Simulation Step 6 Simulation Study

July 8, 2024

1 Prelude

[1]:
```
import matplotlib as mpl
import matplotlib.pyplot as plt
import pulp
import math
import random
import pandas as pd
import numpy as np
import simpy
```

2 Utilities

2.1 Points and Distances

[2]:
```
def dist(p1, p2):
    (x1, y1) = p1
    (x2, y2) = p2
    return int(math.sqrt((x1-x2)**2+(y1-y2)**2))
```

2.2 PlotMap

[3]:
```
def label(i):
    return (label(i//26-1)+chr(65+i%26)) if i>25 else chr(65+i)
```

[4]:
```
def plotMap(G, T=[], P=[], w=None,
            style='r-o', lw=1, ms=3,
            styleT='go', msT=3,
            styleP='b-o', lwP=2, msP=3,
            stylePT='go', msPT=7,
            styleW='ro', msW=9,
            text=None, grid=False, labels=False, scale=False):

    V, E = G

    def round_down(x, level): return (x//level)*level
    def round_up(x, level): return (x//level+1)*level
```

```
    xmin = round_down(min([ x for (x, _) in V ]), 100)
    xmax = round_up(max([ x for (x, _) in V ]), 100)
    ymin = round_down(min([ y for (_, y) in V ]), 100)
    ymax = round_up(max([ y for (_, y) in V ]), 100)
    dx = xmax-xmin
    dy = ymax-ymin
    yoffset = (ymax-ymin)//10

    fig = plt.gcf()
    fig.set_size_inches(4, 4)
    plt.xlim(xmin, xmax)
    plt.ylim(ymin-yoffset, ymax)

    if not grid:
        plt.axis('off')

    for e in E:
        p1, p2 = e
        plt.plot( [ p1[0], p2[0] ],
                  [ p1[1], p2[1] ],
                  style, lw=lw, ms=ms)
    if scale:
        # plot 1000m scale
        ybar = ymin-0.9*yoffset
        D = [ (xmin, ybar+50), (xmin, ybar), (xmin+1000, ybar), (xmin+1000,␣
↪ybar+50) ]
        plt.plot( [ d[0] for d in D ], [ d[1] for d in D ], 'k-', lw=0.5)
        plt.text(xmin+500, ymin-0.7*yoffset, '1000m' ,␣
↪horizontalalignment='center', size=8)

    if labels:
        for i in range(len(V)):
            x, y = V[i]
            plt.text(x+0.0150*dx, y-0.0350*dy, label(i), size=8)

    for t in T:
        plt.plot( [ t[0] ], [ t[1] ],
                  styleT, ms=msT)

    plt.plot( [ p[0] for p in P ],
              [ p[1] for p in P ],
              styleP, lw=lwP, ms=msP)

    for p in P:
        if p in T:
            plt.plot( [ p[0] ], [ p[1] ],
```

```
                    stylePT, ms=msPT)
    if w is not None:
        plt.plot( [ w[0] ], [ w[1] ],
                    styleW, ms=msW)
    if text is not None:
        plt.text(xmax, ymin-0.7*yoffset, text, horizontalalignment='right',␣
↪size=8)
    if grid:
        plt.grid()
    plt.show()
```

2.3 Add Targets

[5]:
```
def addTargets(M, T):
    V, E = M
    E = E.copy()
    V = V.copy()
    for t in T:
        minD = math.inf
        minE = None
        for e in E:
            P, Q = e
            distT = dist(P, t)+dist(t, Q)-dist(P, Q)
            if distT < minD:
                minD = distT
                minE = e
        P, Q = minE
        E.remove( (P, Q) )
        E.append( (P, t) )
        E.append( (t, Q) )
        V.append(t)
    return V, E
```

2.4 Generate Central Warehouse Location

[6]:
```
from statistics import median

def generateWarehouseLocation(M):
    V, _ = M
    xc = median([ x for (x, y) in V ])
    yc = median([ y for (x, y) in V ])
    cloc = (xc, yc)
    minloc = V[0]
    mindist = dist(minloc, cloc)
    for i in range(1, len(V)):
        d = dist(V[i], cloc)
        if d<mindist:
```

```
            minloc = V[i]
            mindist = dist(V[i], cloc)
    return minloc
```

2.5 Time Handling

Convention: In this project we measure simulation time in seconds. The simulation will start at 0:00. Time related methods will be added as they are needed.

`timestamp(t)` generates a timestamp string in the form `[dd] hh:mm:ss.d`

[7]:
```
def timestamp(t):
    t = round(t, 1)
    day = int(t)//(24*3600)
    t = t - day*24*3600
    hour = int(t)//3600
    t = t - hour*3600
    mins = int(t)//60
    t = t - mins*60
    secs = int(t)
    t = int(round((t-secs)*10,1))
    return f"[{day:2d}] {hour:02d}:{mins:02d}:{secs:02d}.{t:1d}"
```

[8]:
```
timestamp(24*3600*3+17*3600+615.1)
```

[8]:
```
'[ 3] 17:10:15.1'
```

[9]:
```
timestamp(24*3600*12+3*3600+122.1)
```

[9]:
```
'[12] 03:02:02.1'
```

[10]:
```
def day(now):
    return int(now//(24*3600))
```

[11]:
```
def nextHour(env, hour):
    beginningOfDay = int(env.now//(24*3600))*24*3600
    timeOfDay = env.now-beginningOfDay
    if hour*3600 > timeOfDay:
        return hour*3600 - timeOfDay
    else:
        return hour*3600 + 24*3600 - timeOfDay
```

2.6 Plotting Routines

[12]:
```
import scipy.stats as stats

def histPlot(data, title="", xlabel="",
             discrete=False, width=None, height=None):
```

```
    minx = min(data)
    maxx = max(data)
      = np.mean(data)
      = np.std(data)

    fig = plt.figure()
    fig.set_figwidth(width if width is not None else 4)
    fig.set_figheight(height if height is not None else 2.5)
    ax = fig.gca()

    if discrete:
        bins = [ i for i in range(maxx+1) ]
        hist=plt.hist(data, bins=bins, density=True)
    else:
        hist=plt.hist(data, density=True)
    plt.xlabel(xlabel)
    plt.ylabel('Density')
    plt.title(title)

    if discrete:
        poisson=stats.poisson( )
        x = [ i for i in range(maxx+1) ]
        y =[ poisson.pmf(i) for i in range(maxx+1) ]
        ax.plot(x, y, lw=1, color='red')
    else:
        x = np.linspace(minx, maxx, 100)
        y = [ stats.norm(loc= , scale= ).pdf(p) for p in x]
        ax.plot(x, y, lw=1, color='red')

    ax.axvline(x= , color='red')
    maxy = max(max(y), max(hist[0]))
    ax.text(maxx, maxy,
            f' ={ :2.2f}\n ={ :2.2f}',
            ha='right', va='top',
            color='red', fontsize=12)

    ax.grid(True)
    plt.show()

def dailyPlot(data,
              title="", ylabel="",
              width=None, height=None):

    days = len(data)

    fig = plt.figure()
```

```
    fig.set_figwidth(width if width is not None else 6)
    fig.set_figheight(height if height is not None else 2)

    ax = fig.gca()
    diff = (max(data)-min(data))*0.1
    ymin = int(math.floor(min(data)-diff))
    ymax = int(math.ceil(max(data)+diff))
    ax.set_xlim(-0.5, days-1+0.5)
    ax.set_ylim(ymin, ymax)
    ax.grid(True)

    ms = 2 if len(data)>=100 else 3
    lw = 0.5 if len(data)>=100 else 1

    x = np.arange(0, len(data))
    y = np.array([ y for y in data ])
    b, m = np.polynomial.polynomial.polyfit(x, y, 1)
    ax.xaxis.set_major_locator(mpl.ticker.MaxNLocator(integer=True))

    plt.plot(x, y, 'bo-', linewidth=lw, markersize=ms)
    plt.plot(x, m*x+b, 'r-')

    plt.xlabel('Day')
    plt.ylabel(ylabel)
    plt.title(title)
    plt.show()

def countPlot(A, B, days,
              title="", ylabel="",
              width=None, height=None):

    assert(len(A)==len (B))
    days = len(A)
    xmax = days-1
    ymax = A.max()

    fig = plt.figure()
    fig.set_figwidth(width if width is not None else 6)
    fig.set_figheight(height if height is not None else 4)
    ax = fig.gca()
    ax.set_xlim(-0.5, xmax+0.5)
    ax.set_ylim(0, ymax)

    def double(l, offset=0):
        return [] if l==[] else [l[0]+offset, l[0]+offset]+double(l[1:], offset)

    x = double([i for i in range(days)])+[days]
```

```
    xz = double([i+days*0.006 for i in range(days)])+[days]
    y = [0+ymax*0.006] + double(list(A), offset=ymax*0.006)
    z = [0] + double(list(B))

    ax.yaxis.set_major_locator(mpl.ticker.MaxNLocator(integer=True))
    ax.xaxis.set_major_locator(mpl.ticker.MaxNLocator(integer=True))

    for i in range(days):
        ax.fill_between([i, i+1],
                        [z[2*i+1], z[2*i+2]],
                        [y[2*i+1], y[2*i+2]], color='blue', alpha=0.2)

    lw = 1 if days>=50 or ymax>=100 else 2
    ax.plot(x, y, color='blue', lw=lw)
    ax.plot(xz, z, color='red', lw=lw)
    plt.xlabel('Day')
    plt.ylabel(ylabel)
    plt.title(title)
    ax.grid(True)
    plt.show()
```

3 Finding Shortest Path (as before)

[13]:
```
def pathLength(P):
    return 0 if len(P)<=1 else \
            dist(P[0], P[1])+pathLength(P[1:])
```

[14]:
```
def shortestPath(M, A, B):

    def h(p):
        return pathLength(p)+dist(p[-1],B)

    # candidates C are pairs of the path so far and
    # the heuristic function of that path,
    # sorted by the heuristic function, as maintained by
    # insert function
    def insert(C, p):
        hp = h(p)
        c = (p, hp)
        for i in range(len(C)):
            if C[i][1]>hp:
                return C[:i]+[c]+C[i:]
        return C+[c]

    V, E = M
    assert(A in V and B in V)
```

```
    C = insert([], [A])

    while len(C)>0:
        # take the first candidate out of the list of candidates
        path, _ = C[0]
        C = C[1:]
        if path[-1]==B:
            return path
        else:
            for (x, y) in E:
                if path[-1]==x and y not in path:
                    C = insert(C, path+[y])
                elif path[-1]==y and x not in path:
                    C = insert(C, path+[x])
    return None
```

