each floor and at the distribution panels for building services.

Figures 3 to 6 give examples of measured current and voltage waveforms and their harmonic content. We would like to highlight the following points:

- Some phase conductors, particularly those for lighting circuits, have over 75% total harmonic current distortion (3rd, 5th, and 7th harmonic) – see Fig. 6. There is significant 3rd harmonic current distortion in circuits serving IT and lighting equipment – see Figs. 4, 5 (neutral conductor), and 6. In some neutral conductors, the harmonic currents are more than twice the phase current.
- Both UPS show current distortion in phase and neutral conductors – see Figures 4 and 5.
- Even-order harmonics appear in more than one measurement (approx. 30% in Figure 5). This means that the waveform of the current does not have the usual symmetry.
- In some cases, the waveform produces more than two zero-crossings per cycle of the sine wave (Figure 5).

- Rather high permanent currents are detected in the ground conductor. This is a typical indication that the TN-S configuration has not been preserved, i.e. that there are multiple connections between the neutral conductor and earth. It must be ensured that there is only one main earthing point with a connection between neutral and ground. On-site personnel need to be briefed to avoid making any connection between the neutral and ground in the LV distribution.

The instrument used to make these measurements was a Fluke 43 single phase, 0 - 600 V, CT 600 A / 1 mV/A power quality analyzer.

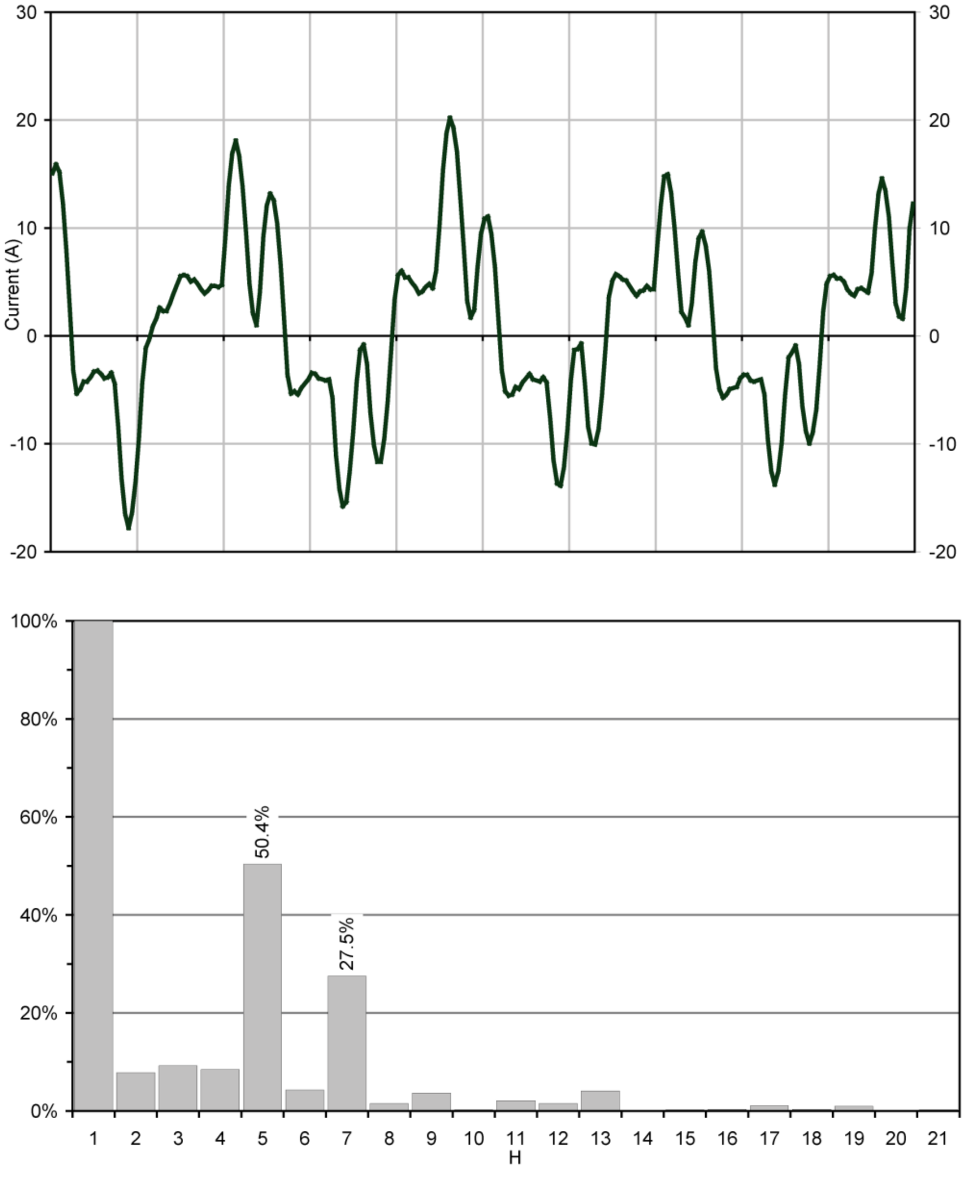

Figure 3 – Waveform and harmonic contents of phase current (phase L1) at main LV power panel in the line feeding elevators 1 and 2.

