

# SA: Markov Sick-Sicker model in R

The DARTH workgroup

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Please cite our publications when using this code:

- Jalal H, Pechlivanoglou P, Krijkamp E, Alarid-Escudero F, Enns E, Hunink MG. An Overview of R in Health Decision Sciences. *Med Decis Making*. 2017; 37(3): 735-746. <https://journals.sagepub.com/doi/abs/10.1177/0272989X16686559>
- Krijkamp EM, Alarid-Escudero F, Enns EA, Jalal HJ, Hunink MGM, Pechlivanoglou P. Microsimulation modeling for health decision sciences using R: A tutorial. *Med Decis Making*. 2018;38(3):400–22. <https://journals.sagepub.com/doi/abs/10.1177/0272989X18754513>
- Krijkamp EM, Alarid-Escudero F, Enns E, Pechlivanoglou P, Hunink MM, Jalal H. A Multidimensional Array Representation of State-Transition Model Dynamics. *Med Decis Making*. Online First <https://doi.org/10.1177/0272989X19893973>

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Change `eval` to `TRUE` if you want to knit this document.

```
rm(list = ls())      # clear memory (removes all the variables from the workspace)
```

## 01 Load packages

```
if (!require('pacman')) install.packages('pacman'); library(pacman) # use this package to conveniently
# load (install if required) packages from CRAN
p_load("here", "dplyr", "devtools", "scales", "ellipse", "ggplot2", "lazyeval", "igraph", "truncnorm",
# load (install if required) packages from GitHub
# install_github("DARTH-git/dampack", force = TRUE) Uncomment if there is a newer version
p_load_gh("DARTH-git/dampack", "DARTH-git/darthtools")
```

## 02 Load functions

```
# No function needed
```

## 03 Input model parameters

```
# Strategy names
v_names_str <- c("No Treatment", "Treatment")

# Markov model parameters
age      <- 25          # age at baseline
max_age  <- 55          # maximum age of follow up
n_t      <- max_age - age # time horizon, number of cycles
v_n      <- c("H", "S1", "S2", "D") # the 4 states of the model: Healthy (H), Sick (S1),
                                     # Sicker (S2), Dead (D)
v_init   <- c(1, 0, 0, 0) # initial cohort distribution

# Transition probabilities (per cycle)
p_HD     <- 0.005        # probability to die when healthy
p_HS1    <- 0.15         # probability to become sick when healthy, conditional on surviving
p_S1H    <- 0.5          # probability to become healthy when sick, conditional on surviving
p_S1S2   <- 0.105        # probability to become sicker when sick, conditional on surviving
hr_S1    <- 3            # hazard ratio of death in sick vs healthy
hr_S2    <- 10           # hazard ratio of death in sicker vs healthy
r_HD     <- -log(1 - p_HD) # rate of death in healthy
r_S1D    <- hr_S1 * r_HD  # rate of death in sick
r_S2D    <- hr_S2 * r_HD  # rate of death in sicker
p_S1D    <- 1 - exp(-r_S1D) # probability to die in sick
p_S2D    <- 1 - exp(-r_S2D) # probability to die in sicker

# Cost and utility inputs
c_H      <- 2000         # cost of remaining one cycle in the healthy state
```

```

c_S1    <- 4000          # cost of remaining one cycle in the sick state
c_S2    <- 15000         # cost of remaining one cycle in the sicker state
c_trt   <- 12000         # cost of treatment(per cycle)
c_D     <- 0             # cost of being in the death state
u_H     <- 1             # utility when healthy
u_S1    <- 0.75          # utility when sick
u_S2    <- 0.5           # utility when sicker
u_D     <- 0             # utility when dead
u_trt   <- 0.95          # utility when being treated
d_e     <- d_c <- 0.03   # discount rate per cycle equal discount of costs and QALYs by 3%

n_str    <- length(v_names_str) # Number of strategies
n_states <- length(v_n)         # number of states

# Discount weights for costs and effects
v_dwc <- 1 / (1 + d_c) ^ (0:n_t)
v_dwe <- 1 / (1 + d_e) ^ (0:n_t)

```

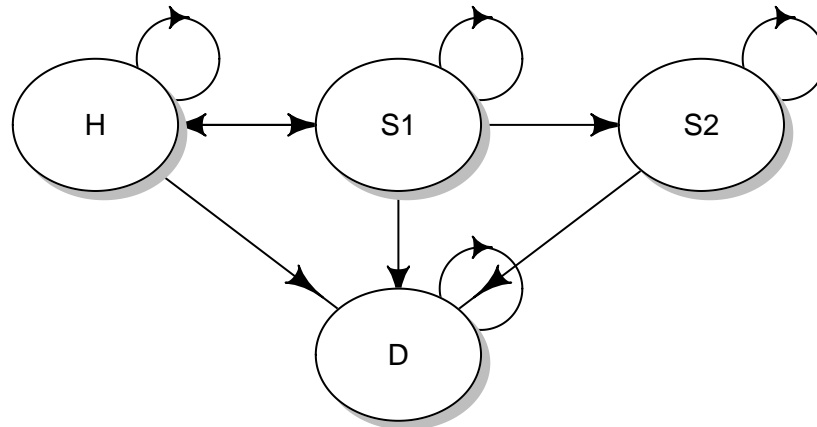
Create a state-transition diagram of the cohort model

```

m_P_diag <- matrix(0, nrow = n_states, ncol = n_states, dimnames = list(v_n, v_n))
m_P_diag["H" , "S1"] = ""
m_P_diag["H" , "D" ] = ""
m_P_diag["H" , "H" ] = ""
m_P_diag["S1", "H" ] = ""
m_P_diag["S1", "S2"] = ""
m_P_diag["S1", "D" ] = ""
m_P_diag["S1", "S1"] = ""
m_P_diag["S2", "D" ] = ""
m_P_diag["S2", "S2"] = ""
m_P_diag["D", "D" ] = ""
layout.fig <- c(3, 1)

plotmat(t(m_P_diag), t(layout.fig), self.cex = 0.5, curve = 0, arr.pos = 0.7,
        latex = T, arr.type = "curved", relsize = 0.9, box.prop = 0.8,
        cex = 0.8, box.cex = 0.9, lwd = 1)

```



## 04 Define and initialize matrices and vectors

### 04.1 Cohort trace

```

# create the markov trace matrix M capturing the proportion of the cohort in each state
# at each cycle
m_M_notrt <- m_M_trt <- matrix(NA,
                                nrow      = n_t + 1, ncol = n_states,
                                dimnames = list(paste("cycle", 0:n_t, sep = " "), v_n))

head(m_M_notrt) # show first 6 rows of the matrix

```

```

##           H S1 S2 D
## cycle 0 NA NA NA NA
## cycle 1 NA NA NA NA
## cycle 2 NA NA NA NA
## cycle 3 NA NA NA NA
## cycle 4 NA NA NA NA
## cycle 5 NA NA NA NA

```

```

# The cohort starts as healthy
m_M_notrt[1, ] <- m_M_trt[1, ] <- c(1, 0, 0, 0) # initiate first cycle of cohort trace

```

## 04.2 Transition probability matrix

```
# create the transition probability matrix for NO treatment
m_P_notrt <- matrix(0,
                    nrow = n_states,
                    ncol = n_states,
                    dimnames = list(v_n, v_n)) # name the columns and rows of the matrix
m_P_notrt
```

```
##      H S1 S2 D
## H    0  0  0  0
## S1   0  0  0  0
## S2   0  0  0  0
## D    0  0  0  0
```

Fill in the transition probability matrix:

```
# from Healthy
m_P_notrt["H", "H" ] <- (1 - p_HD) * (1 - p_HS1)
m_P_notrt["H", "S1" ] <- (1 - p_HD) * p_HS1
m_P_notrt["H", "D" ] <- p_HD
# from Sick
m_P_notrt["S1", "H" ] <- (1 - p_S1D) * p_S1H
m_P_notrt["S1", "S1" ] <- (1 - p_S1D) * (1 - (p_S1H + p_S1S2))
m_P_notrt["S1", "S2" ] <- (1 - p_S1D) * p_S1S2
m_P_notrt["S1", "D" ] <- p_S1D
# from Sicker
m_P_notrt["S2", "S2" ] <- 1 - p_S2D
m_P_notrt["S2", "D" ] <- p_S2D
# from Dead
m_P_notrt["D", "D" ] <- 1

# Check that transition probabilities are in [0, 1]
check_transition_probability(m_P_notrt, verbose = TRUE)
# Check that all rows sum to 1
check_sum_of_transition_array(m_P_notrt, n_states = n_states, n_cycles = n_t, verbose = TRUE)

# create transition probability matrix for treatment same as no treatment
m_P_trt <- m_P_notrt
```

