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Original Article

A Service-Constrained Multi-Level Framework for Energy Loss Minimization in Electrical Loads: Integrated Assessment on a Rural Distribution Network

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Abstract *- Energy-efficiency measures for lighting, buildings and public infrastructure are usually planned and reported one at a time, so their savings cannot be ranked against each other, funded from one budget or traced to the network that carries them. This paper formulates device retrofit, facility design and operational control as one mixed-integer program, the Service-Constrained Energy Minimization (SCEM) model. Lamp models, appliance ratings and street switching are decision variables in a single problem with illuminance, cooling, switching-window and phase-balance constraints, a common lamp-procurement constraint and a shared budget, and the objective weights each saving by the network loss it avoids at its hour. The model is solved by branch-and-bound and applied to Chandragiri Mandal, Andhra Pradesh, using a field inventory of 3,170 road lights, a 29-room hospital design and household lamp statistics. With the full budget of Rs 28.2 lakh, the program selects 5-star 9 W lamps, BLDC fans, 5-star air conditioners and switches on 118 streets, saving at most 124,076 kWh/yr. With Rs 3 lakh, it saves 67,769 kWh/yr, against 27,715 kWh/yr when the same money is split among the measures in proportion to cost. Choosing the 923 lm lamp implied by the published hospital design would remove the household saving entirely. A load flow on a representative feeder calibrated to the approved 10.88% loss gives 23,800 to 37,800 kWh/yr of avoided losses. Monte Carlo analysis gives a median end-use saving of 85,600 kWh/yr (90% interval 65,600 to 108,500) and a positive net present value in 99.8% of cases. All savings are model estimates; the road-light inventory is the only field-measured input.*

Keywords *- Demand-Side Management, Distribution Losses, Energy Efficiency, Mixed-Integer Programming, Phase Imbalance, Street Lighting.*

1. Introduction

Electricity demand in India grew at about 5.7% a year between 2012-13 and 2021-22, and lighting, fans and air conditioning take a large share of residential, commercial and public use. How much energy these loads draw is fixed by three decisions: which devices are installed, how the building or system is designed, and how it is operated. Each kilowatt-hour they waste also carries a network cost, because it is delivered through 33 kV, 11 kV and LT lines and transformers; in Andhra Pradesh the approved 33 kV-to-LT loss is 10.88%.

Utilities and local bodies rarely act on one of these decisions alone. A rural mandal may at the same time retrofit household lamps, build a hospital and repair road-light switching, all from a limited budget and on the same feeders. Planning them separately leaves three questions open: which measure should be funded first, whether a choice made for one measure constrains another, and how much network loss the combined programme avoids. Earlier work by the authors developed one method for each decision [1-3]. Those studies used different procedures, constants and sites, and reported savings only at the meter, so they cannot answer these questions.

This paper builds a single optimization model for the three decisions and evaluates it on one network. Table 1 separates what is taken from the earlier studies from what is developed here. The contributions are: (i) a mixed-integer formulation in which retrofit, design and operational variables share one objective, one lamp catalogue, one procurement constraint and one budget; (ii) identification of the lamp implied by the published hospital design and a check of how far that identification holds; (iii) a budget frontier showing

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what joint allocation gains over separate allocation; (iv) a load-flow evaluation of avoided losses on a representative feeder, with explicit calculation boundaries; and (v) life-cycle economics and Monte Carlo uncertainty for every reported result.

Table 1. Reused inputs and new contributions

Element	Source	Status in this paper
BEE lamp catalogue; lumen-equivalence replacement rule	[1]	Reused as input data
Hospital room plan, appliance ratings, phase loads	[2]	Reused as input data
Road-light inventory: 3,170 lights, 417 on in daytime, 12.73 kW	[3]	Reused as input data
Street-level distribution of day-on lights; targeted switching	Survey file of [3]	New analysis
Unified mixed-integer model with coupling and budget constraints	-	New (Sections 3.1-3.2)
Lamp implied by the hospital design (923 lm); coupling saving	-	New (Section 3.3)
Household tube stock of the mandal	Census 2011; CEEW [22]	New to this work
Common schedules, constants and tariff for all measures	-	New (Section 3.6)
Load-flow loss evaluation and calculation boundaries	-	New (Section 3.4)
Life-cycle economics and Monte Carlo uncertainty	-	New (Section 3.5)

2. Literature Review

2.1. Lighting Retrofit

LED sources have the highest efficacy and the lowest life-cycle cost of common lamps, and LED systems cut indoor lighting energy substantially [4-6]. Adaptive controls add further savings, and energy labels influence purchase [7,8]. These studies compare technologies; they do not give a rule for choosing a replacement lamp that keeps the delivered illuminance, which is where a poorly chosen low-wattage lamp can leave a space under-lit.

2.2. Building and Healthcare Energy

Hospitals use about 0.27 MWh/m² a year [9]. Wider windows with suitable glazing and daylight-linked dimming can lower the primary energy demand of patient rooms by up to 17% [10], and medical equipment and building management systems have been studied separately [11,12]. These studies address existing buildings or single subsystems, not the choice of lamps, fans and air conditioners room by room before construction.

2.3. Street-Lighting Control

Sensors, LDR, GPS and IoT controllers reduce unnecessary operation of urban street lights [13-15]. Rural lights wired without switches, or with failed switches, are a different problem: they stay on through the day, and their loss had not been measured before the field survey of [3].

2.4. Network Impact of Demand-Side Measures

Technical losses vary with the square of current, so a saving at peak avoids more loss than the same saving off-peak. Empirical loss-factor relations of the form $LLF = k \cdot LF + (1 - k) \cdot LF^2$, with k between about 0.08 and 0.3, link energy losses to peak losses [16]. Because demand varies across the day, consumption timing directly affects losses, which is an argument for demand-side measures [21].

A measurement-based evaluation of a utility efficiency portfolio found savings above 12% at territory level and up to 42% on individual feeders [20]. Distribution-transformer losses are bounded by IS 1180 [17]. Phase imbalance raises neutral current and loss; imbalance of 25% or more is classed as poor [18], and optimal phase swapping on a Taipower feeder cut neutral current from 93 A to 25 A and daily loss from 2.8% to 1.8% [19].

2.5. Research Gap

Studies at each level are mature, but none of those reviewed formulates retrofit, design and operational measures as one optimization problem with shared variables and a shared budget, or evaluates the combined measures with a network model of the feeder that serves them.