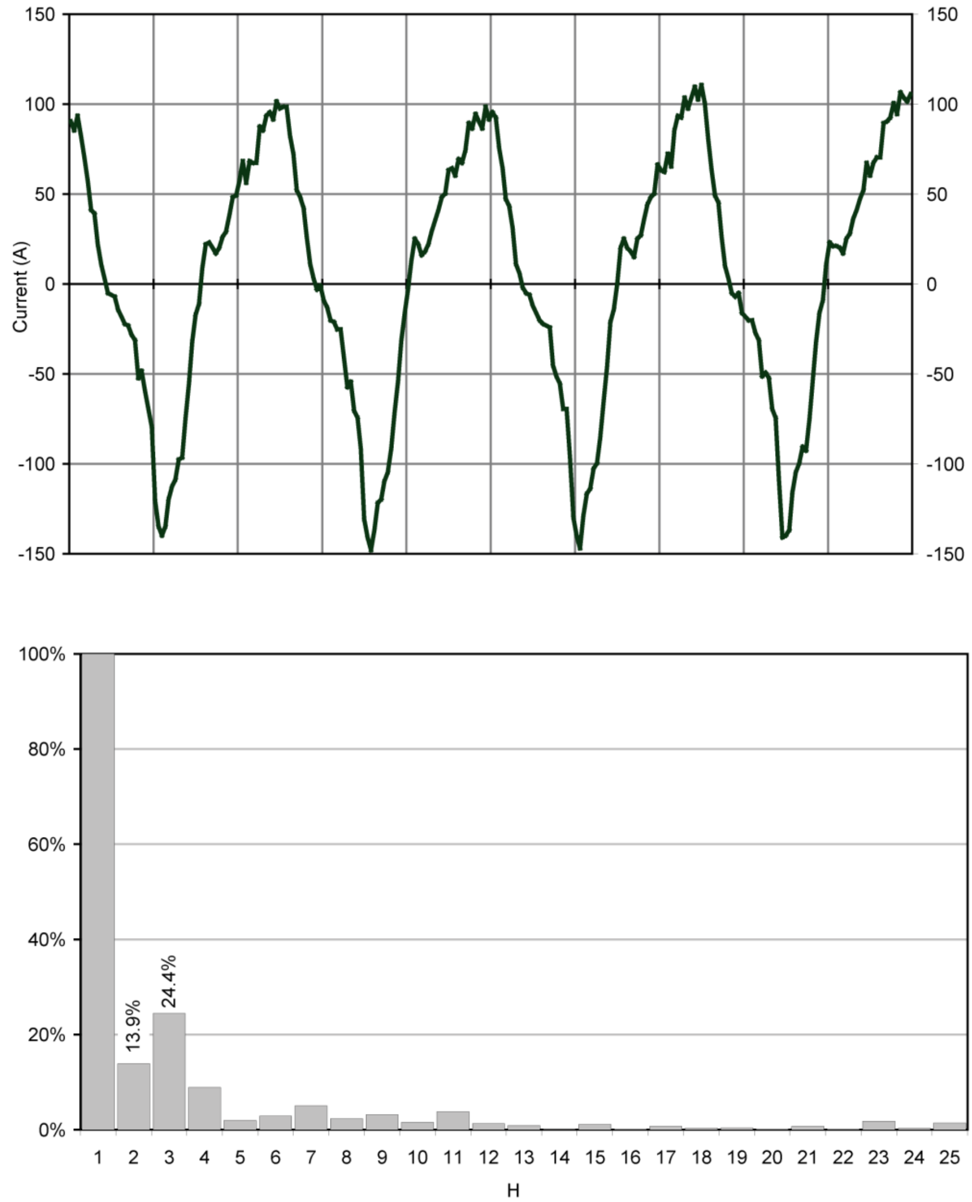

Figure 4 – Waveform and harmonic contents of phase current (phase L1) in the 80 kVA line to the uninterruptible Power Supply - UPS (open office space).