## 05 Run Markov model

```
for (t in 1:n_t){      # loop through the number of cycles
  m_M_notrt[t + 1, ] <- t(m_M_notrt[t, ]) %*% m_P_notrt # estimate the Markov trace
                                                            # for the next cycle (t + 1)
  m_M_trt[t + 1, ]    <- t(m_M_trt[t, ]) %*% m_P_trt   # estimate the Markov trace
                                                            # for the next cycle (t + 1)
} # close the loop

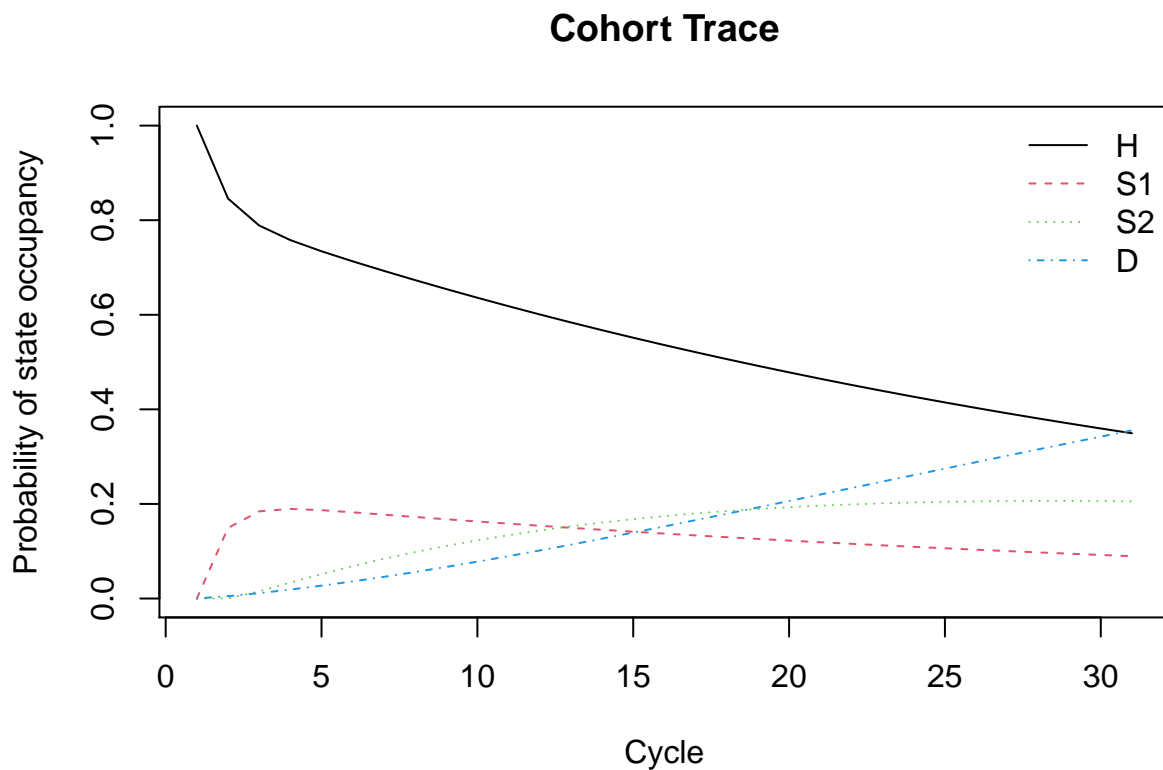
head(m_M_notrt) # show the first 6 lines of the matrix
```

```
##           H           S1           S2           D
## cycle 0 1.0000000 0.0000000 0.0000000 0.0000000
## cycle 1 0.8457500 0.1492500 0.0000000 0.0050000
## cycle 2 0.7888043 0.1843020 0.01543735 0.01145632
## cycle 3 0.7579069 0.1894418 0.03374551 0.01890581
## cycle 4 0.7343069 0.1868303 0.05169021 0.02717260
## cycle 5 0.7130610 0.1822918 0.06848747 0.03615973
```

## 06 Compute and Plot Epidemiological Outcomes

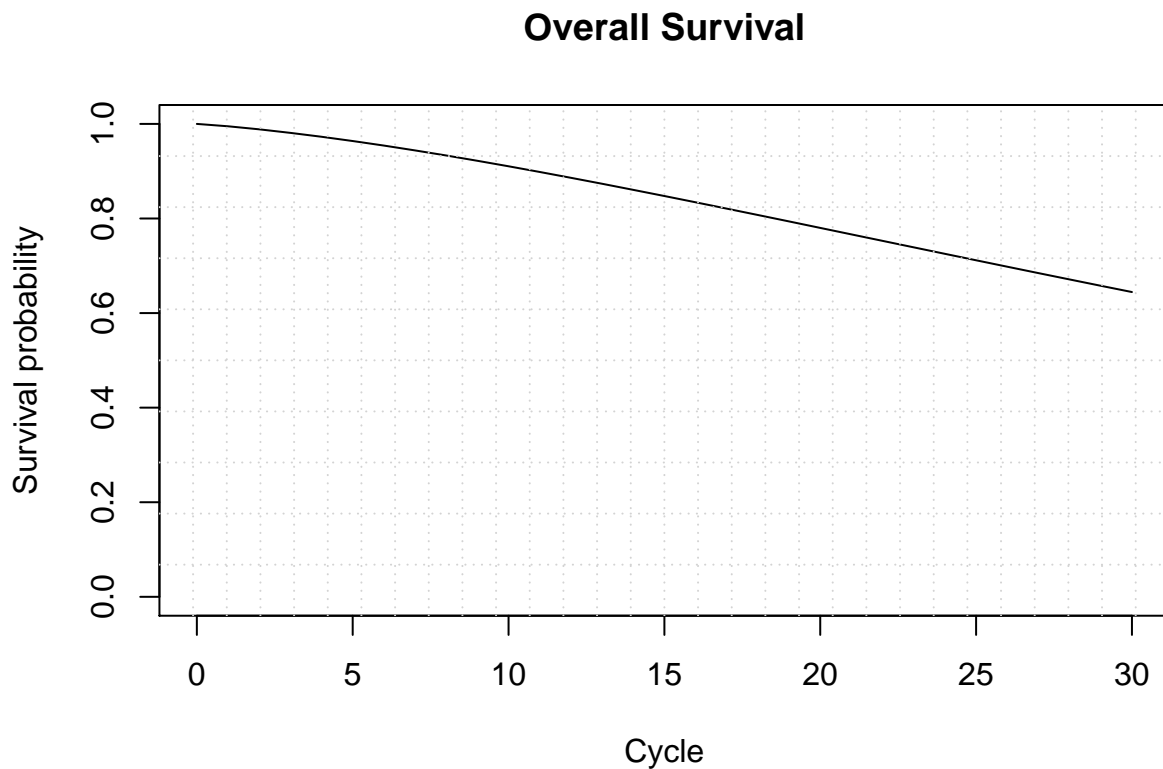
### 06.1 Cohort trace

```
# create a plot of the data
matplot(m_M_notrt, type = 'l',
        ylab = "Probability of state occupancy",
        xlab = "Cycle",
        main = "Cohort Trace")
# add a legend to the graph
legend("topright", v_n, col = 1:n_states, lty = 1:n_states, bty = "n")
```



## 06.2 Overall Survival (OS)

```
# calculate the overall survival (OS) probability for no treatment
v_os_notrt <- 1 - m_M_notrt[, "D"]
# alternative way of calculating the OS probability
v_os_notrt <- rowSums(m_M_notrt[, 1:3])
# create a simple plot showing the OS
plot(0:n_t, v_os_notrt, type = 'l',
     ylim = c(0, 1),
     ylab = "Survival probability",
     xlab = "Cycle",
     main = "Overall Survival")
# add grid
grid(nx = n_t, ny = 10, col = "lightgray", lty = "dotted", lwd = par("lwd"),
     equilogs = TRUE)
```

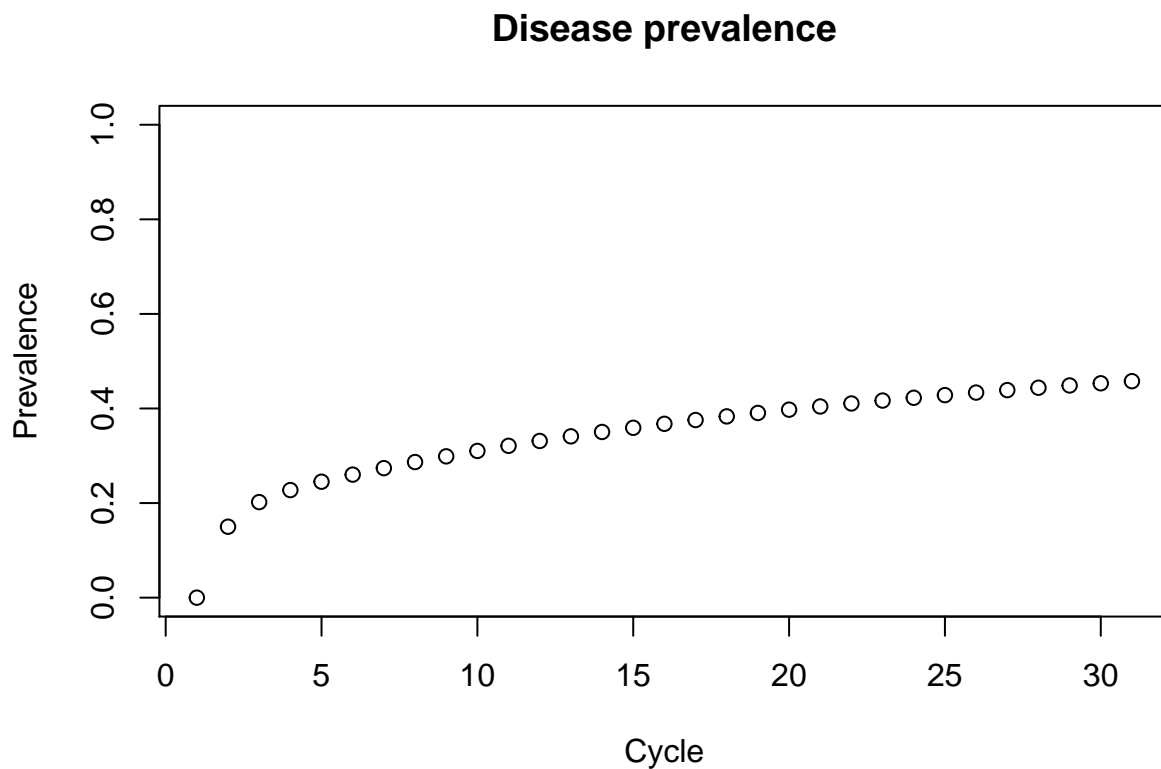


### 06.2.1 Life Expectancy (LE)

```
v_le <- sum(v_os_notrt) # summing probability of OS over time (i.e. life expectancy)
```