Without such a model, it is not possible to say which measure a limited budget should fund first or how a lamp choice in one programme affects another.

3. Materials and Methods

The model is summarized in Figure 1, and the symbols are listed in Table 2.

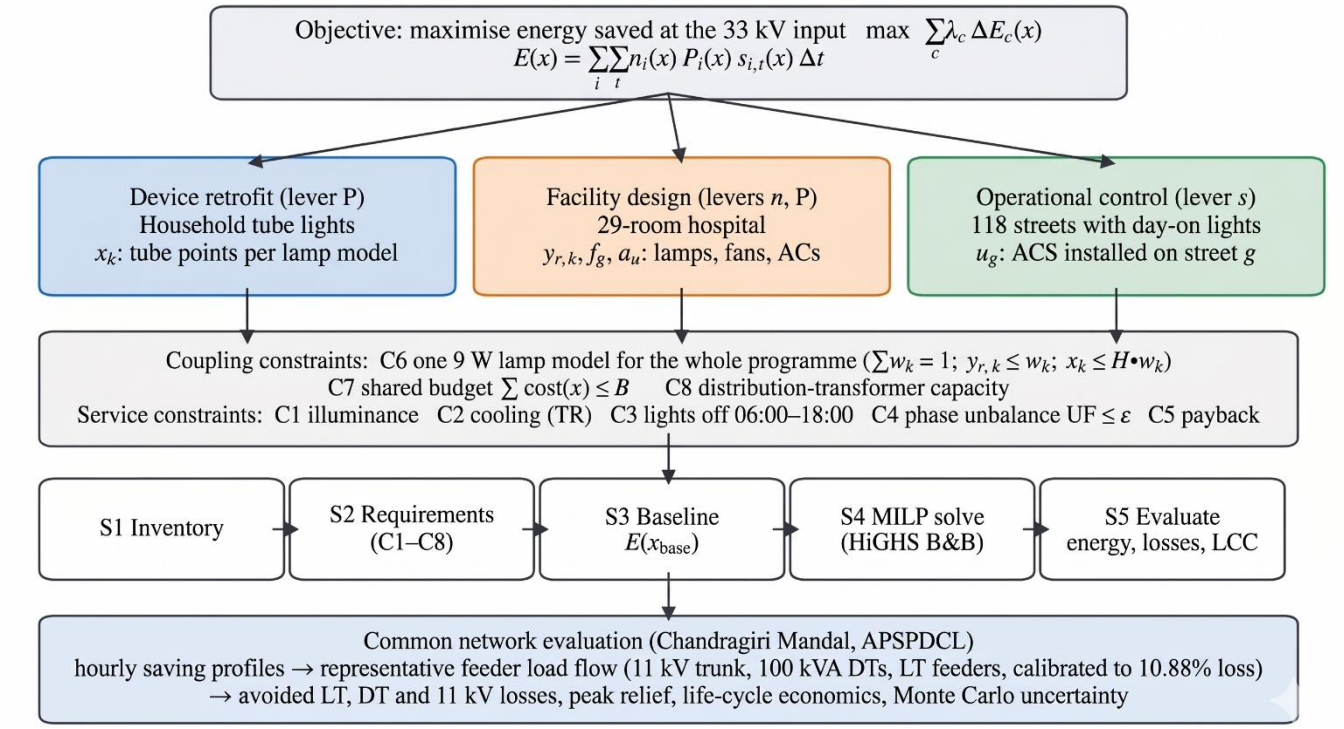


Fig. 1 Structure of the SCEM model: one objective, three groups of decision variables linked by coupling constraints, a five-step procedure and evaluation on a common network

Table 2. Nomenclature

Symbol	Meaning	Unit
E, ΔE	Annual energy; energy saved	kWh/yr
n_i, P_i, $s_{i,t}$	Count, power and on-state of device type i at hour t	-, W, 0/1
E_r, A_r, h_r	Required illuminance, area and annual lighting hours of room r	lux, m², h
Φ_k, c_k	Lumens and price of 9 W lamp model k	lm, Rs
N_{rk}, m_k	Lamps of model k needed in room r; per tube point	-
y_{rk}, w_k	Room r uses model k; model k procured (binary)	-
x_k	Household tube points retrofitted with model k (integer)	-
f_g, a_u	BLDC fans in group g (integer); 5-star AC in unit u (binary)	-
u_g	Astronomical clock switch (ACS) on street g (binary)	-
B, λ_c	Budget; loss weight of measure c	Rs, -
CUF, MF	Utilization and maintenance factors	-
L, LF, LLF	Loss fraction, load factor, loss load factor	-
S_r, S_1, ΔS	DT rating, loading and load removed	kVA
UF	Phase unbalance factor	%

3.1. Unified Formulation

Annual energy of any group of loads is the product of how many devices there are, their power and how long they are on (Equation 1). Retrofit changes P, design changes n and P, and operational control changes s.

$$E(x) = \sum_i \sum_t n_i\,(x)\, P_i(x)\, s_{i,t}(x)\, \Delta t \qquad (1)$$

The three measures are optimized together. The objective is the energy saved at the 33 kV input, that is, the end-use saving of each measure c multiplied by a loss weight λ_c that depends on when the saving occurs (Equation 2). The weights come from the load flow of Section 3.4: 1.415 for household lighting, which falls on the evening peak, 1.234 for the hospital and 1.217 for daytime road lights.

$$\max_x \sum_c \lambda_c\, \Delta E_c(x), \qquad \Delta E_c = E_c(x_{base}) - E_c(x) \qquad (2)$$

The decision variables of the three measures are given below, with C1 (illuminance) built into the admissible counts. In the hospital, each room r uses either the 40 W design fitting or one 9 W model k, in the number N_{rk} needed to meet its

illuminance (Equation 3). In households, each 36 W tube point retrofitted with model k needs m_k lamps so that the replacement gives at least the tube is 3,350 lm (Equation 4). Each street g with day-on lights receives an ACS or not (Equation 5), which enforces C3, lights off between 06:00 and 18:00.