4 Finding Short Delivery Route (as before)

4.1 Greedy Algorithm

[15]:
```
def FW(M):

    V, E = M

    n = len(V)
    d = [ [ math.inf for j in range(n) ] for i in range(n) ]
    p = [ [ None for j in range(n) ] for i in range(n) ]

    for (A, B) in E:
        a = V.index(A)
        b = V.index(B)
        d[a][b] = d[b][a] = dist(A, B)
        p[a][b] = [A, B]
        p[b][a] = [B, A]

    for i in range(n):
        d[i][i] = 0
        p[i][i] = [V[i]]

    for k in range(n):
        for i in range(n):
            for j in range(n):
                dk = d[i][k] + d[k][j]
                if d[i][j] > dk:
                    d[i][j] = dk
                    p[i][j] = p[i][k][:-1] + p[k][j]
```

```
    return d, p
```

[16]:
```
def createLoopG(M, T, timing=False):

    def makeLoop(L, V, P):
        loop = []
        for i in range(len(L)-1):
            A = L[i]
            B = L[i+1]
            a = V.index(A)
            b = V.index(B)
            sub = P[a][b]
            loop += sub if len(loop)==0 else sub[1:]
        return loop

    if timing:
        start_time = time.time()
        last_time = time.time()

    V, E = M
    D, P = FW(M)   # note these are the distances between all vertices in M␣
↪(and T)
    W = T[0]
    customers = T[1:]
    if len(T)==1:
        L = T
    elif len(T)<=3:
        L = T + [T[0]]
    else:
        L = T[:3]+[T[0]]
        T = T[3:]
        while len(T)>0:
            minExt = math.inf
            minInd = None
            selInd = None
            for k in range(len(T)):
                C = T[k]
                c = V.index(C)
                for i in range(0, len(L)-1):
                    A = L[i]
                    B = L[i+1]
                    a = V.index(A)
                    b = V.index(B)
                    ext = D[a][c] + D[c][b] - D[a][b]
                    if ext<minExt:
                        minExt, minInd, selInd = ext, i+1, k
            L = L[:minInd]+[T[selInd]]+L[minInd:]
```

```
            T = T[:selInd]+T[selInd+1:]

    if timing:
        print(f"createLoopG:    {time.time()-start_time:6.2f}s")

    return makeLoop(L, V, P)
```

5 Finding Optimal Delivery Route

5.1 Iterative Integer Programming

[17]:
```
def createTables(M, T):

    def reverse(P):
        return [ P[-i] for i in range(1,len(P)+1) ]

    def index(x, L):
        for i in range(len(L)):
            if x==L[i]:
                return i
        return None

    n = len(T)
    d = [ [ math.inf for t in T ] for t in T ]
    p = [ [ None for t in T ] for t in T ]
    for i in range(n):
        d[i][i] = 0
        p[i][i] = [ T[i] ]
    for i in range(n):
        for j in range(n):
            if p[i][j] is None:
                s = shortestPath(M, T[i], T[j])
                d[i][j] = d[j][i] = pathLength(s)
                p[i][j] = s
                p[j][i] = reverse(s)
                for m in range(len(s)-1):
                    smi = index(s[m], T)
                    if smi is None:
                        continue
                    for l in range(m+1, len(s)):
                        sli = index(s[l], T)
                        if sli is None:
                            continue
                        sub = s[m:l+1]
                        if p[smi][sli] is None:
                            p[smi][sli] = sub
                            p[sli][smi] = reverse(sub)
```

```
                            d[smi][sli] = d[sli][smi] = pathLength(sub)
    return d,p
```

[18]:
```
def roundtrips(x, n):

    def isElem(x, l):
        for i in range(len(l)):
            if l[i]==x:
                return True
        return False

    def startpoint(trips):
        for i in range(n):
            for t in trips:
                if isElem(i, t):
                    break
            else:
                return i

    def totalLength(trips):
        s=0
        for i in range(0, len(trips)):
            s += len(trips[i])-1
        return s

    trips = []
    while totalLength(trips)<n:
        start = startpoint(trips)
        trip = [ start ]
        i = start
        while len(trip) < n-totalLength(trips):
            for j in range(0, n):
                if pulp.value(x[i][j])==1:
                    trip.append(j)
                    i=j
                    break
            if pulp.value(x[trip[-1]][start])==1:
                trip.append(start)
                break
        trips.append(trip)
    return sorted(trips, key=lambda t: len(t), reverse=True)
```

[19]:
```
import time

def createLoop(M, T, timing=False):

    if timing:
```

```
    start_time = last_time = time.time()

D, P = createTables(M, T)   # These are the distances between customers and␣
↪warehouse only

if timing:
    print(f"createTables:   {time.time()-start_time:6.2f}s")
    last_time = time.time()

n = len(T)
# create variables
x = pulp.LpVariable.dicts("x", ( range(n), range(n) ),
                          lowBound=0, upBound=1, cat=pulp.LpInteger)
# create problem
prob = pulp.LpProblem("Loop",pulp.LpMinimize)
# add objective function
prob += pulp.lpSum([ D[i][j]*x[i][j]
                          for i in range(n) for j in range(n) ])
# add constraints
constraints=0
for j in range(n):
    prob += pulp.lpSum([ x[i][j] for i in range(n) if i!=j ]) ==1
constraints += n
for i in range(n):
    prob += pulp.lpSum([ x[i][j] for j in range(n) if i!=j ]) ==1
constraints += n
for i in range(n):
    for j in range(n):
        if i!=j:
            prob += x[i][j]+x[j][i] <= 1
            constraints += 1

def cycles(k, n):
    if k==1:
        return [ [i] for i in range(0,n) ]
    else:
        sc=cycles(k-1, n)
        all=[]
        for c in sc:
            for i in range(0,n):
                if c.count(i)==0:
                    all.append(c+[i])
        return all

for k in range(3, 4):
    cycs=cycles(k,n)
    for c in cycs:
```

```
            c.append(c[0])
            prob+=pulp.lpSum([ x[c[i]][c[i+1]] for i in range(0,k)]) <= k-1
            constraints += 1

    # initialise solver
    solvers = pulp.listSolvers(onlyAvailable=True)
    solver = pulp.getSolver(solvers[0], msg=0, timeLimit=2)
    res = prob.solve(solver)

    if timing:
        print(f"Solver:         {time.time()-last_time:6.2f}s {constraints:6,d}␣
↪Constraints")
        last_time = time.time()

    trips = roundtrips(x, n)
    while len(trips)>1:
        longest = max([ len(t) for t in trips ])
        for t in trips:
            if len(t)<longest:
                prob += pulp.lpSum([ x[t[i]][t[i+1]] + x[t[i+1]][t[i]]
                                     for i in range(0,len(t)-1) ]) <=␣
↪len(t)-2
                constraints += 1
            else:
                longest = math.inf

        res = prob.solve(solver)

        if timing:
            print(f"Solver:         {time.time()-last_time:6.2f}s {constraints:
↪6,d} Constraints")
            last_time = time.time()

        trips = roundtrips(x, n)
    trip = trips[0]
    # print(trip)
    loop = []
    for k in range(len(trip)-1):
        sub = P[trip[k]][trip[k+1]]
        loop += sub if len(loop)==0 else sub[1:]

    if timing:
        print(f"createLoop:     {time.time()-start_time:6.2f}s")

    return loop
```

6 Class Recorder

We willl use a class Recorder as a reference point for capturing data during the simulation. There will be only one recorder. It will be created at the beginning of every simulation run. Every entity will carry a reference to the Recorder.