### 06.3 Disease prevalence

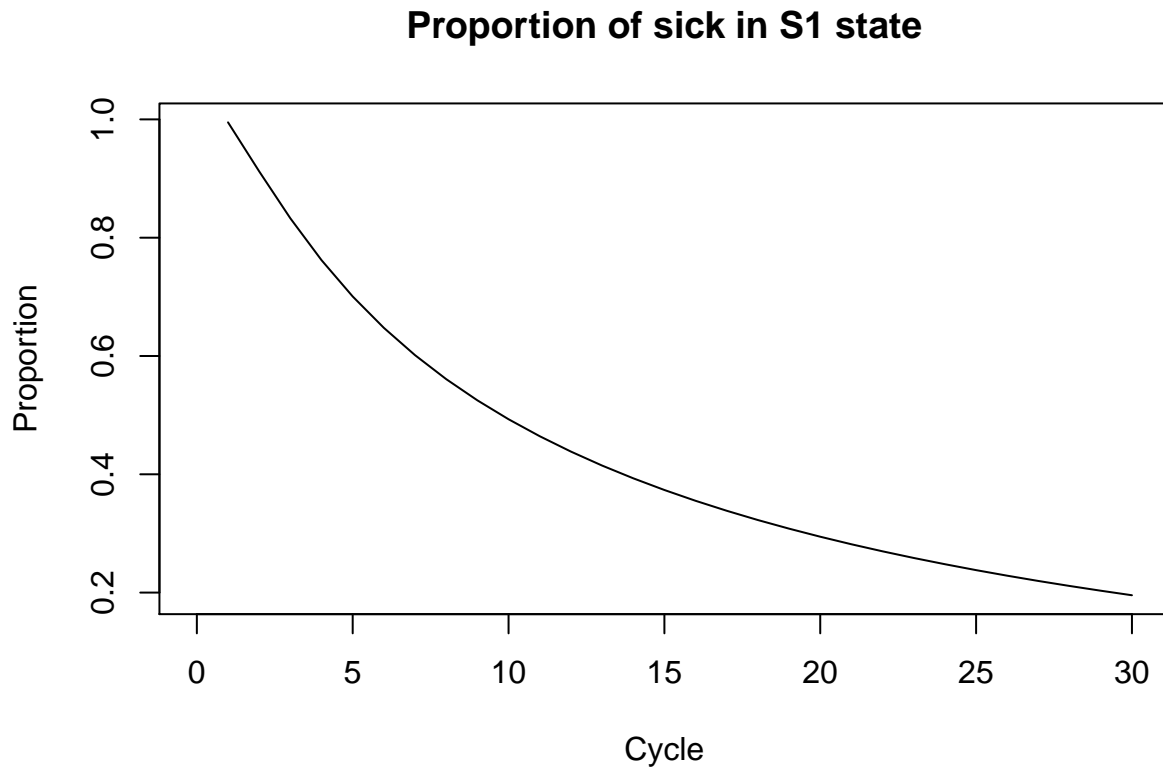
```
v_prev <- rowSums(m_M_notrt[, c("S1", "S2")]) / v_os_notrt
plot(v_prev,
     ylim = c(0, 1),
     ylab = "Prevalence",
     xlab = "Cycle",
     main = "Disease prevalence")
```



### 06.4 Proportion of sick in S1 state

```
v_prop_S1 <- m_M_notrt[, "S1"] / v_prev
plot(0:n_t, v_prop_S1,
     xlab = "Cycle",
     ylab = "Proportion",
     main = "Proportion of sick in S1 state",
     col = "black", type = "l")
```





## 07 Compute Cost-Effectiveness Outcomes

```
# Vectors with costs and utilities by treatment
v_u_notrt <- c(u_H, u_S1, u_S2, u_D)
v_u_trt   <- c(u_H, u_trt, u_S2, u_D)

v_c_notrt <- c(c_H, c_S1, c_S2, c_D)
v_c_trt   <- c(c_H, c_S1 + c_trt, c_S2 + c_trt, c_D)
```

### 07.1 Mean Costs and QALYs for Treatment and NO Treatment

```
v_tu_notrt <- m_M_notrt %*% v_u_notrt
v_tu_trt   <- m_M_trt   %*% v_u_trt

v_tc_notrt <- m_M_notrt %*% v_c_notrt
v_tc_trt   <- m_M_trt   %*% v_c_trt
```

## 07.2 Discounted Mean Costs and QALYs

```
tu_d_notrt <- t(v_tu_notrt)  %>% v_dwe
tu_d_trt   <- t(v_tu_trt)   %>% v_dwe

tc_d_notrt <- t(v_tc_notrt)  %>% v_dwc
tc_d_trt   <- t(v_tc_trt)   %>% v_dwc

# store them into a vector
v_tc_d     <- c(tc_d_notrt, tc_d_trt)
v_tu_d     <- c(tu_d_notrt, tu_d_trt)

# Dataframe with discounted costs and effectiveness
df_ce      <- data.frame(Strategy = v_names_str,
                        Cost      = v_tc_d,
                        Effect    = v_tu_d
                        )

df_ce
```

```
##      Strategy      Cost      Effect
## 1 No Treatment  75795.04  15.84802
## 2   Treatment 141511.41  16.41446
```

## 07.3 Compute ICERs of the Markov model

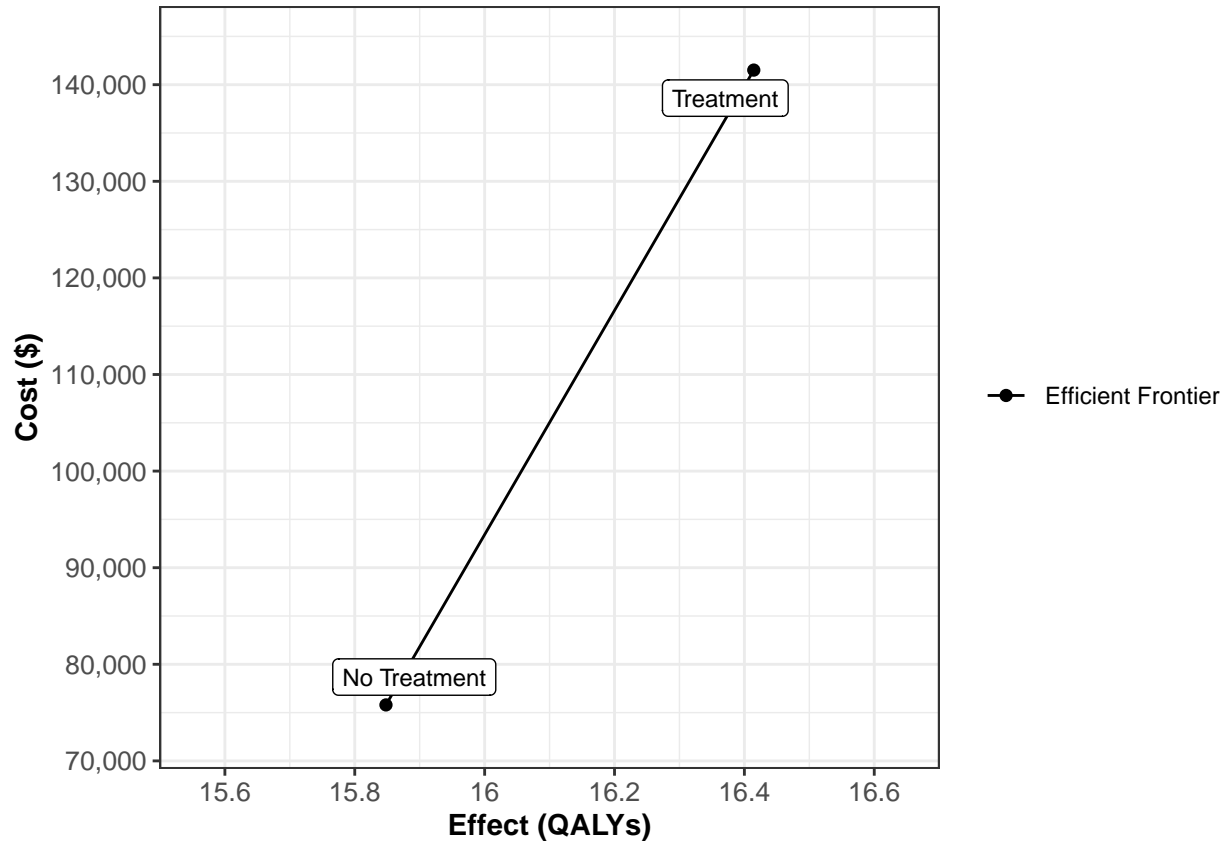
```
df_cea <- calculate_icers(cost      = df_ce$Cost,
                        effect     = df_ce$Effect,
                        strategies = df_ce$Strategy
                        )

df_cea
```

```
##      Strategy      Cost      Effect Inc_Cost Inc_Effect      ICER Status
## 1 No Treatment  75795.04  15.84802      NA      NA      NA      ND
## 2   Treatment 141511.41  16.41446  65716.37  0.5664367 116017.2      ND
```