$$\Delta E_{h,L} = \sum_r \frac{h_r}{1000}\left(40N_r^{40} - \sum_k 9\ y_{rk}N_{rk}\right), \quad N_{rk} = \left\lceil \frac{E_r A_r}{\Phi_k\ CUF\ MF} \right\rceil \tag{3}$$

$$\Delta E_{hh} = \sum_k x_k\ \frac{(36 - 9m_k)\ h_{hh}}{1000}, \qquad m_k = \left\lceil \frac{3350}{\Phi_k} \right\rceil \tag{4}$$

$$\Delta E_{rl} = \sum_g u_g\ \frac{P_g\ h_{day}}{1000}, \qquad h_{day} = 4380 \text{ h/yr} \tag{5}$$

Fan and air-conditioner terms are linear in f_g and a_u, with the savings of 52 W to 26 W BLDC fans and of 1.4 kW/TR to 0.99 kW/TR units at fixed tonnage (C2). The three measures are linked by two coupling constraints. First, one 9 W lamp model is procured for the whole programme, so the households and the hospital draw on the same choice (Equation 6, C6). Second, all investments share one budget B (Equation 7, C7). Each room takes exactly one option, and no more than the H existing tube points can be retrofitted (Equation 8).

$$\sum_k w_k = 1, \qquad y_{rk} \le w_k, \qquad x_k \le H\ w_k \tag{6}$$

$$\sum_{r,k} y_{rk}\ (c_k N_{rk} - c_{40} N_r^{40}) + \sum_k c_k\ m_k x_k + c_f \sum_g f_g + c_a \sum_u a_u + c_s \sum_g u_g \le B \tag{7}$$

$$y_{r,40} + \sum_k y_{rk} = 1\ \ \forall r, \qquad \sum_k x_k \le H \tag{8}$$

Distribution-transformer Capacity (C8) and phase balance (C4, UF ≤ 2%) are checked on the solution; both are slack because every measure removes load. Taking the worst case in which the whole lighting reduction of the hospital falls on one phase, UF rises from 0.27% to 1.07%. The payback limit (C5) is not imposed in the base runs so that the budget frontier shows the full trade-off.

3.2. Solution Algorithm

The model has 381 variables (all integer or binary) and 250 linear constraints. It is solved with the HiGHS branch-and-bound solver [23] to a relative gap of 10^{-6}; each solve takes about 0.3 s. The procedure follows the five SCEM steps:

S1, Inventory: rooms, appliances, tube points and streets with their ratings. S2, Requirements: illuminance, tonnage, switching window and unbalance limit; options that violate C1 are removed before optimization (for example, a single 30 W lamp of 3,150 lm cannot replace a 3,350 lm tube). S3, Baseline: energy of the 40 W fittings, 52 W fans, 1.4 kW/TR air conditioners, existing tubes and uncontrolled lights. S4, Optimization: compute λ_c by load flow, solve Equations 2-8 for a given B, and repeat over a range of B to trace the budget frontier. S5, Evaluation: energy, avoided losses, peak demand, transformer loading, life-cycle cost and uncertainty, with the constants of Section 3.6.

For comparison, a separate-planning case gives each measure a share of B in proportion to its full investment and solves each measure on its own share. This represents three programmes planned independently.

3.3. Lamp Implied by the Hospital Design

Applying Equation 3 to the rooms of the hospital shows that the published 9 W counts [2] are reproduced with Φ ≈ 922-925 lm per lamp (about 102 lm/W), between the 2-star (900 lm) and 3-star (945-950 lm) lamps of the catalogue [1]. With Φ = 923 lm the counts agree exactly in 23 rooms: the 8 ground-floor rooms whose labels match between the room and lamp tables of [2], and all 15 first-floor rooms. The 40 W option is reproduced with Φ ≈ 2,960 lm, and rebuilding the ground floor gives the published 28 fittings.

The identification does not hold for 7 ground-floor rooms (R4-R9 and R16), whose rows in [2] cannot be matched to the room list. For these, illuminance was assigned by room type (300 lux clinical, 100 lux toilets and scanning, 150 lux open areas), and the rebuilt ground-floor total is 65 lamps against 68 published. These rooms are marked in Appendix 1. Replacing the 923 lm lamp with the 5-star lamp (1,215 lm) saves 951 kWh/yr under the schedule of Section 3.6, of which 782 kWh/yr comes from the 23 verified rooms and 169 kWh/yr from the 7 assumed rooms. The saving therefore lies between 782 kWh/yr (verified rooms only) and 1,018 kWh/yr (measured against the published 68 ground-floor lamps); 951 kWh/yr is used, and it is part of the hospital saving, not an addition to it (Table 4).

Table 3. Hospital lighting by lamp model

Lighting design	Lamps	Load (W)	Saving vs 40 W
40 W fittings (baseline)	54	2,160	-
Published 9 W design [2]	127	1,143	47.1%
Rebuilt room by room, 923 lm	124	1,116	48.3%
4-star, 1,150 lm	102	918	57.5%
5-star, 1,215 lm (selected)	98	882	59.2%

3.4. Network Model and Calculation Boundaries

Feeder-level measurements are not available for the mandal: transformer-wise loading is not published, and fewer than a quarter of distribution transformers in the state are

metered. Avoided losses are therefore estimated in two independent ways and compared.

Analytical bounds. With loss fraction L, load factor LF and loss load factor LLF = k·LF + (1 - k)·LF² (k = 0.2), the peak loss fraction is l_{pk} = L·LF/LLF, and the avoided loss on an average and on a peak-marginal basis is given by Equation 9, where p is the relative system load when the saving occurs.

$$\Delta E_{loss}^{avg} = \frac{\Delta E}{1-L} - \Delta E, \qquad \Delta E_{loss}^{marg} = \frac{\Delta E}{1-2\,l_{pk}\,p} - \Delta E \tag{9}$$

Load flow. A representative rural network was built with 25 transformers of 100 kVA on an 11 kV ACSR Rabbit trunk and three 3-phase, 4-wire LT feeders per transformer, each with ten load points. Conductor resistance is corrected to 65 °C, transformer losses follow IS 1180 (83 W no-load, 1,567 W full-load copper), the power factor is 0.9 and the transformers peak at 70% loading. The hourly load shape has its peak at 19:00-21:00 and a load factor of 0.64; its loss load factor is 0.442, close to the 0.456 given by the formula with k = 0.2. Line lengths were scaled until the annual technical loss equalled the approved 10.88%, which gives a 24.9 km trunk and 0.93 km LT feeders, typical of rural feeders in the region. A backward/forward sweep [24] is run for each hour with and without each measure's hourly saving profile (Figure 4), and the difference in annual loss is the avoided loss. The calibration attributes the whole approved loss to load-dependent losses; a share of 5-30% of fixed losses (core losses and upstream equipment) is treated as uncertain in Section 3.5.