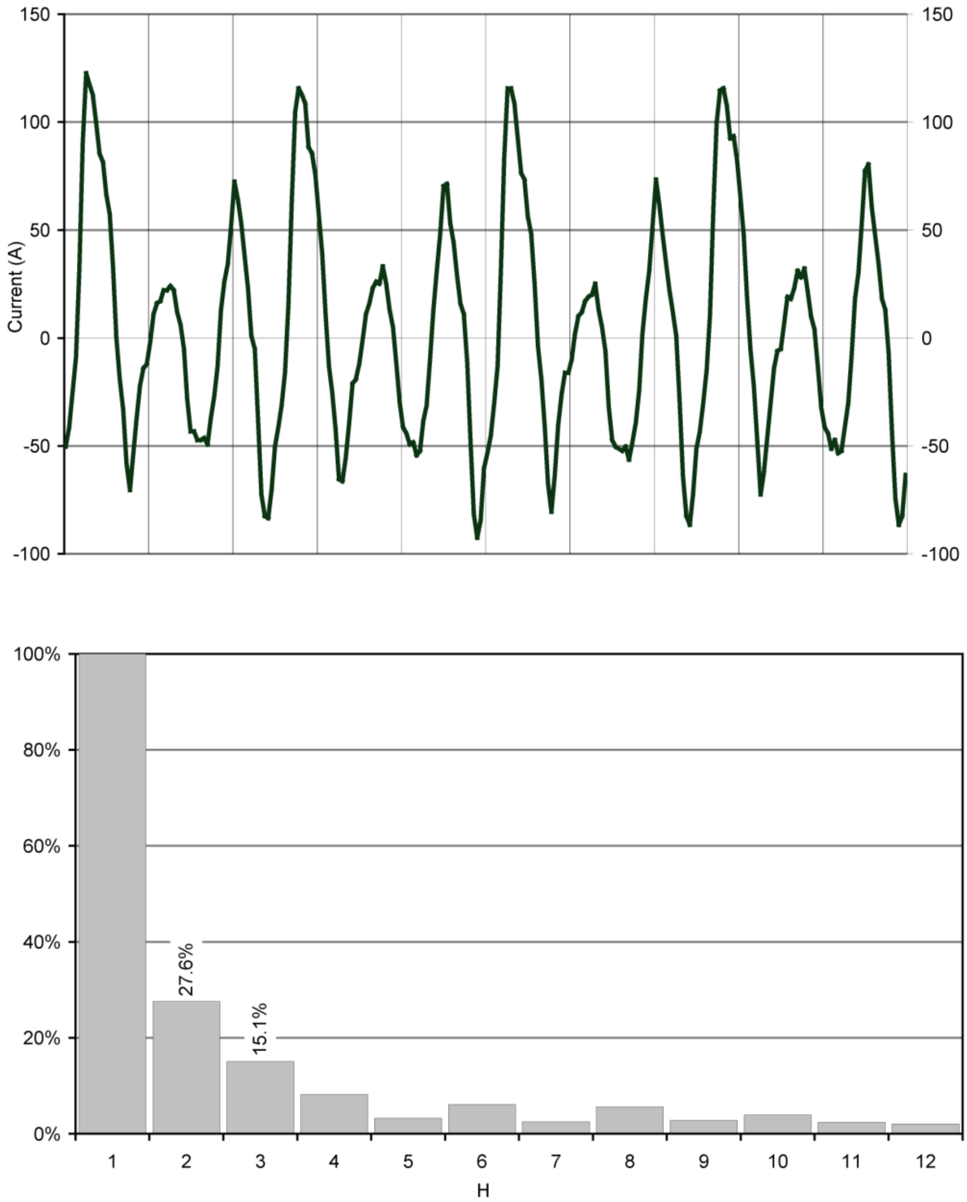

Figure 5 – Waveform and harmonic contents of neutral current in the 80 kVA UPS line (open office space).

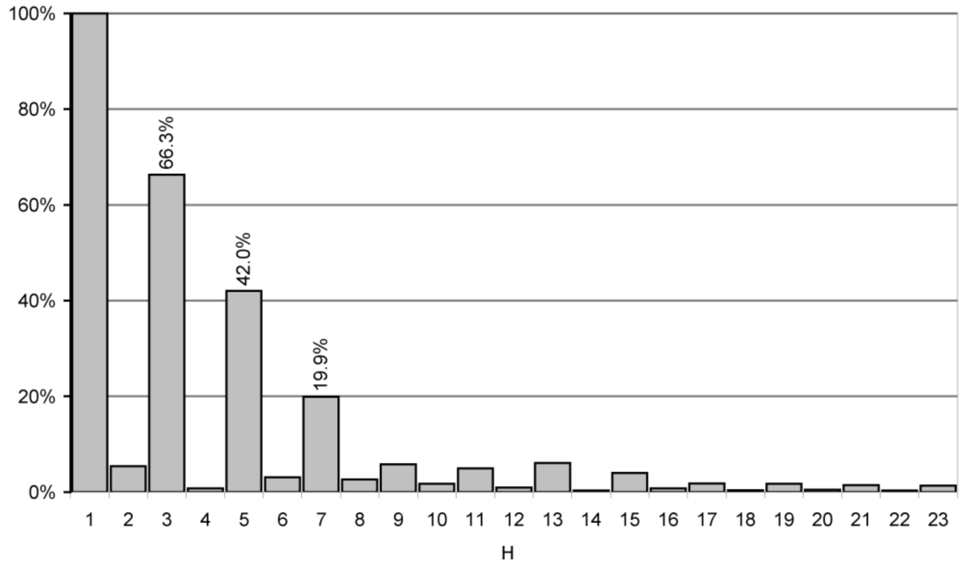

Figure 6 –Harmonic contents of phase L2 current at main LV distribution panel in the line feeding ground floor distribution panel (mainly lighting circuits).

EVENTS

The building occupant experienced a high and increasing number of events and faults, principally related to the overheating of lines and nuisance tripping of protection devices.