[20]:
```
import time

class Recorder:

    def __init__(self, env, M, W, C, D, days,
                 log=False, plot=False, timing=False):
        self.env = env
        self.M = M
        self.W = W
        self.C = C
        self.D = D

        self.parcels = sum([ len(d) for d in D ])
        self.days = days
        self.log = log
        self.plot = plot

        # create a data frame for time records per working day
        self.daily = pd.DataFrame()
        self.daily['begin work at'] = [None]*days
        self.daily['end work at'] = [None]*days
        self.daily['tour length'] = [None]*days
        self.daily['parcels arrived'] = [0]*days
        self.daily['parcels out for delivery'] = [0]*days
        self.daily['parcels returned from delivery'] = [0]*days
        self.daily['parcels delivered'] = [0]*days
        self.daily['parcels left over'] = [0]*days

        self.parcel = pd.DataFrame()
        self.parcel['arrived at'] = [None]*self.parcels
        self.parcel['delivered at'] = [None]*self.parcels

    def trace(self, event):
        if self.log:
            print(timestamp(self.env.now), event)

    def recordDriverBeginsWork(self):
        self.trace("Driver arrives for work")
        self.daily.at[day(self.env.now), 'begin work at'] = int(round(self.env.
↪now))
```

```
    def recordDriverEndsWork(self):
        self.trace("Driver goes home")
        self.daily.at[day(self.env.now), 'end work at'] = int(round(self.env.
↪now))

    def recordTourLength(self, length):
        self.daily.at[day(self.env.now), 'tour length'] = int(length)

    def recordParcelArrived(self, parcel):
        today = day(self.env.now)
        self.daily.at[today, 'parcels arrived'] += 1
        self.parcel.at[parcel.i, 'arrived at'] = today

    def recordParcelOutForDelivery(self, parcel):
        self.daily.at[day(self.env.now), 'parcels out for delivery'] += 1

    def recordParcelReturnedFromDelivery(self, parcel):
        self.daily.at[day(self.env.now), 'parcels returned from delivery'] += 1

    def recordParcelDelivered(self, parcel):
        today = day(self.env.now)
        self.daily.at[today, 'parcels delivered'] += 1
        self.parcel.at[parcel.i, 'delivered at'] = today

    def recordParcelsLeftOver(self, n):
        self.trace(f"{n:d} parcels left over for next day")
        self.daily.at[day(self.env.now), 'parcels left over'] = n

    def finish(self):
        # simulation is finished for good
        # by removing the simulation environment we can
        # pickle recorder
        self.env = None

        self.daily['working time'] = (self.daily['end work at']-self.
↪daily['begin work at'])//60
        self.daily['cost'] = self.daily['working time'].apply(lambda x: max(60,␣
↪x*30/60))
        self.daily['cost'] += 0.08/1000*self.daily['tour length']
        self.daily['cum arrival'] = self.daily['parcels arrived'].cumsum()
        self.daily['cum delivery'] = self.daily['parcels delivered'].cumsum()

        self.parcel['delivery delay'] = self.parcel['delivered at']-self.
↪parcel['arrived at']
```

```
    def histWorkingTime(self):
        histPlot(self.daily['working time'],
                 xlabel='Working Time [min]',
                 title=f'Daily Working Time ({self.days:d} days)')

    def plotWorkingTime(self):
        dailyPlot(self.daily['working time'],
                  ylabel='Working Time [min]',
                  title=f'Daily Working Time ({self.days:d} days)')

    def histTourLength(self):
        histPlot(self.daily['tour length'],
                 xlabel='Tour Length [m]',
                 title=f'Daily Tour Length ({self.days:d} days)')

    def plotTourLength(self):
        dailyPlot(self.daily['tour length'],
                  ylabel='Tour Length [m]',
                  title=f'Daily Tour Length ({self.days:d} days)')

    def histDailyCost(self):
        histPlot(self.daily['cost'],
                 xlabel='DailyCost [€]',
                 title=f'Daily Cost ({self.days:d} days)')

    def plotDailyCost(self):
        dailyPlot(self.daily['cost'],
                  ylabel='Daily Cost [€]',
                  title=f'Daily Cost ({self.days:d} days)')

    def histParcelsArrived(self):
        histPlot(self.daily['parcels arrived'], discrete=True,
                 xlabel='Parcels Arrived',
                 title=f'Parcels Arrived Daily ({self.days:d} Days)')

    def plotParcelsArrived(self):
        dailyPlot(self.daily['parcels arrived'],
                  ylabel='Number of Parcels',
                  title=f'Parcels Arrived Daily ({self.days:d} Days)')

    def histParcelsOutForDelivery(self):
        histPlot(self.daily['parcels out for delivery'], discrete=True,
                 xlabel='Parcels Arrived',
                 title=f'Parcels Daily out for Delivery ({self.days:d} Days)')

    def plotParcelsOutForDelivery(self):
        dailyPlot(self.daily['parcels out for delivery'],
```

```
                ylabel='Number of Parcels',
                title=f'Parcels Daily out for Delivery ({self.days:d} Days)')

    def histParcelsReturnedFromDelivery(self):
        histPlot(self.daily['parcels returned from delivery'], discrete=True,
                 xlabel='Parcels Arrived',
                 title=f'Parcels Daily Returned From Delivery ({self.days:d}␣
↪Days)')

    def plotParcelsReturnedFromDelivery(self):
        dailyPlot(self.daily['parcels returned from delivery'],
                  ylabel='Number of Parcels',
                  title=f'Parcels Daily Returned From Delivery ({self.days:d}␣
↪Days)')

    def histParcelsDelivered(self):
        histPlot(self.daily['parcels delivered'], discrete=True,
                 xlabel='Left-Over Parcels',
                 title=f'Parcels Delivered Daily ({self.days:d} Days)')

    def plotParcelsDelivered(self):
        dailyPlot(self.daily['parcels delivered'],
                  ylabel='Number of Parcels',
                  title=f'Parcels Delivered Daily ({self.days:d} Days)')

    def histParcelsLeftOver(self):
        histPlot(self.daily['parcels left over'], discrete=True,
                 xlabel='Left-Over Parcels',
                 title=f'Parcels Daily Left-Overs ({self.days:d} Days)')

    def plotParcelsLeftOver(self):
        dailyPlot(self.daily['parcels left over'],
                  ylabel='Number of Parcels',
                  title=f'Parcels Daily Left-Overs ({self.days:d} Days)')

    def countPlot(self):
        countPlot(self.daily['cum arrival'], self.daily['cum delivery'], self.
↪days,
                  ylabel='Parcels',
                  title=f'Parcel Arrival/Delivery ({self.parcels:3,d} Parcels,␣
↪{self.days:d} Days)')

    def histParcelDeliveryDelay(self):
        histPlot(self.parcel['delivery delay'], discrete=True,
                 xlabel='Days',
                 title=f'Parcel Delivery Delay in Days ({self.parcels:3,d}␣
↪Parcels)')
```

7 Class Customer

[21]:
```
class Customer:

    def __init__(self, rec, id, location):
        self.rec = rec
        self.id = id
        self.location = location
        self.atHome = True
        self.answersDoor = False
        self.parcelsReceived = []
        rec.env.process(self.process())

    def __str__(self):
        return f"Customer {self.id:d} at {str(self.location):s}"

    def leaveHouse(self):
        assert(self.atHome and not self.answersDoor)
        # self.rec.trace(str(self)+" leaves house")
        self.atHome = False

    def returnHome(self):
        assert(not self.atHome)
        # self.rec.trace(str(self)+" returns home")
        self.atHome = True

    def answerDoor(self):
        if self.atHome:
            answerTime = random.expovariate(1/AVG_TIME_ANSWER_DOOR)
            if answerTime < WAIT_TIME_IF_CUSTOMER_DOESNT_ANSWER_DOOR:
                yield self.rec.env.timeout(answerTime)
                self.rec.trace(str(self)+" answers door")
                self.answersDoor = True
            else:
                yield self.rec.env.
↪timeout(WAIT_TIME_IF_CUSTOMER_DOESNT_ANSWER_DOOR)
                self.rec.trace(str(self)+" to slow to answer the door")
                self.answersDoor = False
        else:
            yield self.rec.env.timeout(WAIT_TIME_IF_CUSTOMER_DOESNT_ANSWER_DOOR)
            self.rec.trace(str(self)+" not at home")
            self.answersDoot = False

    def acceptParcel(self, parcel):
        assert(self.answersDoor)
        self.parcelsReceived += [parcel]
        self.rec.trace(str(self)+" accepts "+str(parcel))
```

```
        self.rec.recordParcelDelivered(parcel)

    def signOff(self):
        assert(self.answersDoor)
        self.rec.trace(str(self)+" signs off")
        self.answersDoor = False

    def process(self):
        yield self.rec.env.timeout(nextHour(self.rec.env, 8))
        while day(self.rec.env.now)<self.rec.days:
            # in a refinement we may use random times
            self.leaveHouse()
            returnTime = 22 if random.random()<CUSTOMER_NOT_AT_HOME else 18
            yield self.rec.env.timeout(nextHour(self.rec.env, returnTime))
            self.returnHome()
            yield self.rec.env.timeout(nextHour(self.rec.env, 8))
```

8 Class Parcel

Parcels follow through a sequence of states: - processing - in transit (from manufacture to distribution centre) - arrived in distribution centre - ready for delivery - out for delivery - customer not present - returned to distribution centre - delivered

[22]:
```
class Parcel:

    def __init__(self, rec, i, day, cust):
        self.rec = rec
        self.i = i
        self.arrival = day
        self.cust = cust
        self.status = [  ] # status record and
        self.timing = [  ] # timing

    def __str__(self):
        return f"Parcel {self.i:d} for cust {self.cust.id:d}"

    def index(self):
        return self.i

    def destination(self):
        return self.cust.location

    def __reg(self, state):
        self.status += [ state ]
        self.timing += [ self.rec.env.now ]
        self.rec.trace(str(self)+" "+state)
```

```
    def arrivedAtDeliveryCentre(self):
        self.__reg('arr at delivery centre')
        self.rec.recordParcelArrived(self)

    def outForDelivery(self):
        self.__reg('out for delivery')
        self.rec.recordParcelOutForDelivery(self)

    def returnFromDelivery(self):
        self.__reg('return from delivery')
        self.rec.recordParcelReturnedFromDelivery(self)
```

9 Class Driver

[23]:
```
class Driver:

    def __init__(self, rec, DC):
        self.rec = rec
        self.DC = DC
        self.location = None
        self.parcels = None
        self.tour = None
        self.rec.env.process(self.process())

    # activity
    def __drive(self, target):
        assert(self.tour[0] == self.location)
        while self.location!=target:
            d = dist(self.location, self.tour[1])
            yield self.rec.env.timeout(d / AVG_SPEED)
            self.location = self.tour[1]
            self.tour = self.tour[1:]
        assert(self.tour[0] == self.location == target)

    def arriveForWork(self):
        self.location = self.DC.W
        self.parcels = []
        self.returns = []
        self.tour = [ self.DC.W ]
        # self.rec.trace("Driver arrives for work")
        self.rec.recordDriverBeginsWork()

    def goesHome(self):
        self.location = None
        self.parcels = None
```

```
        self.returns = None
        self.tour = None
        # self.rec.trace("Driver goes home")
        self.rec.recordDriverEndsWork()

    def leaveForDelivery(self, tour, parcels, addresses):
        self.tour, self.parcels = tour, parcels
        self.rec.trace(f"Driver leaves for delivery "
                       f"of {len(parcels):d} parcels "
                       f"to {len(addresses):d} customers")
        self.rec.trace(f"Length of delivery tour: {pathLength(tour):,d}m")
        if self.rec.plot:
            plotMap(self.rec.M, T=addresses, P=tour, w=tour[0],
                    text=f"Day {day(self.rec.env.now):d}:, {pathLength(tour):
↪,d}m")

    def process(self):
        yield self.rec.env.timeout(nextHour(self.rec.env, 18))
        while day(self.rec.env.now)<self.rec.days:
            self.arriveForWork()

            ## chnge to deal with time limit
            startTime = self.rec.env.now

            tour, parcels, addresses = self.DC.sendForDelivery()
            if len(parcels)==0:
                self.rec.trace("Nothing to do today")
                self.rec.recordTourLength(0)
            else:
                yield self.rec.env.timeout(PREP_TIME_PER_PARCEL*len(parcels))
                self.rec.recordTourLength(pathLength(tour))
                self.leaveForDelivery(tour, parcels, addresses)
                while len(self.parcels)>0:

                    ## change to deal with time limit
                    currentTime = self.rec.env.now
                    if currentTime-startTime>=self.DC.timeLimit:
                        self.rec.trace("Timelimit reached")
                        while len(self.parcels)>0:
                            self.returns += [self.parcels[0]]
                            self.parcels = self.parcels[1:]
                        break

                    # drive to customer
                    custLocation = self.parcels[0].destination()
                    cust = self.parcels[0].cust
                    self.rec.trace("Driver drives to "+str(cust))
```

```
                    yield from self.__drive(custLocation)
                    self.rec.trace("Driver arrived at "+str(cust))
                    # call at customer
                    yield from cust.answerDoor()

                    if cust.answersDoor:
                        while len(self.parcels)>0 and \
                                custLocation == self.parcels[0].destination():
                            cust.acceptParcel(self.parcels[0])
                            yield self.rec.env.timeout(random.expovariate(1/
↪AVG_TIME_HANDOVER))
                            self.parcels = self.parcels[1:]
                        cust.signOff()
                        yield self.rec.env.timeout(random.expovariate(1/
↪AVG_TIME_SIGNOFF))
                    else:
                        while len(self.parcels)>0 and  \
                                custLocation == self.parcels[0].destination():
                            self.returns += [self.parcels[0]]
                            self.parcels = self.parcels[1:]

                # return to delivery centre
                self.rec.trace("Driver returns to delivery centre")
                yield from self.__drive(self.DC.W)
                self.rec.trace("Driver arrived at delivery centre")

                for parcel in self.returns:
                    self.DC.returnFromDelivery(parcel)
                    yield self.rec.env.timeout(RETURN_TIME_PER_PARCEL)

            self.rec.recordParcelsLeftOver(len(self.DC.parcels)+len(self.DC.
↪leftOver))

            yield self.rec.env.timeout(DAY_END_PROCEDURE)

            self.goesHome()

            yield self.rec.env.timeout(nextHour(self.rec.env, 18))
```