## 07.4 Plot frontier of the Markov model

```
plot(df_cea, effect_units = "QALYs", xlim = c(15.6, 16.6))
```



## 08 Deterministic Sensitivity Analysis

### 08.1 List of input parameters

Create list `l_params_all` with all input probabilities, cost and utilities.

```
l_params_all <- as.list(data.frame(
  p_HD    = 0.005, # probability to die when healthy
  p_HS1   = 0.15,  # probability to become sick when healthy, conditional on surviving
  p_S1H   = 0.5,   # probability to become healthy when sick, conditional on surviving
  p_S1S2  = 0.105, # probability to become sicker when sick, conditional on surviving
  hr_S1   = 3,     # hazard ratio of death in sick vs healthy
  hr_S2   = 10,    # hazard ratio of death in sicker vs healthy
  c_H     = 2000,  # cost of remaining one cycle in the healthy state
  c_S1    = 4000,  # cost of remaining one cycle in the sick state
  c_S2    = 15000, # cost of remaining one cycle in the sicker state
  c_trt   = 12000, # cost of treatment(per cycle)
  c_D     = 0,     # cost of being in the death state
  u_H     = 1,     # utility when healthy
  u_S1    = 0.75,  # utility when sick
  u_S2    = 0.5,   # utility when sicker
  u_D     = 0,     # utility when dead
  u_trt   = 0.95,  # utility when treated
  d_e     = 0.03,  # discount factor for effectiveness
))
```

```

d_c      = 0.03    # discount factor for costs
))

# store the parameter names into a vector
v_names_params <- names(l_params_all)

```

## 08.2 Load Sick-Sicker Markov model function

```

source("Functions_markov_sick-sicker_sol.R")
# Test function
calculate_ce_out(l_params_all)

```

```

##           Strategy      Cost    Effect    NMB
## 1 No Treatment  75795.04 15.84802 1509007
## 2   Treatment 141511.41 16.41446 1499935

```

## 08.3 One-way sensitivity analysis (OWSA)

```

options(scipen = 999) # disabling scientific notation in R
# dataframe containing all parameters, their basecase values, and the min and
# max values of the parameters of interest
df_params_owsa <- data.frame(pars = c("p_S1S2", "c_trt", "u_S1", "u_trt"),
                             min  = c(0.05, 6000, 0.65, 0.80), # min parameter values
                             max  = c(0.155, 18000, 0.85, 0.98) # max parameter values
                             )

owsa_nmb <- run_owsa_det(params_range = df_params_owsa, # dataframe with parameters for OWSA
                        params_basecase = l_params_all, # list with all parameters
                        nsamp = 100, # number of parameter values
                        FUN = calculate_ce_out, # function to compute outputs
                        outcomes = c("NMB"), # output to do the OWSA on
                        strategies = v_names_str, # names of the strategies
                        n_wtp = 120000) # extra argument to pass to FUN

```

```

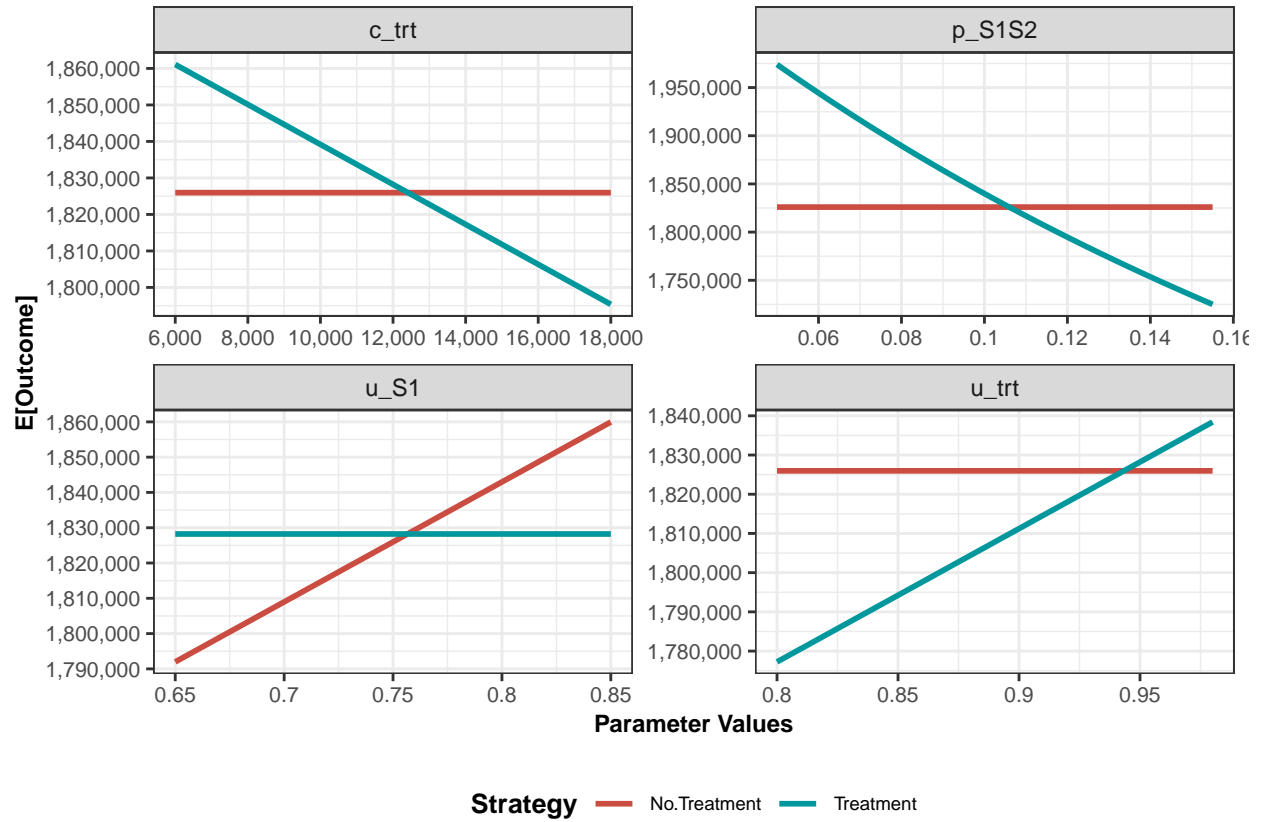
## |

```

```

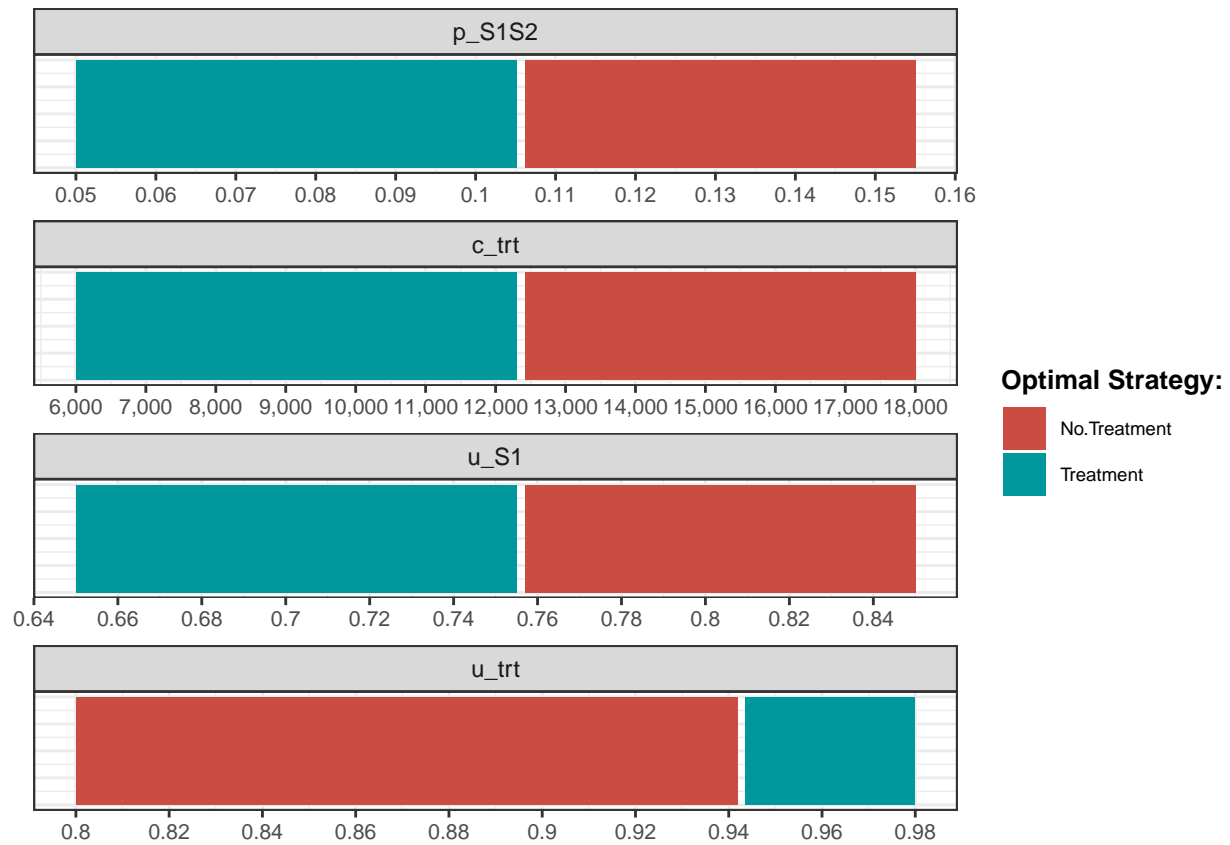
plot(owsa_nmb, txtsize = 10, n_x_ticks = 4,
     facet_scales = "free") +
  theme(legend.position = "bottom")