ANALYSIS OF THE EXISTING SITUATION

The current installation lacks organization and rationality in its approach. This is not compatible with the resilient design the company adopted at the start (supply low-voltage distribution through multiple transformers, UPS, and generator).

Some elements are not in conformance with the current standards. Even full compliance to standards does not guarantee adequate performance from a power quality and EMC viewpoint for a building with mission-critical functions.

DISTRIBUTION SCHEME

The distribution scheme is neither systematic nor rational, probably due to the numerous modifications since the original installation. There are important limitations relating to reserve capacity and independence. Some bottlenecks are present, e.g. at the level of the main LV bus bar (Fig 1). The two transformers are not independent. The floors too are not independent.

LINE OVERHEATING

The high density of information technology equipment such as PC, servers, etc. and electronic lighting produces high levels of harmonic current in many lines.

These phenomena result in neutral overheating (elevated currents in a downsized neutral as well as nuisance tripping of protective devices).

Co-ordination among protection devices and lines

The current capacities of some lines are not co-ordinated with their over-currents protection devices. The large number of lines running in the same trunking make the problem more critical because the operating temperature is higher.

Analysis of a faulty line showed that prolonged overheating was the cause of failure, due to overheating in the trunking. The grouping factors given in informative annexes of national and international wiring regulations should be observed.

Neutral Status

In case of such a multiple feed with TN-S configuration, the neutral current needs to be brought back right to the main earthing terminal. Procedures must be in place to avoid making any additional connection between neutral and ground. Such connections create alternative paths for the neutral current, thus eliminating all the benefits of having a TN-S system.

Design approach

The building occupant, operating in the financial sector, needs to upgrade the installation since reliable power quality is considered mission-critical. The problems shown by the analysis of the current situation and the PQ measurements suggest consideration of an update of the electrical system at different levels:

- Rationalization of mains distribution
- Renewal of the electrical installation on the floors

Load classification

To optimize the main distribution rationalization, the first step is the classification of the loads. All loads are classified into 3 groups:

- Standard
- Preferential
- Privileged

Standard loads are used for daily business, but their non-availability does not result in risk of personal injury, damage to equipment or disruption of business processes. A simple radial circuit suffices for the supply and relatively long intervention times can be tolerated (Table 1).

Preferential loads need a redundant power supply, for example as provided by a dual radial scheme, starting either from the risers or at the level of intermediate connections (Table 2).

Privileged loads are mission-critical. Loss of service means grave danger to personnel or severe damage to the organization’s business processes. The level of independence needs to be determined for each load. At the very least, these loads must be supplied from two independent feeders with automatic switching (Table 3).

Description of standard load	Type of power supply required	Timing needed for intervention
Allows regular functioning of the building, but their unavailability does not result in risk to personnel or equipment: - General services, e.g. air conditioning (but not in server room) - Normal lighting - Heating - Power sockets	Standard radial circuits. Resumption of service can wait for some time without damage. Loads can be switched off.	None Unavailability of service for relatively long time periods can be tolerated.

Table 1 – Description, criteria, design, and intervention requirements for standard loads.

Description of preferential load	Type of power supply required	Timing needed for intervention
Regular functioning of the load is required for comfort and security of personnel and clients, as well as for ensuring smooth business operation. For example: - Lighting of staircases, corridors, and certain rooms - Minimum lighting conditions to avoid panic - Heating or air conditioning of certain rooms - Elevators - UPS	Backup Dual radial primary supply, ensuring the functional and physical independence of the risers. Two separate risers can be employed, supported either by a generator or supplied from two independent grid points. Switching off the load is not acceptable.	According to the norm, a 20 second intervention time for the generator group is acceptable for long interruptions. Typical values for a diesel group: - First attempt: within 5 seconds - Second attempt within 10 seconds - Third attempt within 15s

Table 2 – Description, criteria, design, and intervention requirements for preferential loads.

Description of privileged load	Type of power supply required	Timing needed for intervention
Essential services: - Security lighting - Servers - Telecommunication systems - Personnel retrieval - Alarm & security systems - Fire signalling and anti-fire systems - Closed-loop TV circuits - Certain auxiliary services	Secure Dual radial scheme, with independent risers. At least one riser has to ensure high grid reliability Use of UPS. For certain loads, a dedicated UPS can be considered.	Loads with intervention within 15 seconds. Short-interruption loads, within 0.15 s Some loads need continuous supply.

Table 3 – Description, criteria, design, and intervention requirements for privileged loads.