10 Class Delivery Centre

[24]:
```
class DeliveryCentre:

    def __init__(self, rec, M, W, limit, timeLimit):
        self.rec = rec
        self.M = M
```

```
        self.W = W
        self.limit = limit

        self.timeLimit = timeLimit

        self.leftOver = []    # list of parcels
        self.parcels = []     # list of parcels scheduled for delivery
        self.dest = []        # list of unique customer destinations
        self.tour = [self.W]  # tour planned for delivery

    def __accept(self, parcel):
        custLoc = parcel.destination()

        ## chnge to deal with time limit estimate
        timeEstimate = \
            len(self.parcels)*(PREP_TIME_PER_PARCEL + AVG_TIME_HANDOVER) \
            + len(self.dest)*(AVG_TIME_ANSWER_DOOR + AVG_TIME_SIGNOFF)

        if custLoc not in self.dest:
            MT = addTargets(self.M, self.dest + [custLoc])
            SH = createLoopG(MT, [self.W] + self.dest + [custLoc])

            ## chnge to deal with time limit estimate
            if pathLength(SH)<self.limit and \
                timeEstimate + pathLength(SH)/AVG_SPEED + \
                PREP_TIME_PER_PARCEL + AVG_TIME_ANSWER_DOOR + \
                AVG_TIME_HANDOVER + AVG_TIME_SIGNOFF <= self.timeLimit:

                self.parcels.append(parcel)
                self.dest += [custLoc]
                self.tour = SH
            else:
                self.leftOver.append(parcel)

            ## chnge to deal with time limit estimate
        elif timeEstimate + pathLength(self.tour)/AVG_SPEED + \
                PREP_TIME_PER_PARCEL + AVG_TIME_HANDOVER <= self.timeLimit:
            self.parcels.append(parcel)
        else:
            self.leftOver.append(parcel)

    def acceptParcel(self, parcel):
        parcel.arrivedAtDeliveryCentre()
        self.__accept(parcel)

    def sendForDelivery(self):
        parcels = []
```

```
        tour = self.tour
        addresses = []

        # pick parcels in sequence to be delivered
        for i in range(1, len(tour)-1):
            dest = tour[i]
            for p in self.parcels:
                if p.destination() == dest and p not in parcels:
                    parcels += [p]
                    p.outForDelivery()
                    if dest not in addresses:
                        addresses += [dest]

        # arrange the left overs for next day
        L = self.leftOver
        self.tour = [self.W]
        self.parcels = []
        self.leftOver = []
        self.dest = []
        for p in L:
            self.__accept(p)

        return tour, parcels, addresses

    def returnFromDelivery(self, parcel):
        parcel.returnFromDelivery()
        self.__accept(parcel)

    def getInventory(self):
        return len(self.parcels)+len(self.leftOver)
```

11 Simulation

11.1 Parameters from Specification

The hard time limit for the driver. When this time limit is reached on a delivery tour, the driver is supposed to return immediately

[25]:
```
DELIVERY_TIME_LIMIT = 3*3600 # 3 hours
```

The proportion of customers that for whatever are not at home or return home late

[26]:
```
CUSTOMER_NOT_AT_HOME = 0.1  # 10%
```

The maximum bike range. This is passed as parameter to the Delivery Centre and taken into account for the daily tour planning

[27]:
```
BIKE_RANGE = 40000
```

The time required for driving is based on the distance between way points at an average speed of 15km/h.

[28]:
```
AVG_SPEED = 15/3.6
```

The **cumulative preparation time** (route planning and sorting of the parcels in the delivery order and packing the cargo-bike) is assumed to be 50 sec per parcel to be delivered.

[29]:
```
PREP_TIME_PER_PARCEL = 50
```

Additional assumption: The time to **process returned parcels** in the delivery centre is 30 sec per parce.

[30]:
```
RETURN_TIME_PER_PARCEL = 30
```

The average time to answer the door.

[31]:
```
AVG_TIME_ANSWER_DOOR = 40
```

[32]:
```
WAIT_TIME_IF_CUSTOMER_DOESNT_ANSWER_DOOR = 60
```

[33]:
```
AVG_TIME_HANDOVER = 10
AVG_TIME_SIGNOFF = 10
```

[34]:
```
DAY_END_PROCEDURE = 600
```

11.2 Generate Input Data

[35]:
```
def generateDeliveries(p, C, days, seed=0):
    ## p is the average number of parcels per day per customer
    ## C is the number of customers to be served
    ## days is the number of days for which data are to be generated.
    random.seed(seed)
    deliveries = [ [ ] for _ in range(days) ]
    for c in range(C):
        arr = 0
        while True:
            arr += random.expovariate(p)
            day = int(arr)
            if day>=days:
                break
            deliveries[day].append(c)
    return deliveries
```

11.3 Simulation Routine

[36]:
```
def simulation(M, W, C, p=0.2, days=10, seed=0,
               log=False, plot=False, timing=False):
```

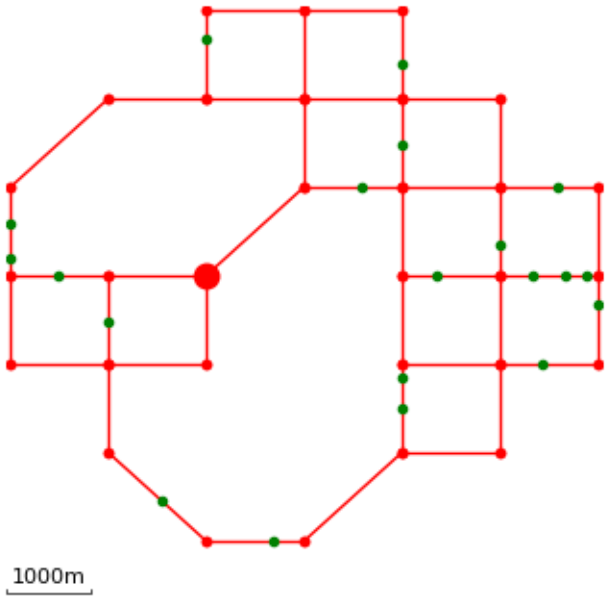
```
    random.seed(seed)
    D = generateDeliveries(p, len(C), days, seed)

    env = simpy.Environment()
    rec = Recorder(env, M, W, C, D, days,
                   log=log, plot=plot, timing=timing)

    print(f"Simulating delivery of {sum([len(d) for d in D]):d} parcels "
          f"over {len(D):d} days to {len(C):d} customers")

    CUSTOMERS = []
    for i in range(len(C)):
        CUSTOMERS.append(Customer(rec, i, C[i]))

    DC = DeliveryCentre(rec, M, W, BIKE_RANGE, DELIVERY_TIME_LIMIT)
    Z = Driver(rec, DC)
    PARCELS = []

    def parcelGeneratorProcess(env, rec, D, C):
        for day in range(len(D)):
            yield env.timeout(nextHour(env, 17.00))
            for c in D[day]:
                cust = CUSTOMERS[c]
                parcel = Parcel(rec, len(PARCELS), day, cust)
                PARCELS.append(parcel)
                DC.acceptParcel(parcel)

    env.process(parcelGeneratorProcess(env, rec, D, C))
    env.run()

    rec.finish()

    if DC.getInventory()>0:
        print(f"Delivery Centre Inventory at the end of last day: {DC.
↪getInventory():d} parcels")

    return rec
```

11.4 Testing

[37]:
```
import pickle
with open('data/testData.pickled', 'rb') as f:
    MT, CT = pickle.load(f)
```