Transformer copper loss for a single transformer is also given by Equation 10, and the LT line loss of the hospital service with neutral current by Equation 11.

$$\Delta P_{cu} = P_{cu,FL}\left[\left(\frac{S_1}{S_r}\right)^2 - \left(\frac{S_1 - \Delta S}{S_r}\right)^2\right] \tag{10}$$

$$P_{line} = R\,(I_R^2 + I_Y^2 + I_B^2) + R\,I_N^2 \tag{11}$$

Calculation boundaries. The quantities reported in Section 4 are of three kinds and are never added across kinds unless stated (Table 4). End-use savings are measured at the customer meter. Avoided network losses are the extra energy saved between the meter and the 33 kV input; transformer copper-loss reductions are a part of these losses and are shown only to explain where the losses fall. The phase-balance benefit compares the balanced hospital design with hypothetical unbalanced allocations; it is not included in either total, because the end-use saving does not depend on phase allocation and the network model assumes balanced loading.

Table 4. Calculation boundaries of reported quantities

Quantity	Boundary	Included in	Not added to
End-use saving ΔE (124,076 kWh/yr upper bound)	Customer meter	Total saving at meter	-
Coupling saving (951 kWh/yr)	Hospital meter	Hospital ΔE	Total (already inside)
Avoided network loss	Meter to 33 kV input	Total saving at 33 kV input	End-use ΔE
DT copper-loss reduction	Distribution transformers	Avoided network loss	Any total
Phase-balance line loss	Hospital LT service	Reported separately	Any total
Targeted switching (118 vs 455 ACS)	Investment only	Cost and payback	Energy

Table 5. Uncertain inputs and ranges

Input	Range	Basis
Household growth since 2011	1.00-1.20	Population +8.8% to 2026 [25]
Tube stock still in use, 2019 to 2026	0.5-1.0	Continuing LED adoption
Share of 36 W (rest 28 W) tubes	0.5-1.0	Not published
Household lighting hours	4-6 h/day	Base 5 h
Days a day-on light stays on	50-100%	Field revisits [3]
AC duty cycle; cooling season	0.6-1.0; 200-300 d	Base 1.0; 240 d
Loss fraction L; fixed share	9-13%; 5-30%	Approved 10.88%
DT peak loading; load factor	50-90%; 0.58-0.70	Base 70%; 0.64
Discount rate; tariff escalation	6-10%; 0-5%/yr	Base 8%; 3%
Capital cost factor; ACS O&M	0.8-1.3; Rs 100-400/yr	Installation variability
ACS availability	85-100%	Battery, calibration faults [3]

3.5. Life-Cycle Economics and Uncertainty

Each measure is evaluated over 15 years at an 8% discount rate with the tariff escalating at 3% a year. LED lamps last 25,000 h, so household lamps are replaced after 13.7 years and hospital lamps in round-the-clock rooms every 2.9 years; the baseline 40 W fittings have the same life, and only the price difference is charged.

BLDC fans are renewed after 12 years and air conditioners after 10, with salvage value for the unused life at year 15. Each ACS costs Rs 2,224 installed [3], lasts 10 years, needs Rs 200 a year for battery and calibration, and is available 95% of the time. The indicators are Net Present Value (NPV), discounted payback and the Cost of Saved Energy (CSE), the present value of costs divided by the present value of the energy saved.

Uncertain inputs are sampled 2,000 times from the uniform ranges of Table 5, and each sample is run through the energy model, the calibrated load flow and the cash-flow model. A one-at-a-time analysis around the mid-range case identifies which inputs matter most.

3.6. Case Study: Chandragiri Mandal

Chandragiri Mandal, Tirupati District, is supplied by APSPDCL. It was chosen because every street in it was covered by the road-light survey of [3]. The study is a model-based assessment on one network, not a field validation: of the three measures, only the road-light inventory is field-measured, the hospital is a design applied as a proposed facility, and the household stock is estimated from statistics (Table 6).

Table 6. Case-study inputs and their basis

Component	Data	Basis
Road lights	3,170 lights on 455 roads in 80 sub-villages; 417 on in daytime (12.73 kW) on 118 streets	Field survey [3]: six months, three times a day, each location visited on two days
Hospital	29-room, two-floor design [2] applied as a proposed hospital; OPD 8 h × 312 d; emergency, ICU and nurse station 24 h; ward lighting 12 h at night; cooling 240 d	Design data; schedule assumed
Households	14,904 households × 0.22 tubes (4.4 lamps per rural household, 5% tubes) = 3,279 tubes of 36 W, 5 h/day	Census 2011; CEEW survey of 2019 [22]
Network	APSPDCL; loss 10.88% (APERC); LF 0.64; 63 kVA DT for hospital, 100 kVA for villages	Utility data; IS 1180 [17]
Constants	Tariff Rs 6/kWh; 0.710 tCO_2/MWh (CEA V21.0); LED Rs 250; BLDC +Rs 2,000; 5-star AC +Rs 7,000	[1]; CEA; market prices

The household count dates from 2011, while the tube ownership comes from a 2019 survey taken after the national LED programme had replaced most bulbs. The two errors run in opposite directions: households have grown (the state population is projected to be 8.8% higher in 2026 than in 2011 [25]), while tubes keep being replaced by LED battens. Both are carried as ranges in Table 5. The road-light saving assumes that each light found on in daytime stays on for 12 h every day of the year. The survey found these lights on at three times of day on two separate visits, mostly because no switch was installed or the switch had failed, which supports persistence; but repairs between visits cannot be excluded, so the deterministic value is an upper bound and 50-100% persistence is used in the uncertainty analysis.

4. Results and Discussion

4.1. End-Use Savings

With an unrestricted budget, the model selects the 5-star 9 W lamp (1,215 lm) for both the hospital and the households, BLDC fans, 5-star air conditioners in all five units, and switches on all 118 streets with day-on lights. The end-use results are in Table 7 and Figure 2. They reproduce the component values computed separately, which confirms that the joint model loses nothing when money is not limited. Because the household stock and road-light persistence are set at their highest values, the deterministic totals are upper bounds; the Monte Carlo medians are given in the last row.