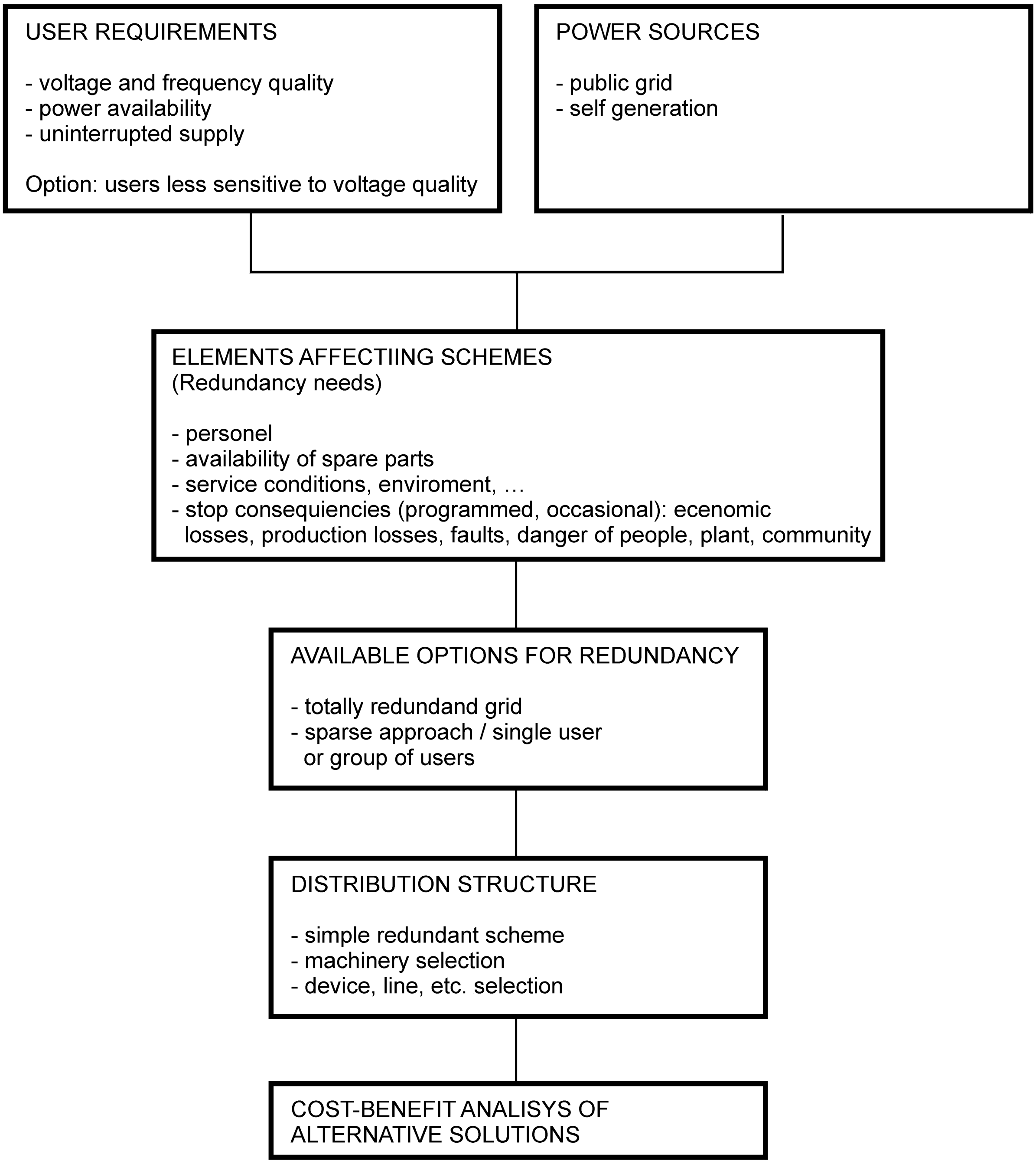

Figure 7 – Flow chart of activities for selecting the right distribution scheme.

In co-operation with the building occupant, all loads have been classified as shown in Table 4.

Type of load	Percentage
Standard	49%
Preferential	13%
Privileged	38%

Table 4 – Classification of type of loads.

Component type	# Outages per 1000 Components per Year	# Outages per Components per Year	Failure Rate
MV/LV transformers	1-2		
MV and LV circuit breakers	0,2-1		
Disconnect switches	1-4		
Electronic relays (single)	5-10		
Electronic relay systems	30-100		
Standby generators		20-75	
failure to start			0,5-2%
Continuous generators		0,3-1	
UPS inverter		0,5-2	
UPS rectifier	30-100		
Underground cable (1000 m)	13-25		
Cable terminations	0,3-1		
Cable joints	0,5-2		

Table 5 – Electrical components used in MV-LV distribution installation dependability statistics (Source: M. H. J. Bollen, Literature search for reliability data of components in electric distribution networks, Eindhoven University of Technology Research Report 93-E-276, August 1993).

MAIN DISTRIBUTION SCHEMES

To avoid the existing bottleneck at LV main bus bar, the primary distribution must be modified as a dual radial distribution (Fig. 8 left).

The rating of the transformers TR1 and TR2 must ensure that each can carry the full load. Considering that, because of the nature of the loads, the load current waveform will be highly distorted, the transformers must be sized to take account of the harmonic content.

To reduce short circuit currents, the system is normally managed with the main bus bar-breaker open, but parallel operation between the two main transformers is possible for short time.