[38]:
```
WT = generateWarehouseLocation(MT)
```

[39]:
```
plotMap(MT, T=CT, w=WT, scale=True)
```

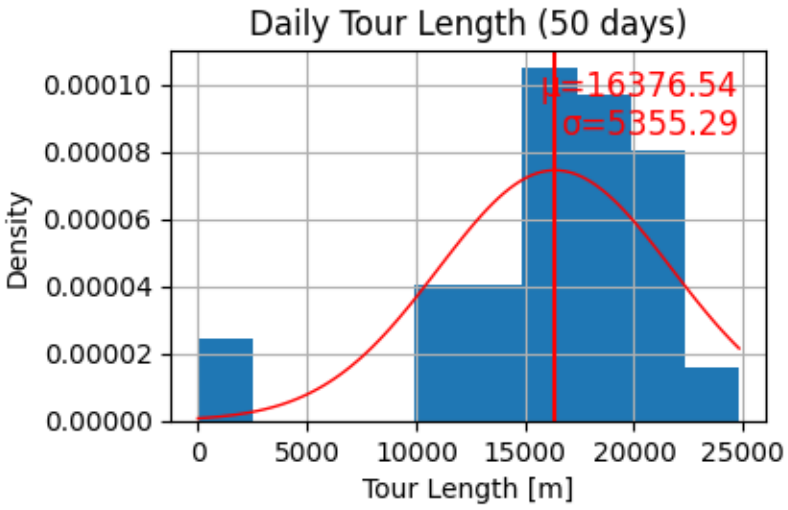


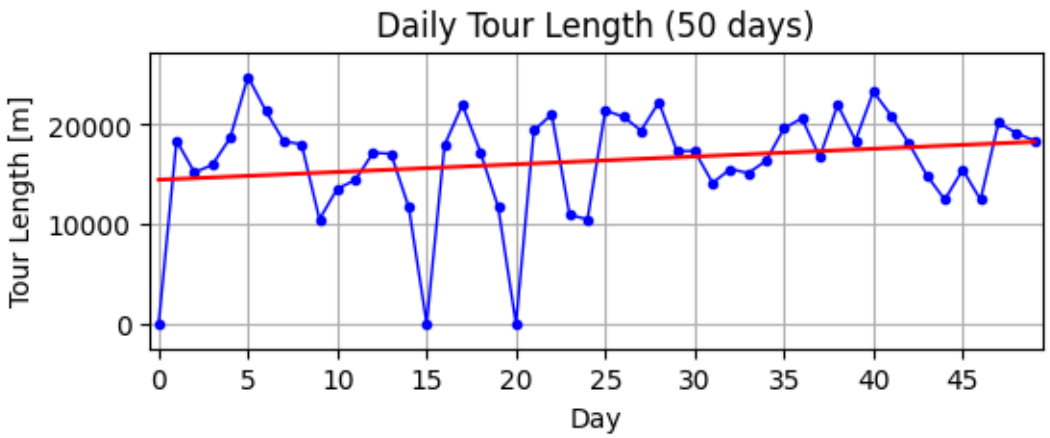
11.4.1 Stable Base Case

[40]:
```
rec1 = simulation(MT, WT, CT, p=0.15, days=50)
```

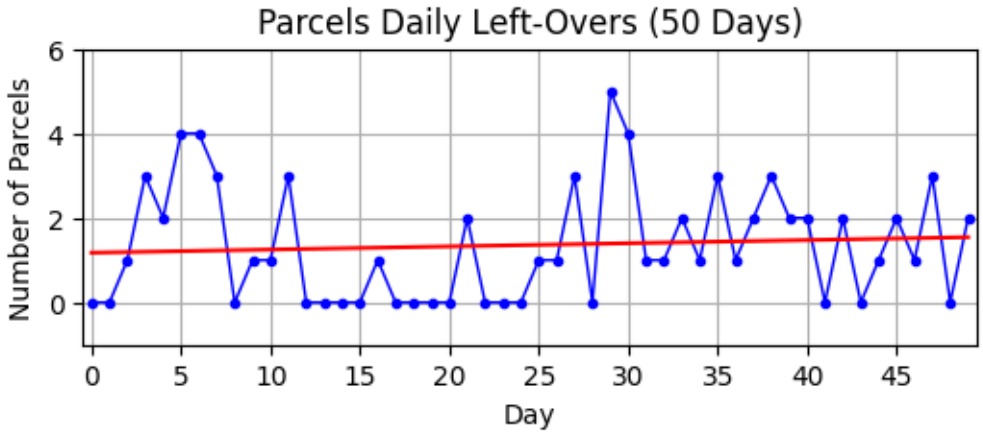
```
Simulating delivery of 134 parcels over 50 days to 20 customers
Delivery Centre Inventory at the end of last day: 2 parcels
```

[41]:
```
rec1.histTourLength()
rec1.plotTourLength()
```

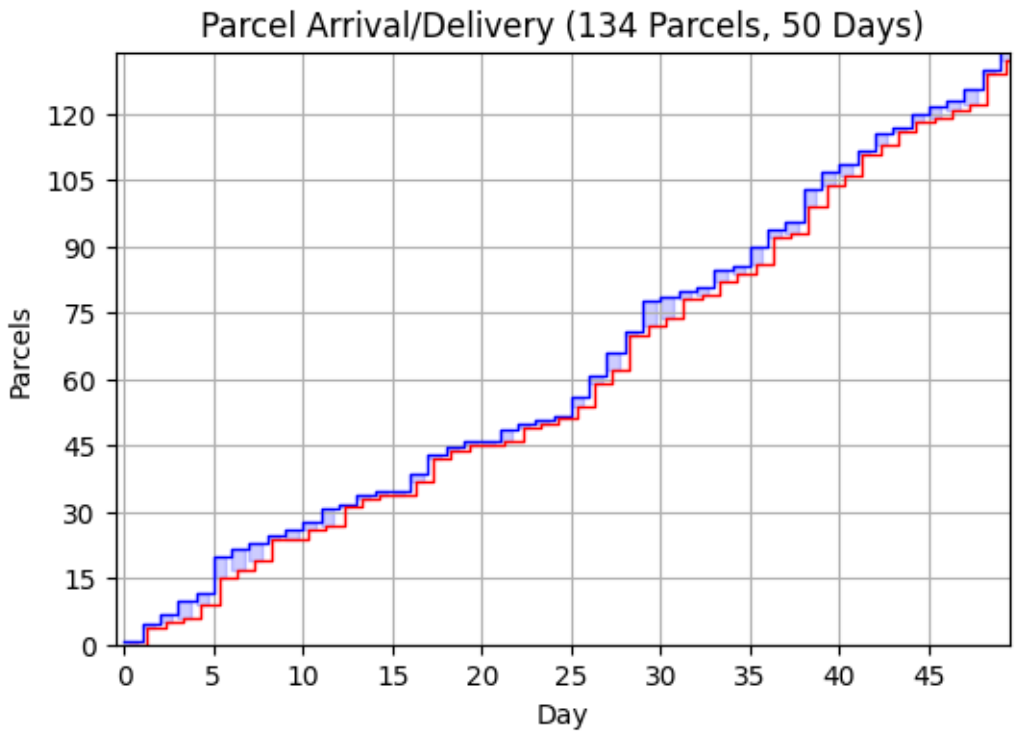




[42]:
```
rec1.plotParcelsLeftOver()
```



[43]:
```
rec1.countPlot()
```

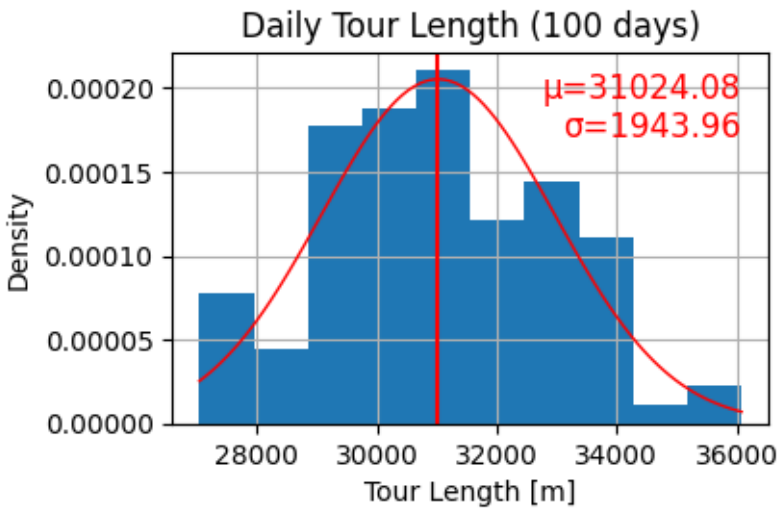


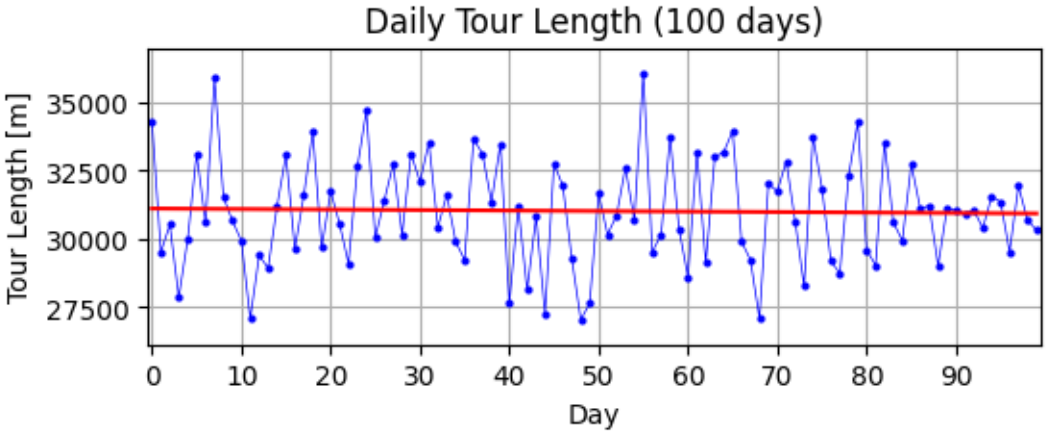
11.4.2 Instable System

[44]:
```
rec2 = simulation(MT, WT, CT, p=2, days=100)
```

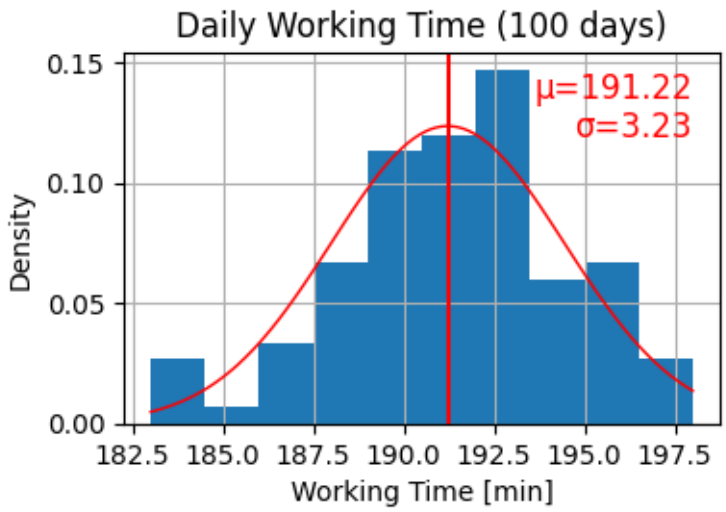
```
Simulating delivery of 3931 parcels over 100 days to 20 customers
Delivery Centre Inventory at the end of last day: 901 parcels
```