Table 7. End-use results by component (deterministic upper bound; Monte Carlo median in last row)

Indicator	Households (P)	Hospital (n, P)	Road lights (s)	Total
E_{base} (kWh/yr)	215,430	39,745	479,621	734,796
E_{opt} (kWh/yr)	161,573	25,284	423,863	610,720
ΔE (kWh/yr)	53,858	14,461	55,757	124,076
Energy saving ratio	25.0%	36.4%	11.6%	16.9%
Cost saving (Rs/yr)	323,145	86,765	334,544	744,455

Investment (Rs)	2,459,250	95,020	262,453	2,816,723
Simple payback (years)	7.6	1.1	0.8	3.8
CO_2 avoided (t/yr)	38.2	10.3	39.6	88.1
ΔE, Monte Carlo median (kWh/yr)	33,300	13,100	38,500	85,600

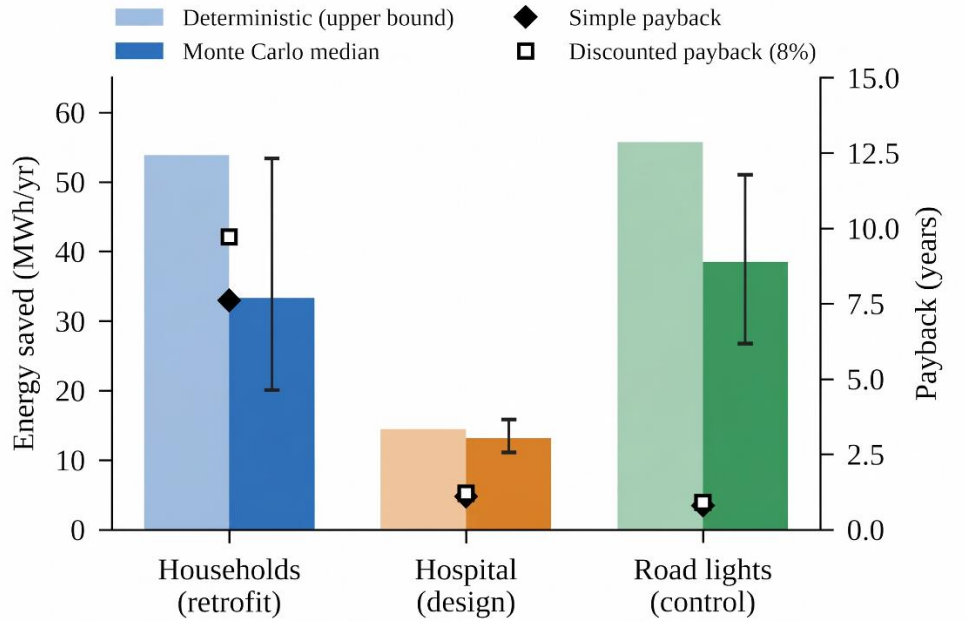


Fig. 2 Annual energy saved by component: deterministic upper bound, Monte Carlo median with 5-95% interval, and simple and discounted payback

4.2. Joint Optimization under a Budget

Figure 3 shows the budget frontier. The joint model first switches the streets with the highest day-on load per ACS, then adds the hospital measures, and funds household retrofits only after all 118 streets are switched, at about Rs 3.6 lakh. With Rs 3 lakh, about 11% of the full investment, it saves 67,769 kWh/yr, 55% of the maximum. Splitting the same Rs 3 lakh among the three measures in proportion to their full cost saves 27,715 kWh/yr. At Rs 10 lakh, the figures are 84,299 and 63,947 kWh/yr. The gap closes only when the budget covers every measure. This is the main practical gain from integration: it does not create extra kilowatt-hours, but it directs a limited budget to where each rupee saves most.

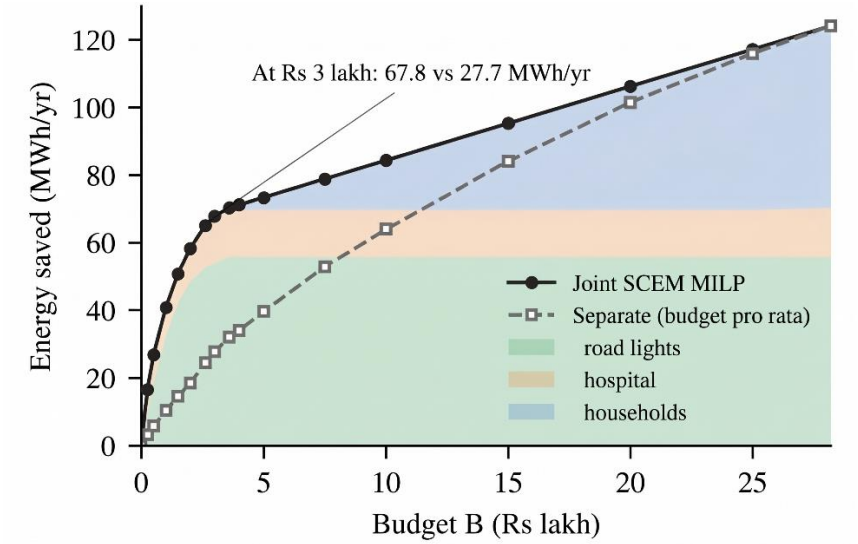


Fig. 3 Budget frontier of the joint model and of separate planning with the budget split in proportion to cost; shaded areas show the joint solution by measure

The procurement Constraint (C6) shows why the measures cannot be planned in isolation. If the programme bought the 923 lm lamp implied by the published hospital design, each household tube point would need four lamps (m_k = ⌈3,350/923⌉ = 4) drawing 36 W, the same as the tube, and the household saving would fall to zero. The hospital saving would also fall by 951 kWh/yr, giving 69,268 kWh/yr in total instead of 124,076. The 4-star lamp meets the household requirement with three lamps but needs 102 lamps in the hospital against 98 for the 5-star lamp, so the model selects the 5-star lamp.

4.3. Avoided Network Losses

Table 8 compares the analytical bounds with the load flow. The average basis gives 15,148 kWh/yr and the peak-marginal basis 37,506 kWh/yr. The load flow, with all losses load-dependent, gives 37,839 kWh/yr, close to the marginal bound, because the household saving falls in the hours when the feeder is most heavily loaded (Figure 4). With 15% and 30% of the losses fixed, the load flow gives 30,490 and 23,849 kWh/yr. The average basis therefore understates the avoided loss, and the marginal formula is a reasonable estimate when most losses are load-dependent. Of the 37,839 kWh/yr, 7,309 kWh/yr is avoided in LT lines, 2,451 kWh/yr in transformer copper and 28,079 kWh/yr on the 11 kV trunk; these parts sum to the total and are not additional to it.