To feed the thermal and HVAC services, the transformer section shall be modified as shown in Figure 8 with a new 800 kVA transformer, TR3, in addition to the existing two. The new transformer has been selected according with the series A0Ak of the standard EN 50546-1 to minimize the losses.

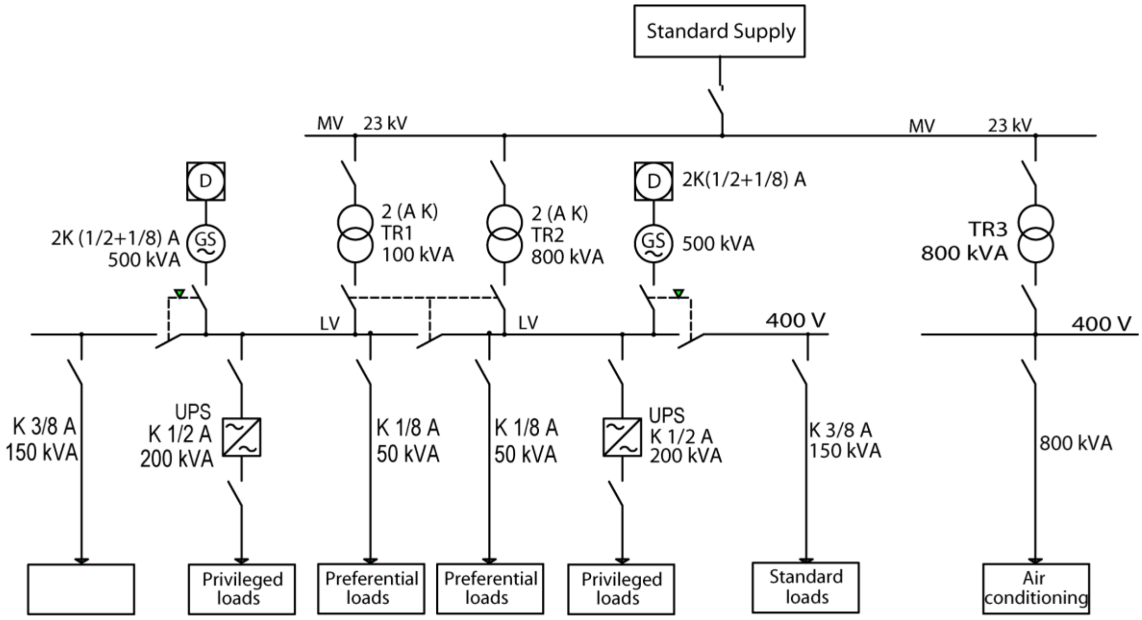

Figure 9 – Main distribution scheme after the modifications.

Standard loads are supplied from a single grid point. The same grid power cable, riser, and radial distribution also supplies preferential and privileged loads.

Two generator groups supply preferential and privileged loads. Standard loads are switched off through the breakers at the extremity of the main bus bar.

Two UPS supply privileged loads, in case of failure of normal and backup power supply.

Primary supply and backup supply is wired TN-S. UPS can be wired either TN-S or IT (meaning, here, isolated earth). Isolated earth systems are excellent for continuity of power supply, but cannot guarantee protection of personnel. Where an IT system is installed, proper security measures have to be taken to ensure that only authorized personnel can have access to the IT circuits.

The second LV PCC has been removed in Figure 8.

Each floor is still supplied by two distribution panels, each having three sections (standard, privileged and preferential) corresponding to the same sections of the main LV power panel.

Final distribution could be done using a shunt (Figure 9) or single radial (Figure 10) scheme.

The shunt scheme (shared line feeding all floors for each type of loads) is cheaper and more flexible in the case of load growth. Unfortunately it is limited by poor resilience to faults in the main line and risers.

The single radial scheme (one line for each floor for each type of load) ensures:

- Minimum interference and voltage drop caused by load
- In case of a fault, only loads supplied by the faulty line are out of service
- Reduced maintenance problems

The radial scheme is therefore the preferred scheme.