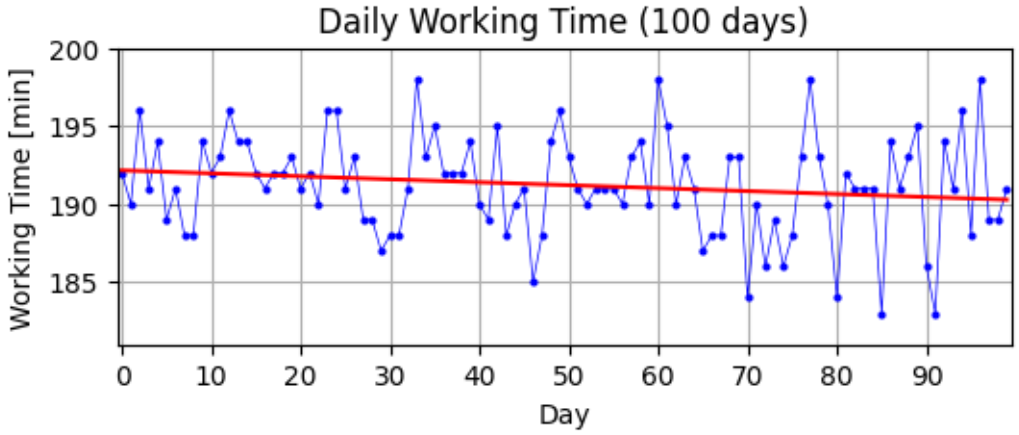
[45]:
```
rec2.histTourLength()
rec2.plotTourLength()
```



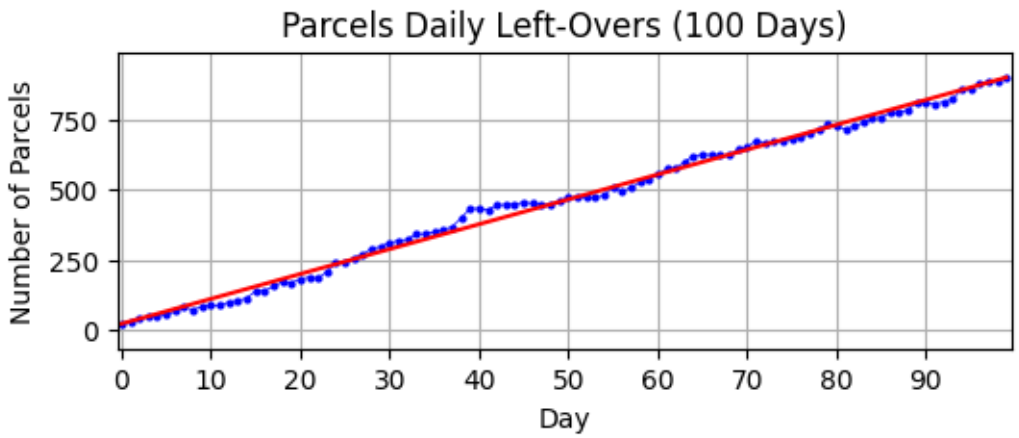


[46]:
```
rec2.histWorkingTime()
rec2.plotWorkingTime()
```





[47]:
```
rec2.plotParcelsLeftOver()
```



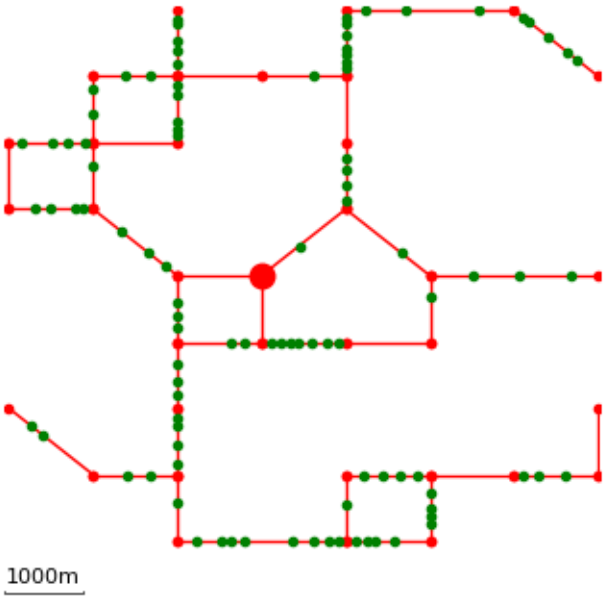
[48]:
```
rec2.countPlot()
```

12 Simulation Study

[49]:
```
import pickle
with open('data/data.pickled', 'rb') as f:
    M, C = pickle.load(f)
```

[50]:
```
W = generateWarehouseLocation(M)
```

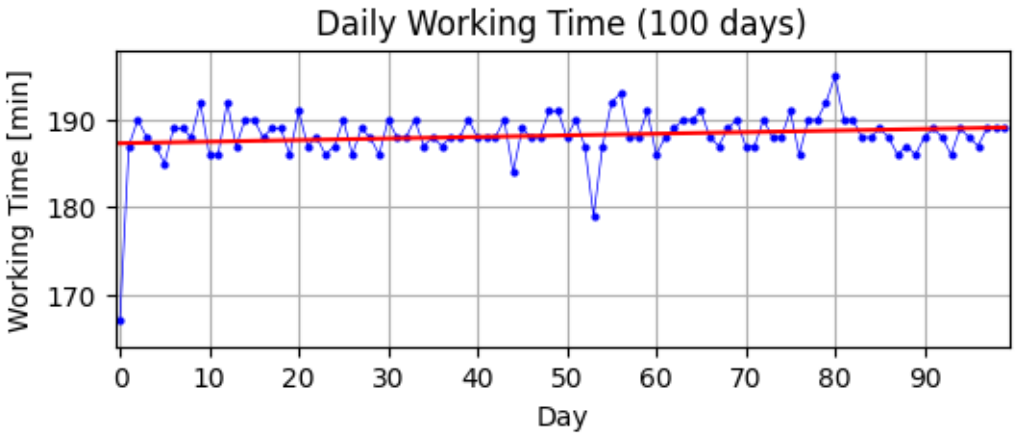
[51]:
```
plotMap(M, T=C, w=W, scale=True)
```

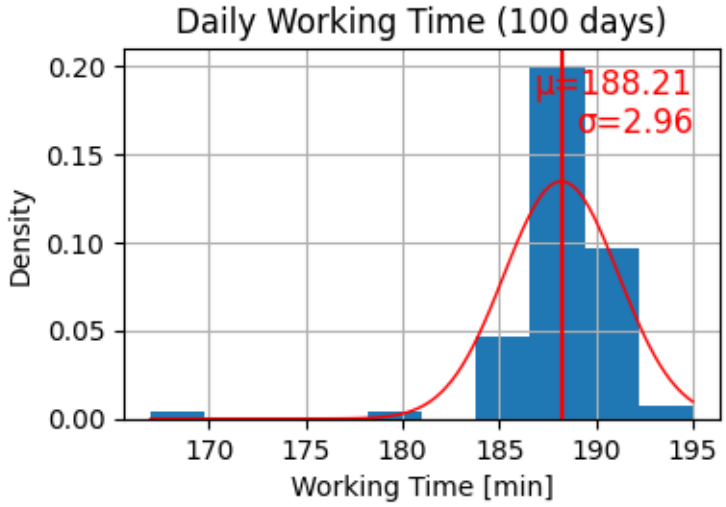


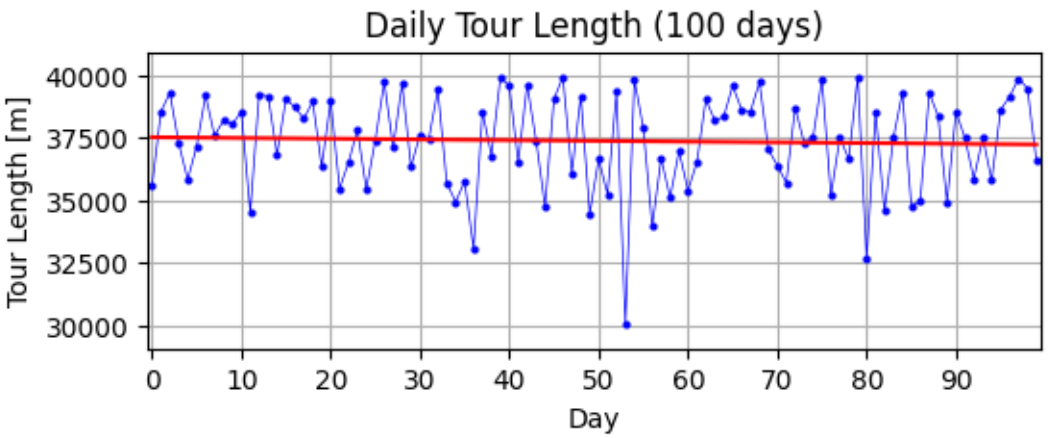
[52]:
```
import pickle

customers = len(C)

days = 100
for p in [0.15, 0.2, 0.25]:

    rec = simulation(M, W, C, p=p, days=days)

    filename = f'rec/SimRec p={p:4.2f} C={customers:d} days={days:d}.pickled'
    with open(filename, 'wb') as f:
        pickle.dump(rec, f)
    print("Simulation Results saved in:", filename)

    rec.plotWorkingTime()
    rec.histWorkingTime()
```

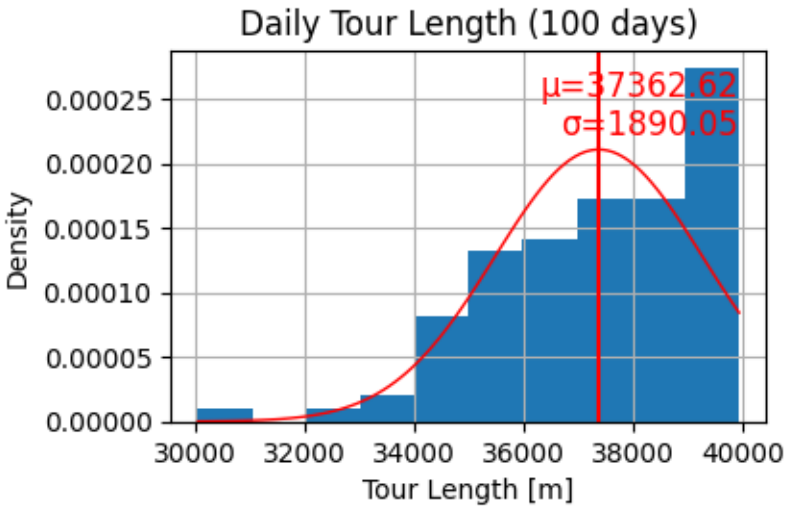
```
    rec.plotTourLength()
    rec.histTourLength()
    rec.histParcelsArrived()
    rec.histParcelsDelivered()
    rec.plotParcelsLeftOver()
    rec.countPlot()
```