The Monte Carlo row is lower than the load-flow rows because it combines the network uncertainty with the smaller end-use savings of Section 4.6. Including avoided losses, the energy saved at the 33 kV input is 147,900-161,900 kWh/yr in the deterministic case (load flow with 30% and 0% fixed losses) and 105,200 kWh/yr at the Monte Carlo median.

Table 8. Avoided network losses by method (kWh/yr)

Method	Households	Hospital	Road lights	Total
Equation 9, average basis	6,575	1,765	6,807	15,148
Equation 9, peak-marginal basis	20,433	3,516	13,557	37,506
Load flow, no fixed losses	22,354	3,380	12,105	37,839
Load flow, 15% fixed losses	17,703	2,769	10,017	30,490
Load flow, 30% fixed losses	13,635	2,198	8,016	23,849
Monte Carlo, median (5-95%)	10,500	2,400	6,600	19,700 (13,300-29,400)

4.4. Peak Demand and Transformer Loading

The measures act at different times of day (Table 9, Figure 4). Road-light control relieves the daytime, and the household retrofit relieves the evening peak, when the feeder is at its maximum. The hospital values are for a working day in the cooling season: OPD loads count only by day, and ward, ICU and emergency loads also in the evening. The evening reduction of 34.5 kVA equals about 35% of one 100 kVA transformer, spread over the mandal's transformers.

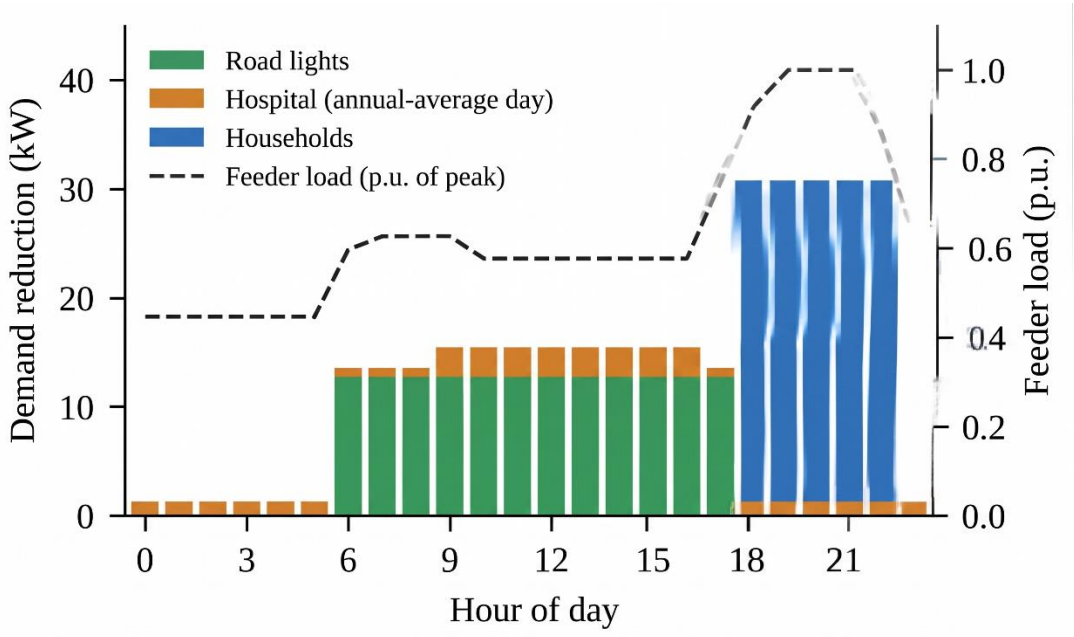


Fig. 4 Hourly demand reduction by component (hospital on the annual-average day) and the feeder load shape used in the load flow

Table 9. Peak-demand reduction (kW)

Window	Households	Hospital	Road lights	Total
Day, 12:00-15:00	0	4.11	12.73	16.84
Evening, 19:00-21:00	29.51	1.58	0	31.09

For a single transformer, Equation 10 gives the copper-loss reductions of Table 10 at 60% and 80% peak loading. Applying the peak loading to every hour, as Equation 10 does, gives 2,638-3,524 kWh/yr; the load flow, which uses the hourly loading, gives 2,451 kWh/yr. Both are part of the avoided losses of Table 8. As Figure 5 shows, the same load removal saves more on a more heavily loaded transformer.

Table 10. Transformer copper-loss reduction

Case	Load removed	At 60% / 80%	kWh/yr
Hospital DT, 63 kVA	4.56 kVA, day	87 / 118 W	348-471
Village DTs, road lights	14.14 kVA, day	266 / 355 W	1,165-1,553
Village DTs, households	32.79 kVA, evening	617 / 822 W	1,125-1,500
Total, Equation 10			2,638-3,524
Total, load flow (hourly)			2,451

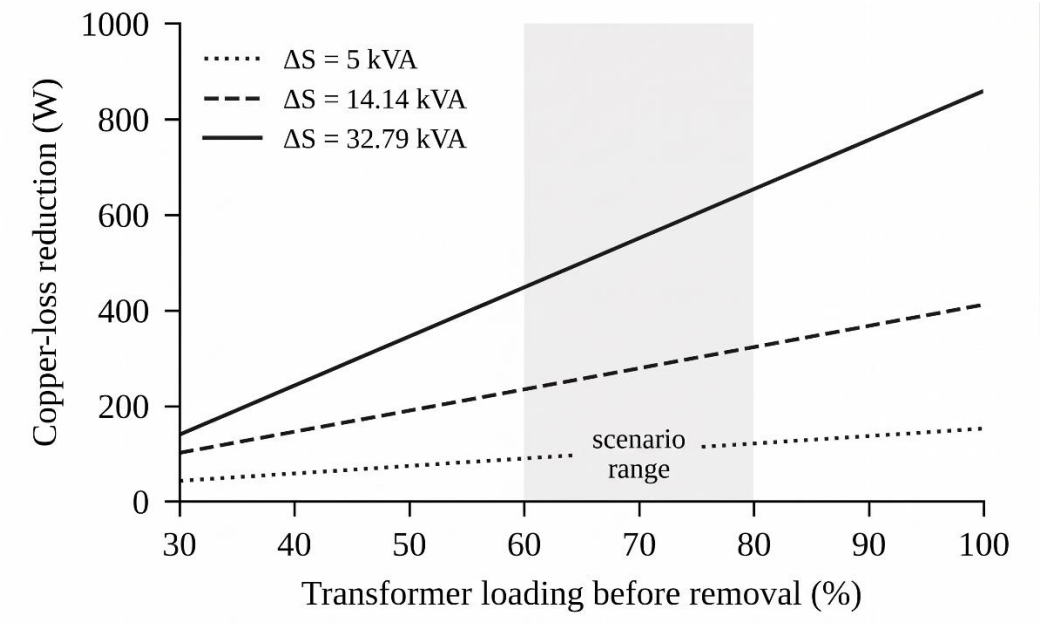


Fig. 5 Copper-loss reduction of a 100 kVA transformer versus loading for three load removals