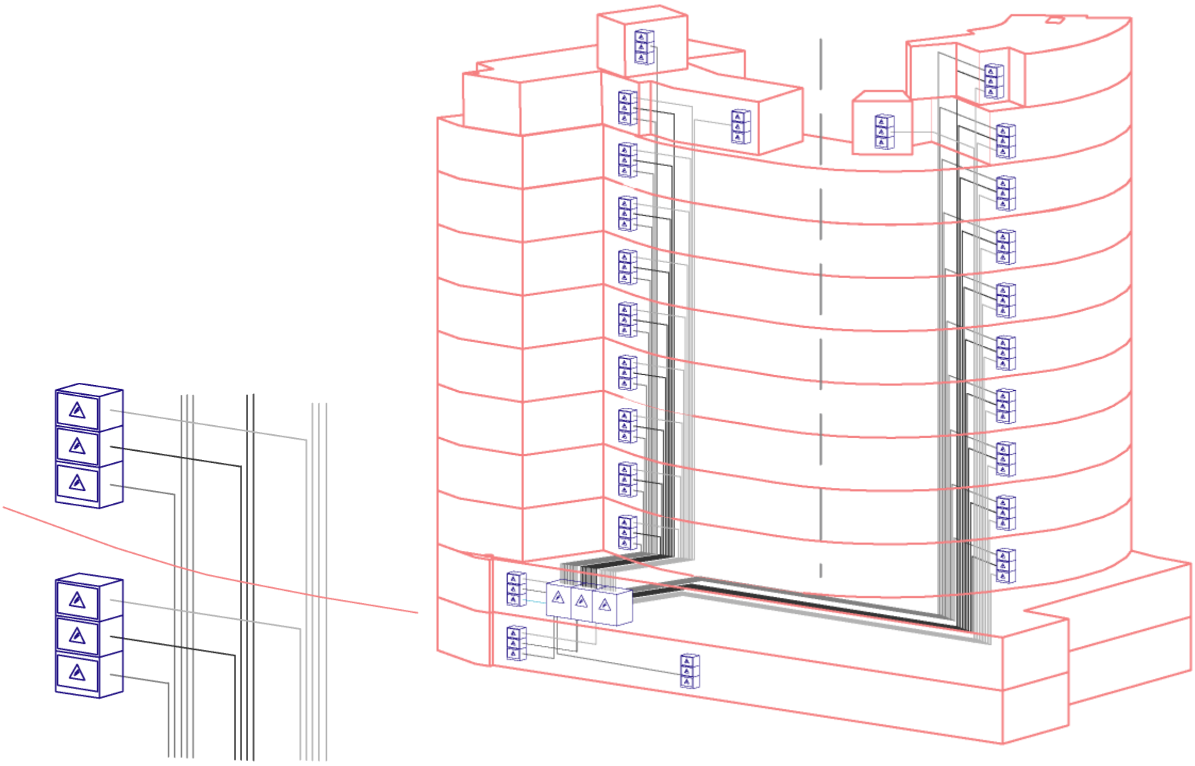

Figure 9 – Solution with radial scheme (10 floors with three types of load = 30 dedicated rising lines). Dark line indicates standard distribution; grey line, preferential distribution; light line, privileged distribution.

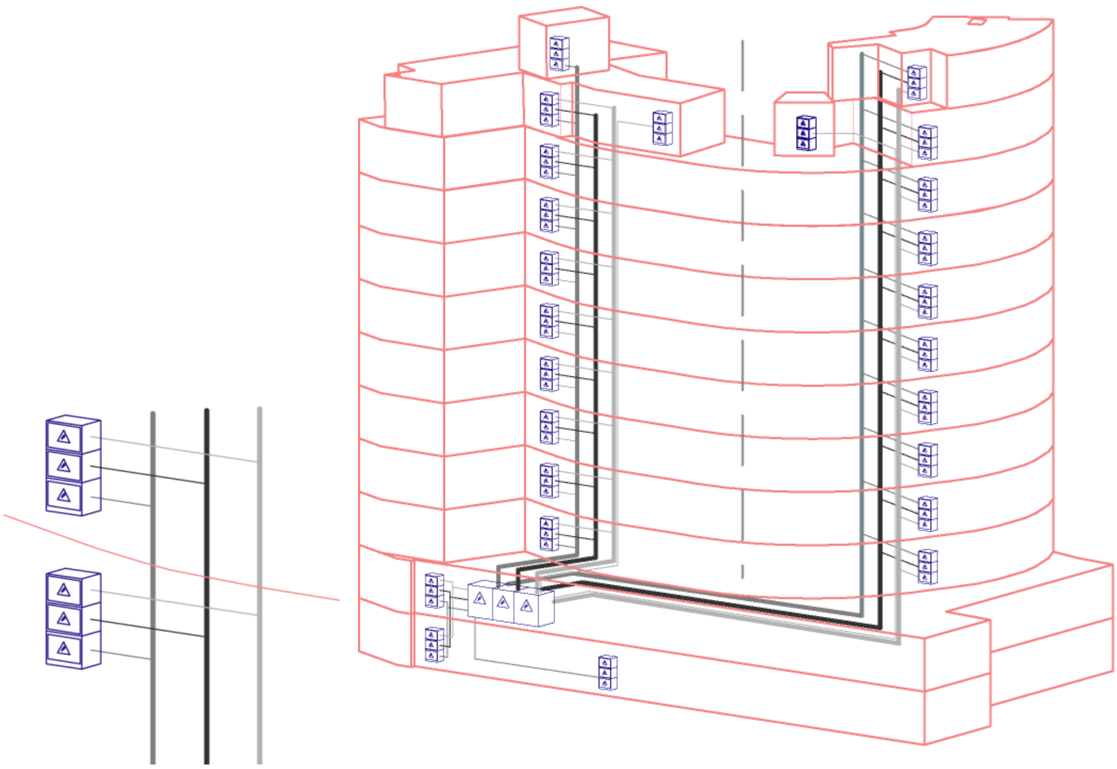

Figure 10 – Solution with unique riser lines (three types of load = three rising lines / bus bar, shared by all floors). Dark line indicates standard distribution; Grey, preferential distribution; Light, privileged distribution.