```



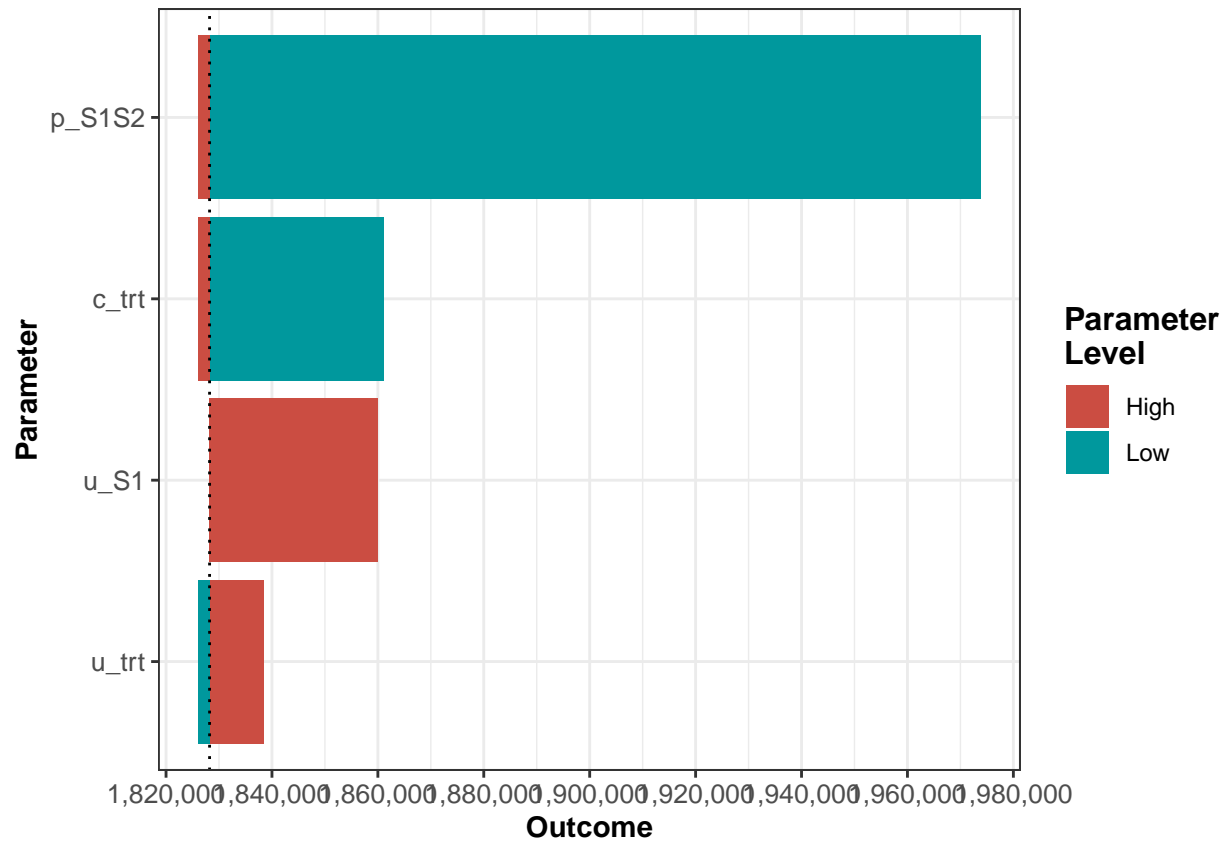
### 08.3.2 Optimal strategy with OWSA

```
owsa_opt_strat(owsa = owsa_nmb, txtsize = 10)
```



### 08.3.3 Tornado plot

```
owsa_tornado(owsa = owsa_nmb)
```



## 08.4 Two-way sensitivity analysis (TWSA)

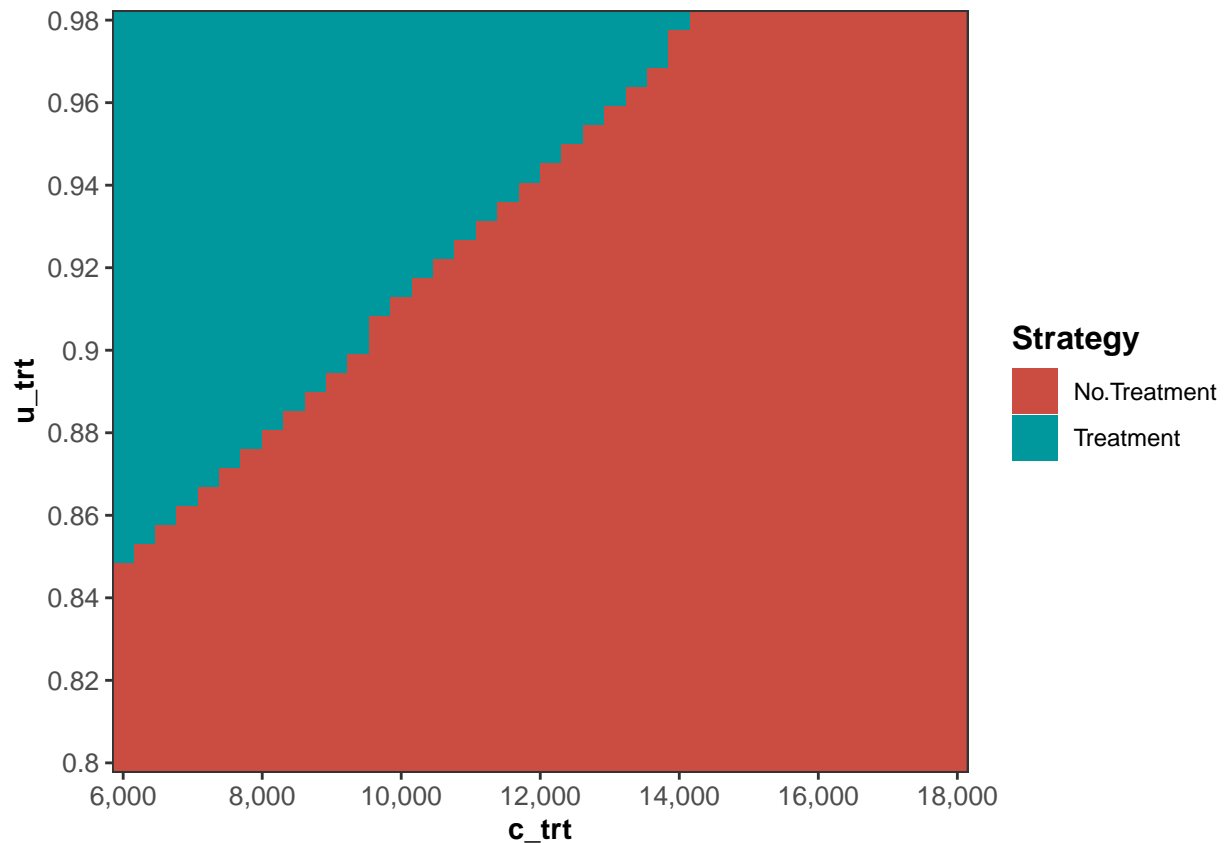
```
# dataframe containing all parameters, their basecase values, and the min and
# max values of the parameters of interest
df_params_twsa <- data.frame(pars = c("c_trt", "u_trt"),
                             min = c(6000, 0.80), # min parameter values
                             max = c(18000, 0.98) # max parameter values
                             )

twsa_nmb <- run_twsa_det(params_range = df_params_twsa, # dataframe with parameters for TWSA
                       params_basecase = l_params_all, # list with all parameters
                       nsamp = 40, # number of parameter values
                       FUN = calculate_ce_out, # function to compute outputs
                       outcomes = "NMB", # output to do the TWSA on
                       strategies = v_names_str, # names of the strategies
                       n_wtp = 120000) # extra argument to pass to FUN
```

```
## |
```

```
|
```

```
plot(twsa_nmb)
```



## 09 Probabilistic Sensitivity Analysis (PSA)

```
# Function to generate PSA input dataset
gen_psa <- function(n_sim = 1000, seed = 071818){
  set.seed(seed) # set a seed to be able to reproduce the same results
  df_psa <- data.frame(
    # Transition probabilities (per cycle)
    p_HS1 = rbeta(n_sim, shape1 = 30, shape2 = 170), # probability to become sick when healthy
    p_S1H = rbeta(n_sim, shape1 = 60, shape2 = 60), # probability to become healthy when sick
    p_S1S2 = rbeta(n_sim, shape1 = 84, shape2 = 716), # probability to become sicker when sick
    p_HD = rbeta(n_sim, shape1 = 10, shape2 = 1990), # probability to die when healthy
    hr_S1 = rlnorm(n_sim, meanlog = log(3), sdlog = 0.01), # rate ratio of death in S1 vs healthy
    hr_S2 = rlnorm(n_sim, meanlog = log(10), sdlog = 0.02), # rate ratio of death in S2 vs healthy

    # State rewards
    # Costs
    c_H = rgamma(n_sim, shape = 100, scale = 20), # cost of remaining one cycle in state H
    c_S1 = rgamma(n_sim, shape = 177.8, scale = 22.5), # cost of remaining one cycle in state S1
    c_S2 = rgamma(n_sim, shape = 225, scale = 66.7), # cost of remaining one cycle in state S2
    c_Trt = rgamma(n_sim, shape = 73.5, scale = 163.3), # cost of treatment (per cycle)
    c_D = 0, # cost of being in the death state

    # Utilities
  )
}
```



```

    u_H   = rbeta(n_sim, shape1 = 200, shape2 = 3),      # utility when healthy
    u_S1  = rbeta(n_sim, shape1 = 130, shape2 = 45),     # utility when sick
    u_S2  = rbeta(n_sim, shape1 = 230, shape2 = 230),    # utility when sicker
    u_D   = 0,                                           # utility when dead
    u_TrT = rbeta(n_sim, shape1 = 300, shape2 = 15),     # utility when being treated
    d_e   = 0.03,                                       # discount factor for effectiveness
    d_c   = 0.03                                       # discount factor for costs
  )
  return(df_psa)
}
# Try it
gen_psa(10)