4.5. Phase-Balance Line Loss

The hospital's 33,195 W connected load was modelled on a 4-wire ACSR Rabbit service at 240 V per phase with Equation 11 (Table 11). Against allocations with 10% and 25% unbalance, the balanced design avoids 6-37 W per 100 m at connected load, or about 25-70 and 158-440 kWh/yr for a 300 m service. This benefit lies outside the totals of Sections 4.1-4.3 (Table 4).

Table 11. LT line loss under different phase allocations

Allocation	UF	I_N	Loss per 100 m	Extra
Balanced design [2]	0.27%	0.2 A	352.3 W	-
10% unbalance	10%	8.0 A	358.1 W	5.9 W
25% unbalance	25%	20.0 A	388.9 W	36.7 W

4.6. Uncertainty

Table 12 summarizes the Monte Carlo results. The median end-use saving is 85,600 kWh/yr, 69% of the deterministic value, with a 90% interval of 65,600-108,500 kWh/yr. The hospital result is the most robust, because its inputs are design data; the household and road-light results carry most of the spread.

Figure 6 ranks the inputs. Road-light persistence, the share of tubes still in use and the share of 36 W tubes dominate the end-use savings; the loss fraction and the fixed-loss share dominate the avoided losses. The transformer loading, load factor and line-length ratio have little effect once the network is calibrated to the approved loss. A household lamp-stock survey and a repeat road-light survey would narrow the result more than any network measurement.

Table 12. Monte Carlo results, 2,000 samples (5th percentile/median / 95th percentile)

Quantity	Households	Hospital	Road lights	Total
End-use ΔE (MWh/yr)	20.1 / 33.3 / 53.4	11.1 / 13.1 / 15.8	26.8 / 38.5 / 51.0	65.6 / 85.6 / 108.5
Avoided loss (MWh/yr)	5.8 / 10.5 / 17.9	1.8 / 2.4 / 3.4	4.3 / 6.6 / 10.1	13.3 / 19.7 / 29.4
NPV (Rs lakh)	-10.3 / -1.4 / 7.9	4.9 / 6.7 / 9.2	9.1 / 17.1 / 27.5	8.7 / 22.8 / 39.8
CSE (Rs/kWh)	5.25 / 7.64 / 11.47	0.85 / 1.17 / 1.56	1.22 / 1.85 / 2.91	2.88 / 4.01 / 5.49
Probability NPV > 0	40%	100%	100%	99.8%

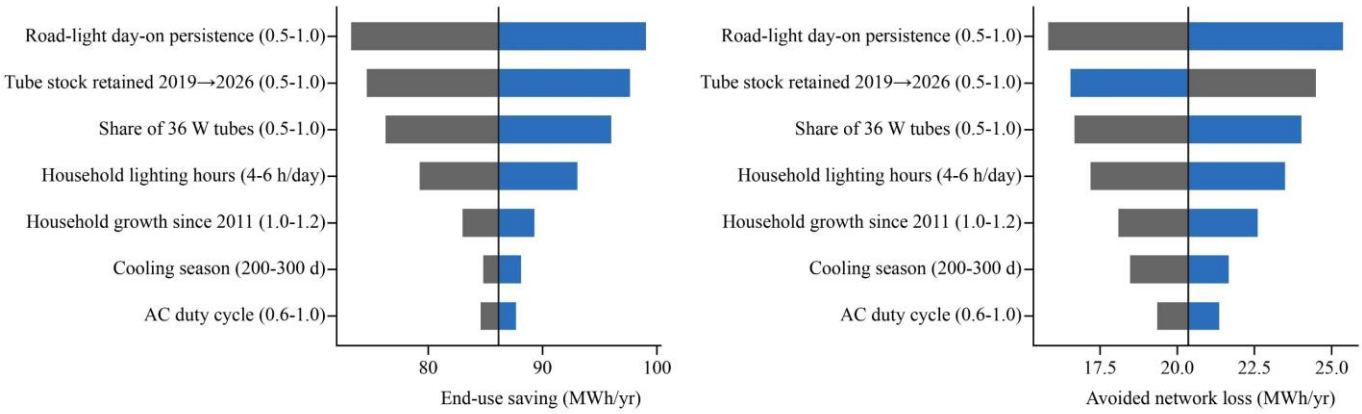


Fig. 6 One-at-a-time sensitivity of the end-use saving and the avoided network loss around the mid-range case

4.7. Life-Cycle Economics

Table 13 gives the life-cycle indicators for the base economic case. Road-light switching and the hospital measures pay back within about a year even after discounting, maintenance and replacement, and their cost of saved energy (Rs 1.0-1.2/kWh) is far below the Rs 6/kWh tariff. The household retrofit is marginal: its cost of saved energy, Rs 5.6/kWh, is close to the tariff, its discounted payback is 9.7 years, and its NPV is positive in only 40% of the Monte Carlo samples, mainly because the 9 W saving per tube point is small. It remains in the programme because it is the only measure that relieves the evening peak, where each kilowatt-hour avoids the most loss. The combined programme has an NPV of Rs 43.6 lakh and a discounted payback of 4.6 years, and its NPV is positive in 99.8% of the samples.