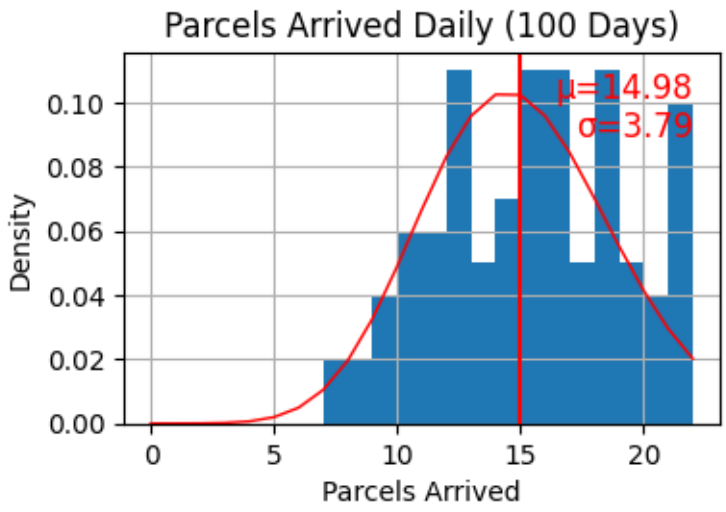
```
Simulating delivery of 1498 parcels over 100 days to 100 customers
Delivery Centre Inventory at the end of last day: 268 parcels
Simulation Results saved in: rec/SimRec p=0.15 C=100 days=100.pickled
```

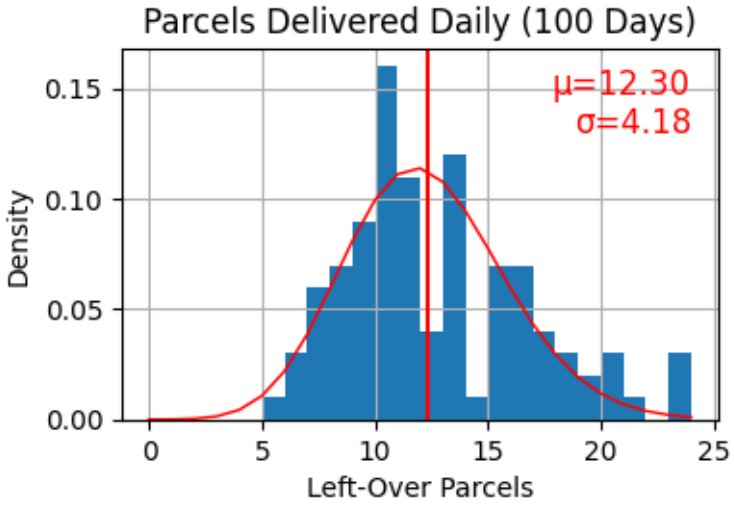


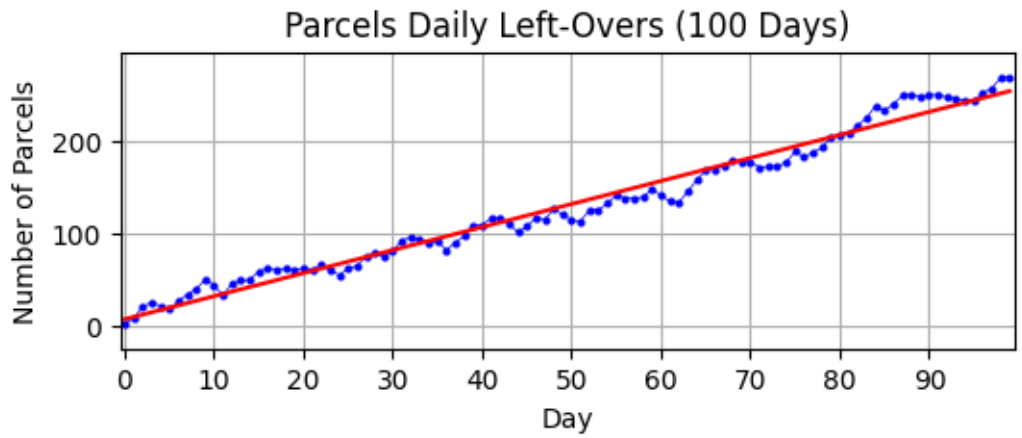



Daily Tour Length (100 days)
Tour Length [m]
40000
37500
35000
32500
30000
0
10
20
30
40
50
60
70
80
90
Day

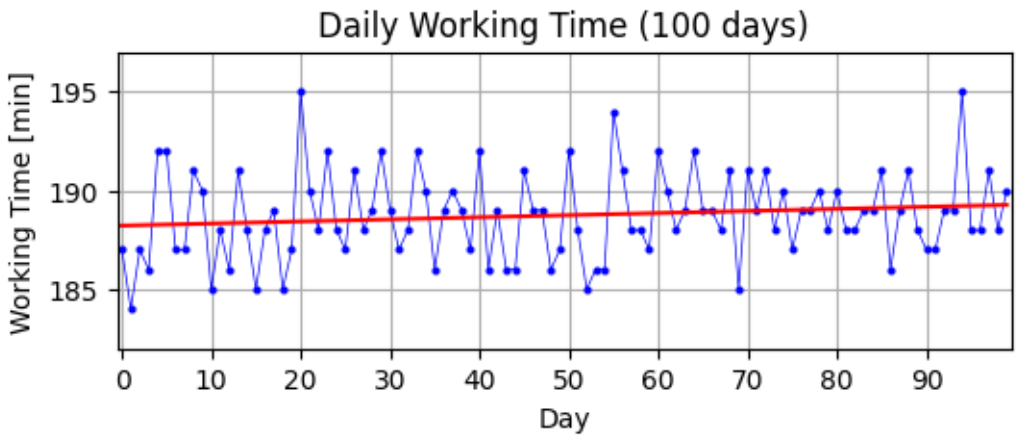

Daily Tour Length (100 days)
μ=37362.62
σ=1890.05
Density
0.00025
0.00020
0.00015
0.00010
0.00005
0.00000
30000
32000
34000
36000
38000
40000
Tour Length [m]

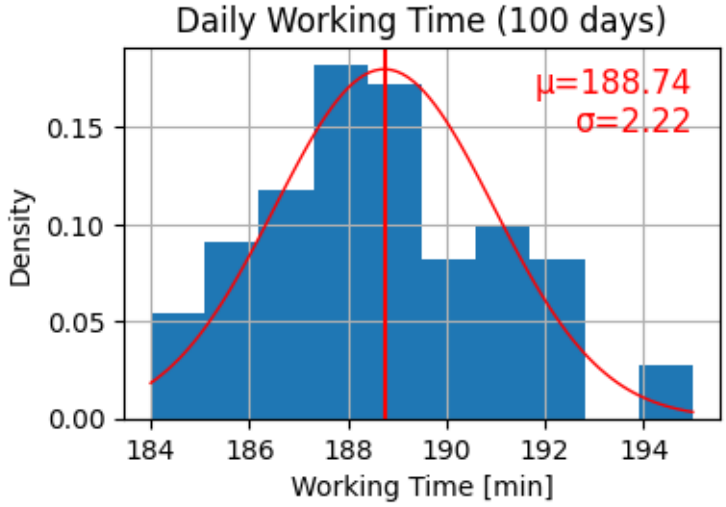

Parcels Arrived Daily (100 Days)
μ=14.98
σ=3.79
Density
0.00
0.02
0.04
0.06
0.08
0.10
0
5
10
15
20
Parcels Arrived

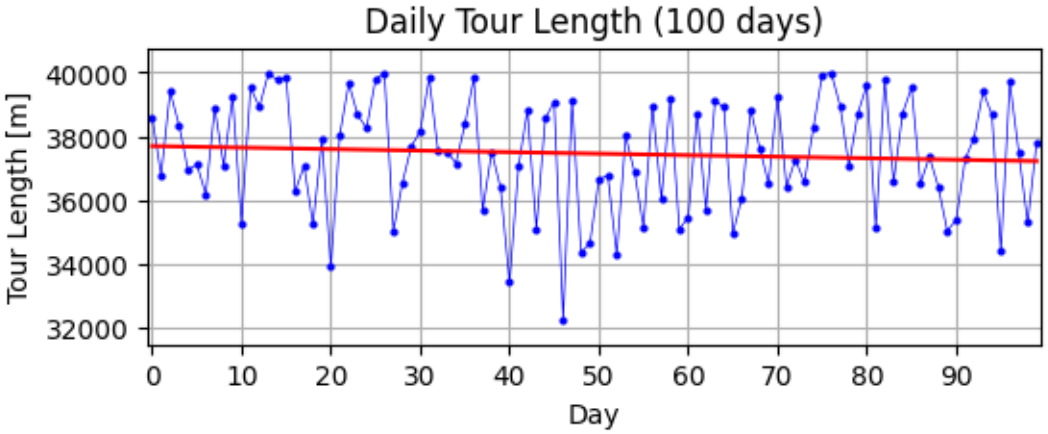

Parcels Delivered Daily (100 Days)
μ=12.30
σ=4.18
Density
0.00
0.05
0.10
0.15
0
5
10
15
20
25
Left-Over Parcels