```

```

##      p_HS1    p_S1H    p_S1S2      p_HD    hr_S1    hr_S2    c_H
## 1  0.15132349 0.4820445 0.08485456 0.003973762 3.055410 10.148768 1887.449
## 2  0.12522484 0.4392546 0.11683397 0.004813328 3.005252  9.928044 1966.291
## 3  0.15673720 0.5311020 0.11925841 0.004491843 2.982392 10.021998 2101.059
## 4  0.11276858 0.4493088 0.09393848 0.010646056 2.981918 10.167486 1728.664
## 5  0.14292946 0.5825087 0.11628065 0.007045338 3.024975 10.006505 2160.895
## 6  0.20088601 0.4580278 0.10403415 0.004058637 2.971345 10.012715 1969.304
## 7  0.14347796 0.5492245 0.09294048 0.005658464 2.989181 10.001860 1641.192
## 8  0.13149270 0.4899896 0.12838861 0.007354969 2.984080  9.919332 2276.032
## 9  0.15593267 0.5705602 0.09237907 0.004162148 2.988974 10.142331 1717.867
## 10 0.09824029 0.5127637 0.10683148 0.002141140 2.968692  9.749869 2132.549
##      c_S1    c_S2    c_TrT c_D      u_H      u_S1      u_S2 u_D      u_TrT
## 1  4173.600 14607.88 10673.74  0 0.9829120 0.7252701 0.4757751  0 0.9435773
## 2  4188.264 14714.84 13380.61  0 0.9693926 0.7610392 0.4591563  0 0.9501528
## 3  4578.682 16664.54 12522.58  0 0.9910033 0.7076433 0.5032719  0 0.9670124
## 4  3395.922 15669.87 13833.65  0 0.9928844 0.7124119 0.5132492  0 0.9649128
## 5  3878.562 15302.70 13154.65  0 0.9748972 0.7344718 0.4895693  0 0.9325969
## 6  3970.522 15303.55 13914.95  0 0.9832065 0.7169406 0.4628316  0 0.9456881
## 7  3680.588 15378.20 12117.86  0 0.9917677 0.7851270 0.4504530  0 0.9093339
## 8  3781.956 15614.73 12070.99  0 0.9727485 0.7582961 0.4727426  0 0.9390084
## 9  3448.146 15401.50 11760.17  0 0.9836544 0.7648816 0.4851046  0 0.9537789
## 10 4656.666 15198.97 10216.98  0 0.9915345 0.7751203 0.5311969  0 0.9577708
##      d_e d_c
## 1  0.03 0.03
## 2  0.03 0.03
## 3  0.03 0.03
## 4  0.03 0.03
## 5  0.03 0.03
## 6  0.03 0.03
## 7  0.03 0.03
## 8  0.03 0.03
## 9  0.03 0.03
## 10 0.03 0.03

```

```

# Number of simulations
n_sim <- 1000

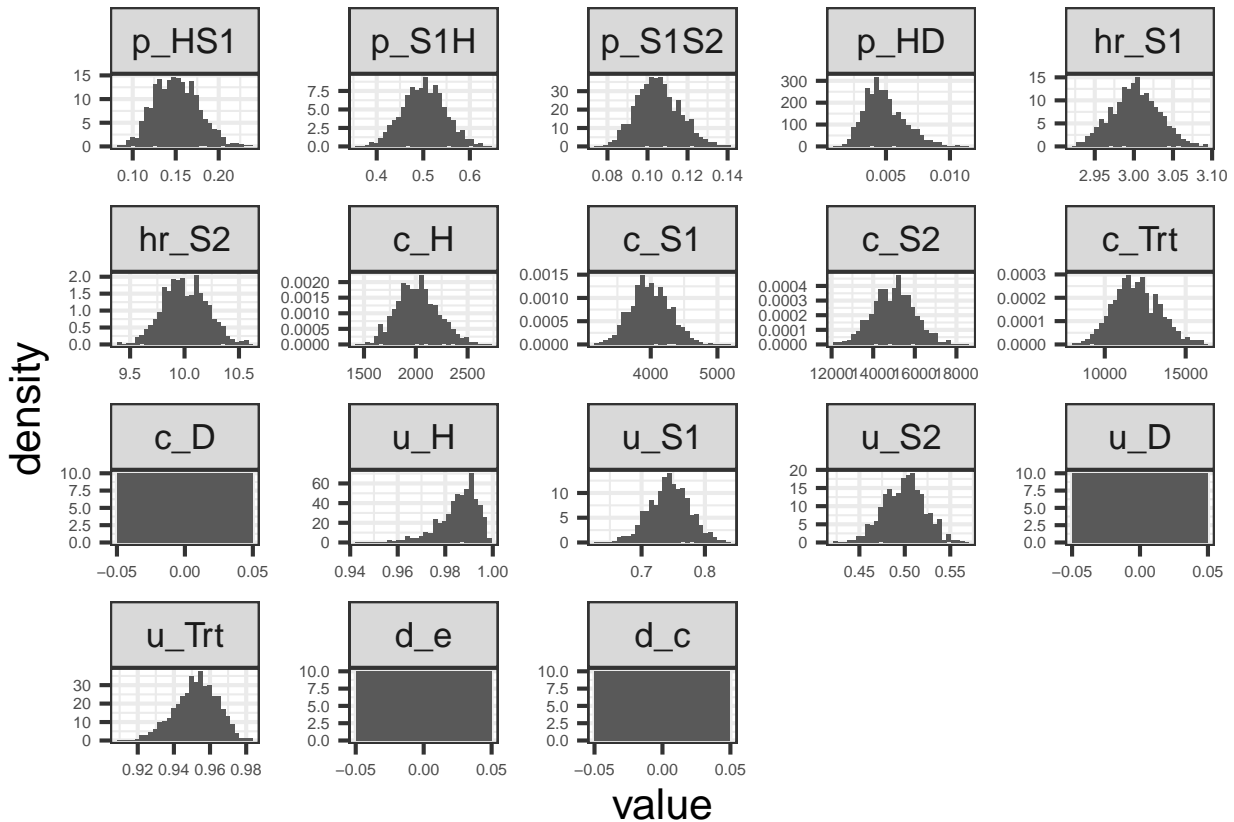
# Generate PSA input dataset
df_psa_input <- gen_psa(n_sim = n_sim)
# First six observations

```

```
head(df_psa_input)
```

```
##      p_HS1    p_S1H    p_S1S2      p_HD    hr_S1    hr_S2      c_H
## 1 0.1513235 0.5617628 0.1033817 0.006269864 2.962948  9.820157 1658.447
## 2 0.1252248 0.4380343 0.1152594 0.005371105 3.014068 10.100813 2050.281
## 3 0.1567372 0.5458102 0.1274505 0.004301015 3.018588  9.825985 2094.425
## 4 0.1127686 0.5106953 0.1015742 0.005319105 2.979709  9.697122 2135.411
## 5 0.1429295 0.5277308 0.1020384 0.004225209 3.025490 10.254387 1665.257
## 6 0.2008860 0.5252364 0.1030676 0.008319206 2.979175 10.366400 2049.794
##      c_S1    c_S2    c_Trt c_D      u_H      u_S1      u_S2 u_D      u_Trt
## 1 4191.109 15165.80 10292.050  0 0.9816602 0.7395884 0.5106656  0 0.9496993
## 2 4133.823 15042.66 10779.006  0 0.9906084 0.7240259 0.4927761  0 0.9731185
## 3 3567.033 15052.49 12811.443  0 0.9834960 0.6910869 0.5024542  0 0.9598494
## 4 3726.226 16084.60 10072.741  0 0.9919197 0.7065183 0.5118351  0 0.9357411
## 5 3654.486 15201.84 14917.228  0 0.9953850 0.6838064 0.5021483  0 0.9635901
## 6 3927.001 17060.57  9581.097  0 0.9813330 0.7766346 0.5035428  0 0.9506926
##      d_e d_c
## 1 0.03 0.03
## 2 0.03 0.03
## 3 0.03 0.03
## 4 0.03 0.03
## 5 0.03 0.03
## 6 0.03 0.03
```

```
# Histogram of parameters
ggplot(melt(df_psa_input, variable.name = "Parameter"), aes(x = value)) +
  facet_wrap(~Parameter, scales = "free") +
  geom_histogram(aes(y = ..density..)) +
  scale_x_continuous(breaks = scales::pretty_breaks(n = 3)) +
  theme_bw(base_size = 16) +
  theme(axis.text = element_text(size=6))
```



```
# Initialize dataframes with PSA output
# Dataframe of costs
df_c <- as.data.frame(matrix(0,
                             nrow = n_sim,
                             ncol = n_str))
colnames(df_c) <- v_names_str
# Dataframe of effectiveness
df_e <- as.data.frame(matrix(0,
                             nrow = n_sim,
                             ncol = n_str))
colnames(df_e) <- v_names_str
```

## 09.1 Conduct probabilistic sensitivity analysis

```
# Run Markov model on each parameter set of PSA input dataset
for(i in 1:n_sim){
  l_out_temp <- calculate_ce_out(df_psa_input[i, ])
  df_c[i, ] <- l_out_temp$Cost
  df_e[i, ] <- l_out_temp$Effect
  # Display simulation progress
  if(i/(n_sim/10) == round(i/(n_sim/10), 0)) { # display progress every 10%
    cat('\r', paste(i/n_sim * 100, "% done", sep = " "))
  }
}
```

```
## 10 % done 20 % done 30 % done 40 % done 50 % done 60 % done 70 % done 80 % done 90 % done 100 % done
```