LINE SIZING

Table 6 shows the power-considered sizing all the main sections of the system.

The total installed load (Columns 2 and 3) is multiplied by utilization and contemporary factors (Columns 4 and 5) to calculate the power requirements of the load (Columns 6 and 7). As a margin for future load growth, lines are sized (Columns 8 and 9) considering an additional factor equal to 130% and 115% for power and lighting circuits respectively.

Load	Installed load (kVA)		Utilization & Contemporary Factors		Power requirement (kVA)		Installed power (kVA)	
	Power (1)	Light (2)	Power (3)	Light (4)	Power (5)	Light (6)	Power (7)	Light (8)
2nd underground	7	10	0.7	1	5	10	6.5	11.5
1st underground	114	15	0.7	1	80	15	104	17.25
Ground and general services	43	15	0.7	1	30	15	39	17.25
First floor	50	17	0.7	1	35	17	45.5	19.55
Second floor	50	17	0.7	1	35	17	45.5	19.55
Third floor	50	17	0.7	1	35	17	45.5	19.55
Fourth floor	50	17	0.7	1	35	17	45.5	19.55
Fifth floor	50	17	0.7	1	35	17	45.5	19.55
Sixth floor	50	17	0.7	1	35	17	45.5	19.55
Seventh floor	50	17	0.7	1	35	17	45.5	19.55
Eighth floor	29	12	0.7	1	20	12	26	13.8
Nine floor	3	2	0.7	1	2	2	2.6	2.3
Thermal Central	29	0	0.7	--	20	0	26	0
HVAC main station	843	0	0.7	--	590	0	767	0
Boxes	14	5	0.7	1	10	5	13	5.75
Elevators	114	0	0.7	1	80	0	104	0
TOTAL	1546	178	--	--	1,082	178	1,407	204.7

Table 6 – Peak-rated and actual sizing of primary distribution system.

Considering the measured waveform of the current, all the new lines have been sized to take into account the harmonic profile and resilience requirements:

- Neutral cross section equal to that of phase
- Derated cables

Special attention should be paid to neutral and phase conductor sizing to avoid overheating and faulty tripping of protection devices. The adoption of a UPS or motor generator is not useful if a line fault occurs after it.

Cost analysis

The cost of existing installation is compared with two possible alternative solutions. These alternatives differ only for risers, and hence for the cost of the main LV panel.

Solution 1 is the shunt scheme, and Solution 2 is the simple radial scheme, which is preferable for new buildings, but difficult to implement as an installation upgrade.

Cost when selected at initial design stage

Item	Existing (k€)	Solution 1 (k€)	Solution 2 (k€)
Main LV panel	62,949	68,850	88,522
Risers	59,015	68,850	118,029
Horizontal distribution	210,485	265,565	265,565
Generator groups	171,142	210,485	210,485
UPS	108,193	206,551	206,551
Motive power	698,339	737,682	737,682
Lighting	983,576	1032,754	1032,754
Total	2293,698	2590,738	2659,589
Total Absolute difference	--	297,040	365,890
Total Relative difference	--	13%	16%

Table 7

Cost for installation upgrade

Total absolute difference	--	830,138	1068,163
Total relative difference	--	36%	46%

Table 8

Regarding this situation, we would like to highlight the following:

- The percentages refer to the cost of the existing installation
- The extra cost of the better solutions is low, if considered at initial design stage
- The cost of the best technical solution (i.e. Solution 2 – single radial scheme at final distribution) differs only by 3% from Solution 1 if considered at initial design stage, but the difference is much greater if considered at refurbishment stage only
- Cost basis 2011
- The cost for the UPS considers only purchase and installation. The additional costs of maintenance must be taken into account

Even if the evaluation of average costs related to a system designed according to good PQ practice is difficult, we have to recognize that:

- The cost estimates include the costs related to the practical difficulties of installing and renewing a building in the center of a major city
- The modification of the main distribution scheme is the most important and useful action to undertake
- The solution with unique riser lines is very difficult to install with the building operational

CONCLUSION

Initial low cost does not necessarily mean good value. A PQ compliant system, initially more expensive, can save a great deal of money during its life. The case study analyzed in this article shows that an electrical installation, designed without attention to PQ issues, results in a considerable amount of unnecessary expenditure, whether to resolve the issues or to simply live with the inconvenience and downtime they cause.

The cost/benefit analysis shows that resilience should be carefully considered at design stage. A mere increase of 16% in the installation cost (1% of the building cost) provides:

- Three lines of defense against power cuts for mission-critical loads (dual panels at each floor, generator, UPS)
- A highly resilient system, with each floor supplied by 2 distribution panels. Each panel is independent from the other, and from all panels on the other floors
- A highly flexible electrical system for future load growth

Expensive though it may seem, the highly resilient solution would typically add only about 1% to the cost of the building. For commercial buildings, where the running costs amount to initial construction costs after 7-8 years, this initial investment will be paid pack by a productivity increase of 10 min per week. Once paid back, all the rest is profit.

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