Table 13. Life-cycle indicators (15 years, 8% discount rate, 3% tariff escalation)

Indicator	Households	Hospital	Road lights	Total
Investment (Rs lakh)	24.59	0.95	2.62	28.17
Simple payback (years)	7.6	1.1	0.8	3.9
Discounted payback (years)	9.7	1.2	0.9	4.6
NPV (Rs lakh)	7.9	7.8	27.9	43.6
Cost of saved energy (Rs/kWh)	5.63	1.03	1.20	3.15

Road-light investment and O&M include Rs 200 per ACS per year and 95% availability, which lowers the road-light saving to 52,970 kWh/yr in this case. Targeting switches to the 118 streets with day-on lights, instead of one per road (455 units), cuts the investment from Rs 10.12 lakh to Rs 2.62 lakh for the same energy.

4.8. Comparison with Reported Results

Table 14 places the results beside comparable studies. The comparison is between different scopes and sites, so it shows where the gains come from rather than ranking the methods.

Table 14. Comparison with reported studies

Study	Scope	Reported result	This work
Lamp replacement [1]	One 36 W tube point	9 W (25%) saved per point	Same per point; shows the 923 lm design lamp saves nothing in households
Hospital rooms [10]	Glazing and dimming	Up to 17% of primary energy	36.4% of lighting, fan and AC energy at design stage

Day-on road lights [3]	One ACS per road	55.8 MWh/yr, 455 ACS	Same energy with 118 ACS; payback 3.0 to 0.8 years
Utility portfolio [20]	Measured, territory and feeders	>12% territory; up to 42% on feeders	16.9% of addressed energy (upper bound); 11.6% at median
Phase balancing [19]	Phase swapping on a feeder	Loss 2.8% to 1.8%	UF 0.27% by design; 6-37 W/100 m avoided
Separate planning	Budget split by cost	27.7 MWh/yr at Rs 3 lakh	67.8 MWh/yr at Rs 3 lakh (joint)

The joint model improves on separate studies for four reasons. It ranks measures by loss-weighted saving per rupee, so a limited budget goes first to cheap operational fixes. It uses street-level data to place switches only where lights are found on. It treats the lamp model as a shared decision, which exposes a choice that is harmless in one programme and removes the savings of another. Moreover, it values a kilowatt-hour by when it is saved, which the separate studies, reporting at the meter, could not do. It does not make any single measure save more energy than its own method allows; because loss varies with the square of current, the combined loss reduction at one transformer is slightly less than the sum of separate reductions.

4.9. Limitations

No result in this paper is a measured saving. The road-light inventory is the only field-measured input; the hospital is a design with an assumed operating schedule; the household stock is estimated from statistics; and network losses come from a representative feeder calibrated to the approved loss, not from a load flow of the actual Chandragiri feeders, whose topology and transformer loading are not published. The Monte Carlo ranges reflect these limits but do not remove them. Transformer-wise metering under the national distribution reform scheme, a household lamp survey and a repeat road-light survey would allow the model to be validated against measurements.

5. Conclusion

Lamp retrofit, facility design and road-light control were formulated as one mixed-integer program with shared decision variables, a common lamp-procurement constraint, a shared budget and loss-weighted savings, and solved by branch-and-bound for Chandragiri Mandal. With the full budget, the model reproduces the separately computed savings, 124,076 kWh/yr at most, and with a limited budget it saves much more than separate planning: 67,769 against 27,715 kWh/yr at Rs 3 lakh, and 84,299 against 63,947 kWh/yr at Rs 10 lakh.

The lamp choice couples the measures: the 923 lm lamp implied by the hospital design would remove all household savings. A load flow on a representative feeder gives 23,800-37,800 kWh/yr of avoided losses, close to the peak-marginal estimate, and Monte Carlo analysis gives a median end-use saving of 85,600 kWh/yr (65,600-108,500) with a 99.8% probability of positive NPV.

Road-light switching and design-stage choices should be funded before household retrofits, which are marginal on cost but give the largest peak-loss benefit. These are model estimates; transformer metering, a household lamp survey and a repeat road-light survey are needed to validate them.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Appendix 1

Room-wise lamp counts follow Equation 3 with CUF = 0.54 and MF = 0.95, using a 40 W fitting of 2,960 lm and 9 W lamps of 923 lm (design), 1,150 lm (4-star) and 1,215 lm (5-star). Rooms marked † could not be matched to the published lamp table [2]; their illuminance was assigned by room type.

Table A1. Ground floor (height 2.70 m; scanning room 3.00 m)

Room	Area (m²)	Lux	40 W	9 W design	9 W 4-star	9 W 5-star
R1 Generator room	3.93	300	1	3	2	2
R2 Pharmacy	5.20	300	2	4	3	3
R3 Waiting hall	18.46	300	4	12	10	9
R4 OP-2 †	12.99	300	3	9	7	7
R16 Scanning room †	3.86	100	1	1	1	1
R5 Toilet †	2.01	100	1	1	1	1
R6 OP-1 †	5.22	300	2	4	3	3
R7 Open area †	6.82	150	1	3	2	2

Room	Area (m²)	Lux	40 W	9 W design	9 W 4-star	9 W 5-star
R8 Emergency room †	10.89	300	3	7	6	6
R9 Toilet †	3.24	100	1	1	1	1
R11 Lab	5.94	300	2	4	4	3
R12 Toilet	1.62	100	1	1	1	1
R13 Toilet under ramp	1.62	100	1	1	1	1
R14 Waiting hall	29.58	150	3	10	8	8
R15 Front open area	11.60	150	2	4	3	3
Ground floor total (published)			28 (28)	65 (68)	53	51

Table A2. First floor (height 3.00 m; all counts equal the published values)

Room	Area (m²)	Lux	40 W	9 W design	9 W 4-star	9 W 5-star
R1 Nurse station	1.90	500	1	3	2	2
R2 Waiting hall	8.62	150	1	3	3	3
R3 ICU	18.46	300	4	12	10	9
R4(a), R4(b) ICU toilets	1.72 each	100	1 + 1	1 + 1	1 + 1	1 + 1
R5 General ward	11.53	300	3	8	6	6
R6-R8 Wash area, toilets	1.76-1.98	100	1 + 1 + 1	1 + 1 + 1	1 + 1 + 1	1 + 1 + 1
R9 Open area	11.69	150	2	4	3	3
R10 Waiting area	15.19	150	2	5	4	4
R11 Ramp area	7.09	150	1	3	2	2
R12 Operation theatre	10.40	500	4	11	9	9
R13 Toilet	3.24	100	1	1	1	1
R14 Lab	5.94	300	2	4	4	3
First floor total (published)			26 (26)	59 (59)	49	47