## 09.2 Create PSA object for dampack

```
l_psa <- make_psa_obj(cost      = df_c,  
                     effectiveness = df_e,  
                     parameters  = df_psa_input,  
                     strategies  = v_names_str)
```

### 09.2.1 Save PSA objects

```
save(df_psa_input, df_c, df_e, v_names_str, n_str, l_psa,  
     file = "markov_sick-sicker_PSA_dataset.RData")
```

## 09.3 Create probabilistic analysis graphs

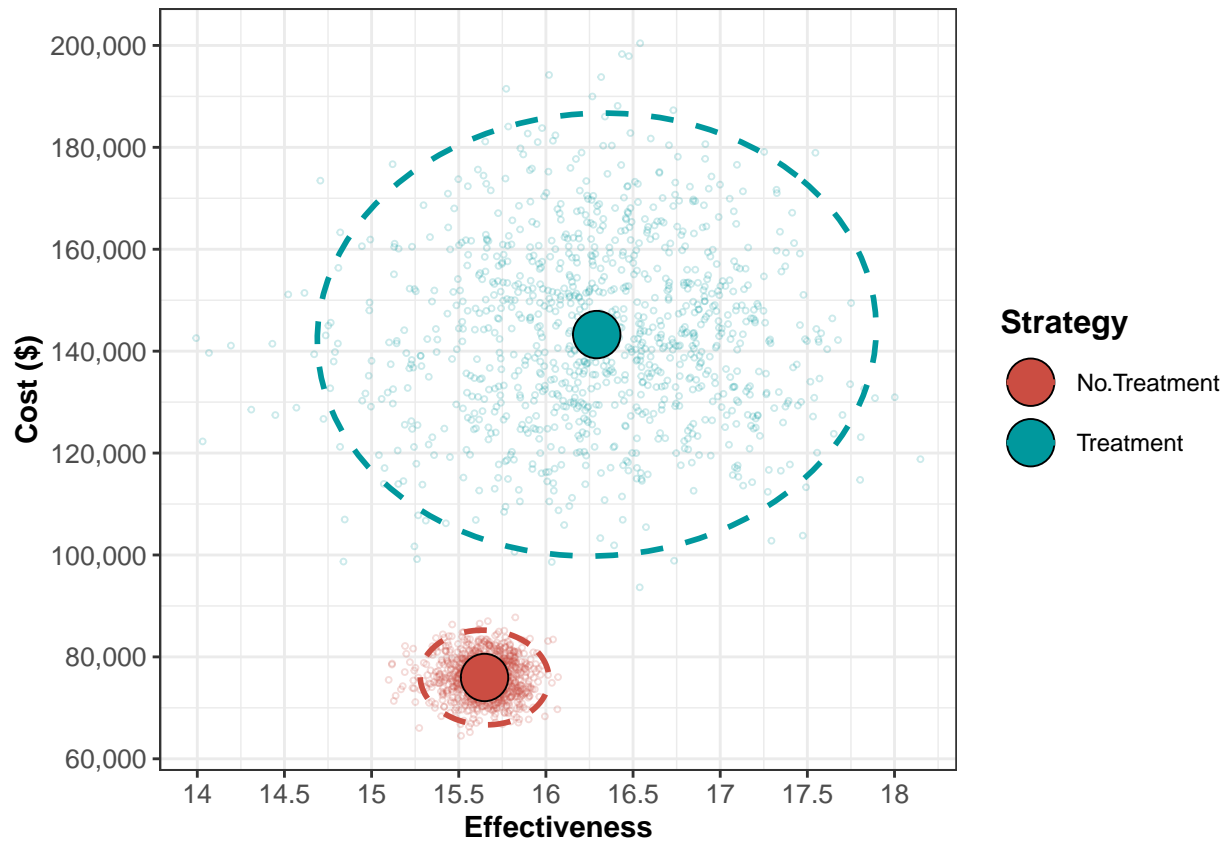
```
load(file = "markov_sick-sicker_PSA_dataset.RData")
```

Vector with willingness-to-pay (WTP) thresholds.

```
v_wtp <- seq(0, 200000, by = 10000)
```

### 09.3.1 Cost-Effectiveness Scatter plot

```
plot(l_psa)
```



## 09.4 Conduct CEA with probabilistic output

```
# Compute expected costs and effects for each strategy from the PSA
df_out_ce_psa <- summary(l_psa)
```

```
# Calculate incremental cost-effectiveness ratios (ICERs)
df_cea_psa <- calculate_icers(cost      = df_out_ce_psa$meanCost,
                             effect    = df_out_ce_psa$meanEffect,
                             strategies = df_out_ce_psa$Strategy)

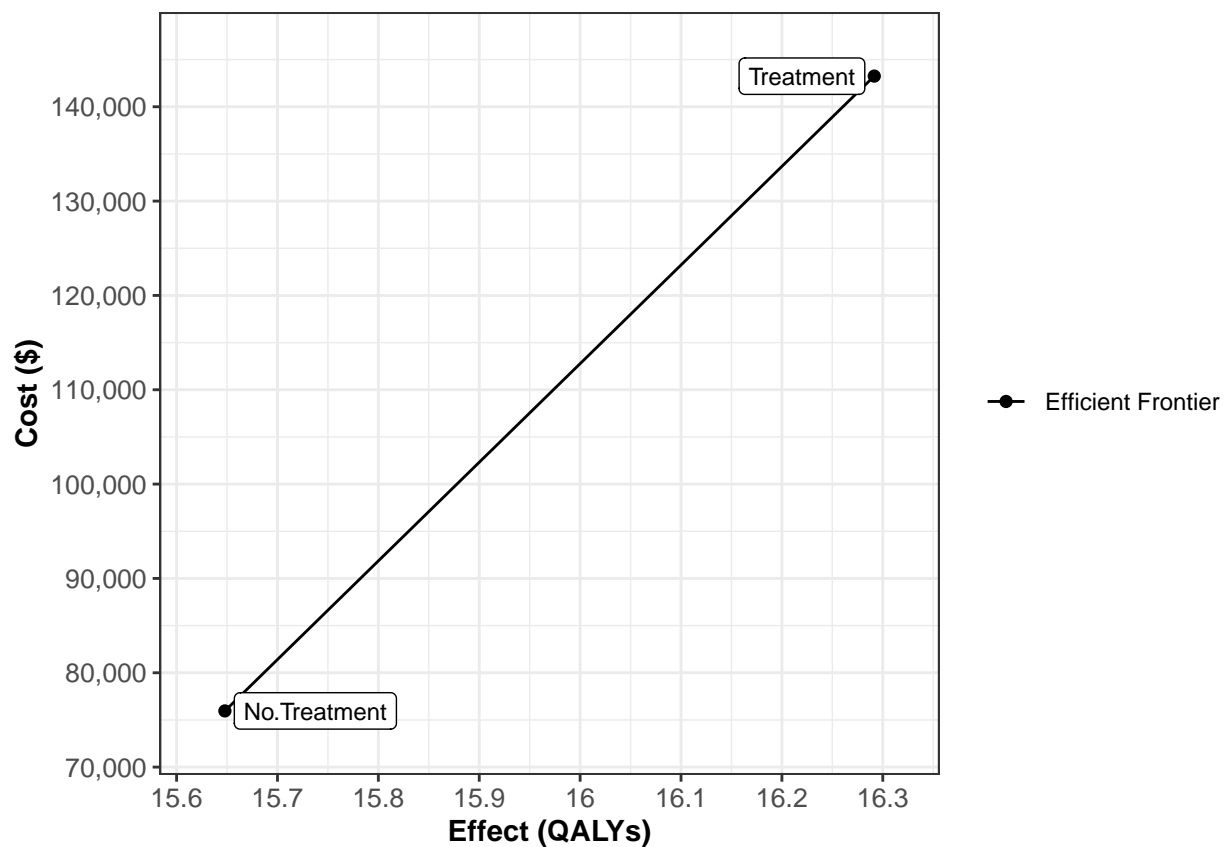
df_cea_psa
```

```
##      Strategy      Cost  Effect Inc_Cost Inc_Effect      ICER Status
## 1 No.Treatment  75955.61 15.64787      NA      NA      NA      ND
## 2 Treatment 143251.54 16.29156 67295.93  0.6436874 104547.5      ND
```

```
# Save CEA table with ICERs
# As .RData
save(df_cea_psa,
     file = "markov_sick-sicker_probabilistic_CEA_results.RData")
# As .csv
write.csv(df_cea_psa,
         file = "markov_sick-sicker_probabilistic_CEA_results.csv")
```

### 09.4.1 Plot cost-effectiveness frontier

```
plot(df_cea_psa)
```

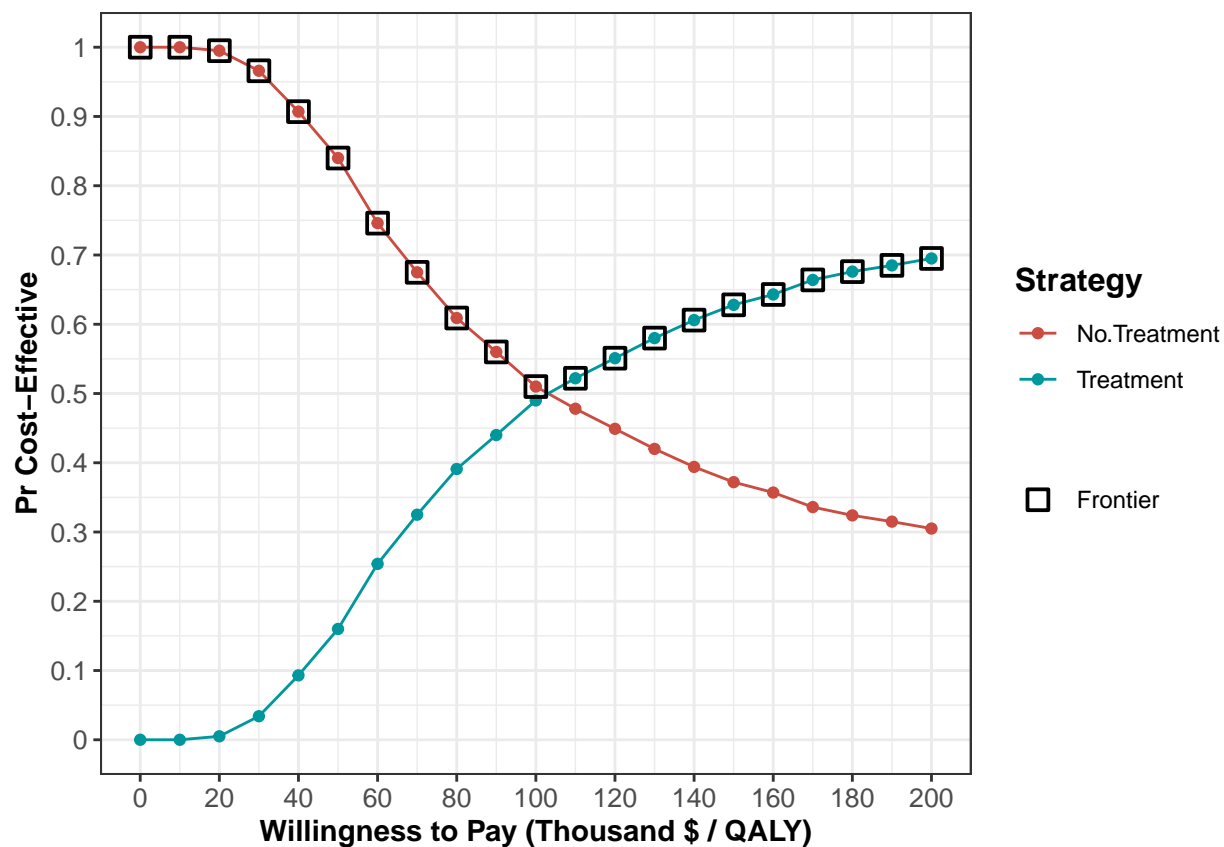


### 09.4.2 Cost-effectiveness acceptability curves (CEACs) and frontier (CEAF)

```
ceac_obj <- ceac(wtp = v_wtp, psa = l_psa)
# Regions of highest probability of cost-effectiveness for each strategy
summary(ceac_obj)
```

```
##   range_min range_max cost_eff_strat
## 1         0    110000    No.Treatment
## 2    110000    200000      Treatment
```

```
# CEAC & CEAF plot
plot(ceac_obj)
```



### 09.4.3 Expected Loss Curves (ELCs)

The expected loss is the the quantification of the foregone benefits when choosing a suboptimal strategy given current evidence.

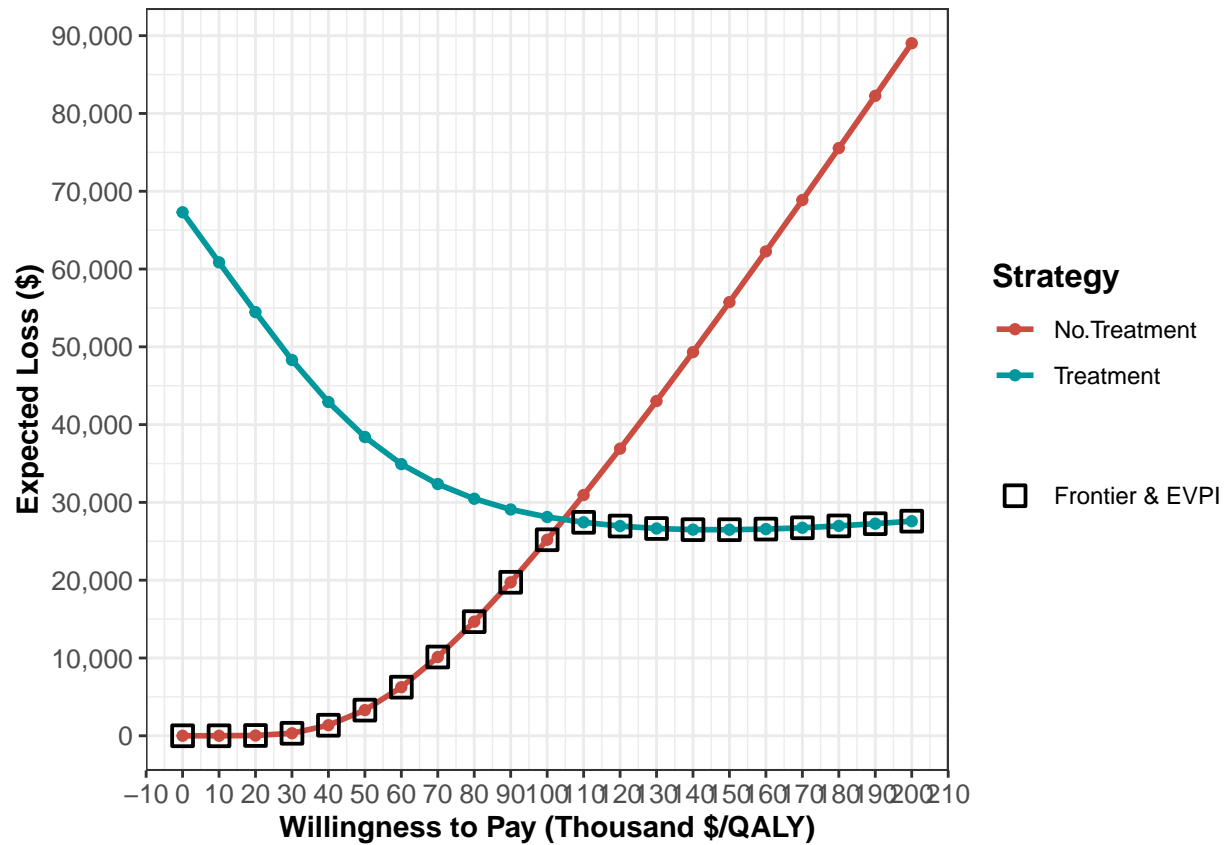
```
elc_obj <- calc_exp_loss(wtp = v_wtp, psa = l_psa)
elc_obj
```

##	WTP	Strategy	Expected_Loss	On_Frontier
## 1	0	No.Treatment	0.00000	TRUE
## 2	0	Treatment	67295.92714	FALSE
## 3	10000	No.Treatment	0.00000	TRUE
## 4	10000	Treatment	60859.05317	FALSE
## 5	20000	No.Treatment	35.95817	TRUE
## 6	20000	Treatment	54458.13738	FALSE
## 7	30000	No.Treatment	322.38988	TRUE
## 8	30000	Treatment	48307.69512	FALSE
## 9	40000	No.Treatment	1357.10595	TRUE
## 10	40000	Treatment	42905.53722	FALSE
## 11	50000	No.Treatment	3297.41004	TRUE
## 12	50000	Treatment	38408.96734	FALSE
## 13	60000	No.Treatment	6248.02097	TRUE
## 14	60000	Treatment	34922.70430	FALSE
## 15	70000	No.Treatment	10123.60585	TRUE

## 16	70000	Treatment	32361.41521	FALSE
## 17	80000	No.Treatment	14668.48694	TRUE
## 18	80000	Treatment	30469.42234	FALSE
## 19	90000	No.Treatment	19729.40367	TRUE
## 20	90000	Treatment	29093.46510	FALSE
## 21	100000	No.Treatment	25199.14250	TRUE
## 22	100000	Treatment	28126.32997	FALSE
## 23	110000	No.Treatment	30950.62051	FALSE
## 24	110000	Treatment	27440.93400	TRUE
## 25	120000	No.Treatment	36908.01787	FALSE
## 26	120000	Treatment	26961.45740	TRUE
## 27	130000	No.Treatment	43029.50480	FALSE
## 28	130000	Treatment	26646.07036	TRUE
## 29	140000	No.Treatment	49318.83174	FALSE
## 30	140000	Treatment	26498.52333	TRUE
## 31	150000	No.Treatment	55747.56036	FALSE
## 32	150000	Treatment	26490.37798	TRUE
## 33	160000	No.Treatment	62263.42425	FALSE
## 34	160000	Treatment	26569.36791	TRUE
## 35	170000	No.Treatment	68869.16074	FALSE
## 36	170000	Treatment	26738.23043	TRUE
## 37	180000	No.Treatment	75547.14077	FALSE
## 38	180000	Treatment	26979.33649	TRUE
## 39	190000	No.Treatment	82267.39582	FALSE
## 40	190000	Treatment	27262.71757	TRUE
## 41	200000	No.Treatment	89028.28011	FALSE
## 42	200000	Treatment	27586.72789	TRUE

```
# ELC plot
plot(elc_obj, log_y = FALSE)
```





#### 09.4.4 Expected value of perfect information (EVPI)

```
evpi <- calc_evpi(wtp = v_wtp, psa = l_psa)
# EVPI plot
plot(evpi, effect_units = "QALY")
```