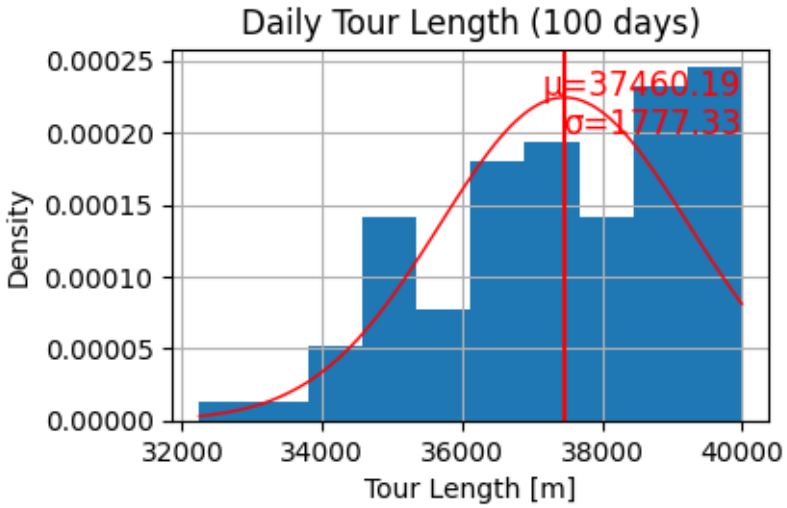


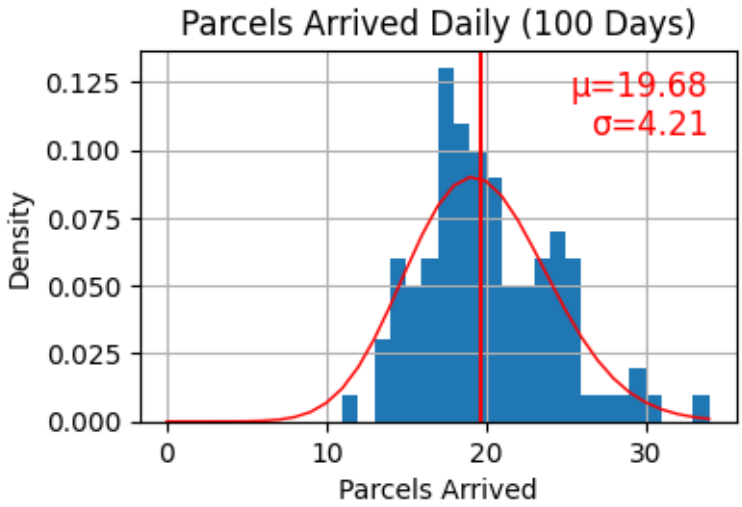

```
Simulating delivery of 1968 parcels over 100 days to 100 customers
Delivery Centre Inventory at the end of last day: 748 parcels
Simulation Results saved in: rec/SimRec p=0.20 C=100 days=100.pickled
```

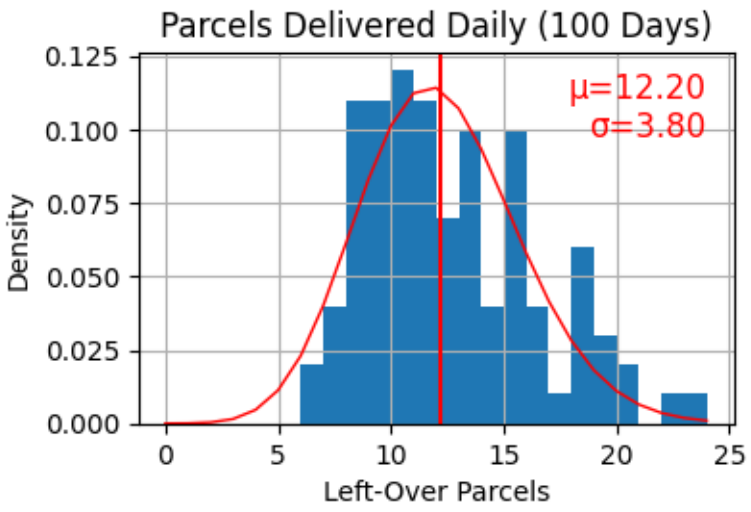

Daily Working Time (100 days)
Working Time [min]
195
190
185
0
10
20
30
40
50
60
70
80
90
Day

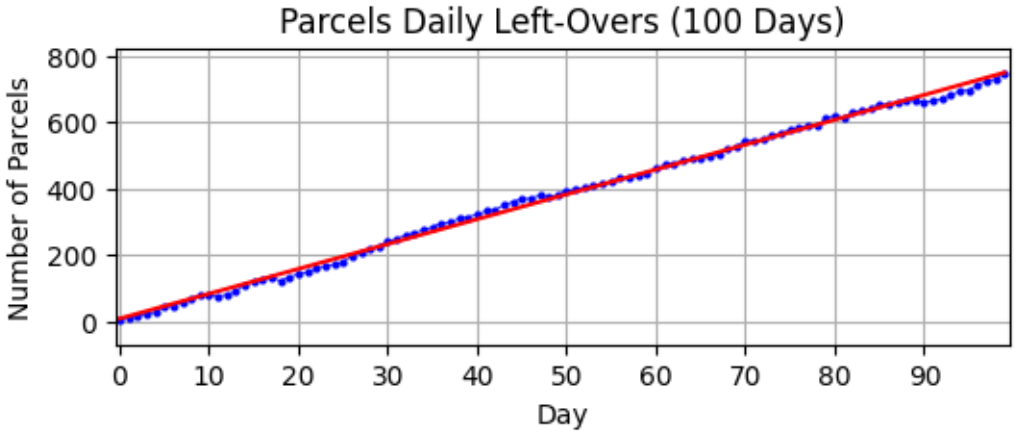

Daily Working Time (100 days)
μ=188.74
σ=2.22
Density
0.15
0.10
0.05
0.00
184
186
188
190
192
194
Working Time [min]

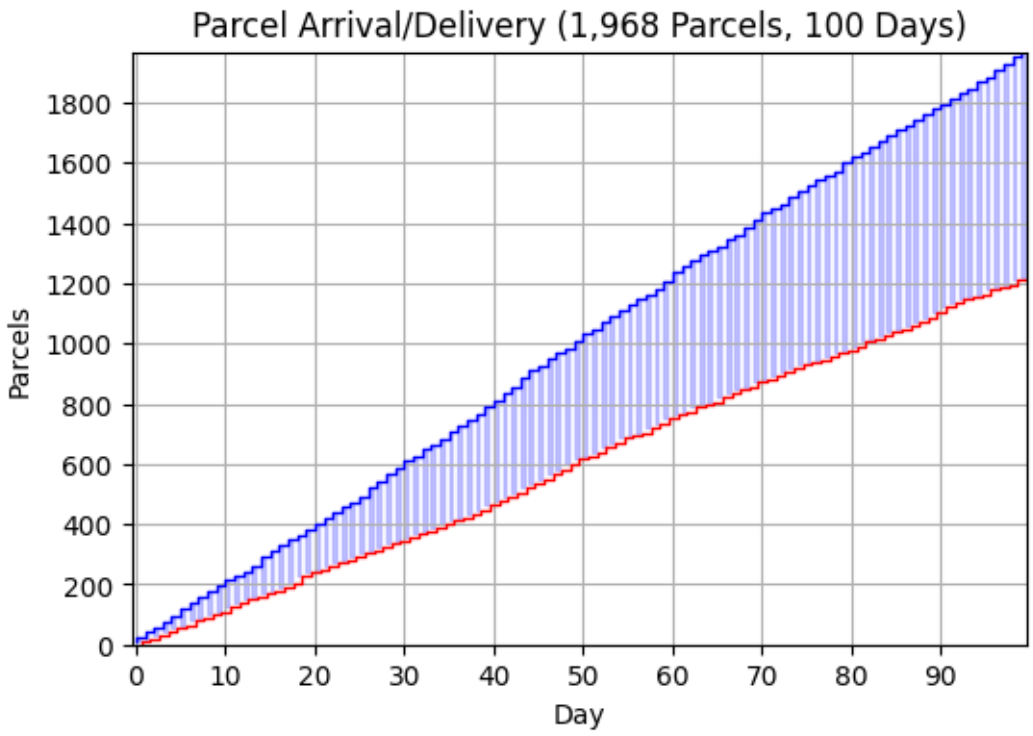

Daily Tour Length (100 days)
Tour Length [m]
40000
38000
36000
34000
32000
0
10
20
30
40
50
60
70
80
90
Day


Daily Tour Length (100 days)
μ=37460.19
σ=1777.33
Density
0.00025
0.00020
0.00015
0.00010
0.00005
0.00000
32000
34000
36000
38000
40000
Tour Length [m]

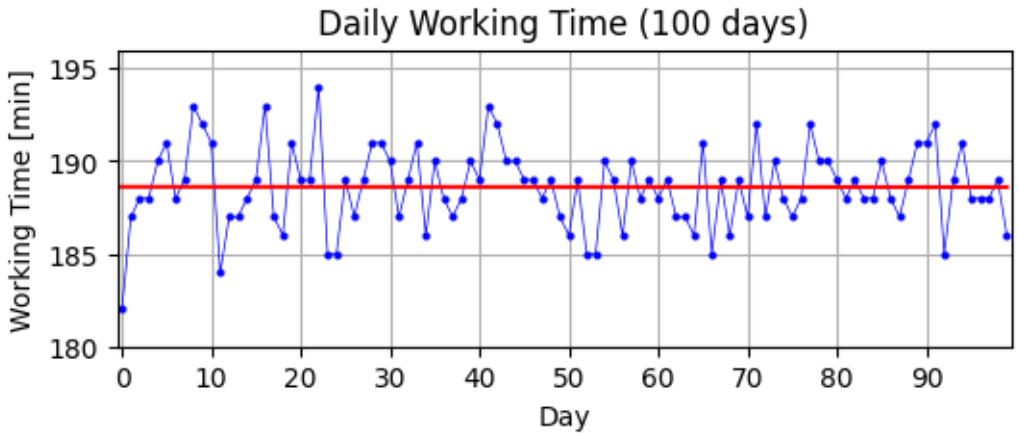

Parcels Arrived Daily (100 Days)
μ=19.68
σ=4.21
Density
0.125
0.100
0.075
0.050
0.025
0.000
0
10
20
30
Parcels Arrived

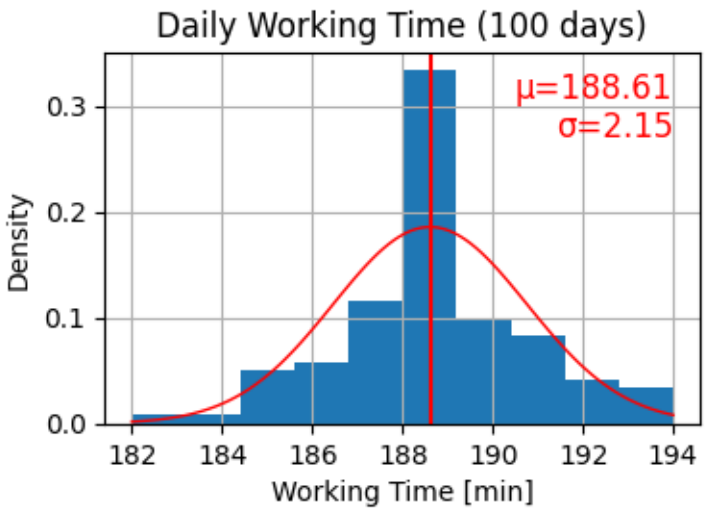

Parcels Delivered Daily (100 Days)
μ=12.20
σ=3.80
Density
0.125
0.100
0.075
0.050
0.025
0.000
0
5
10
15
20
25
Left-Over Parcels

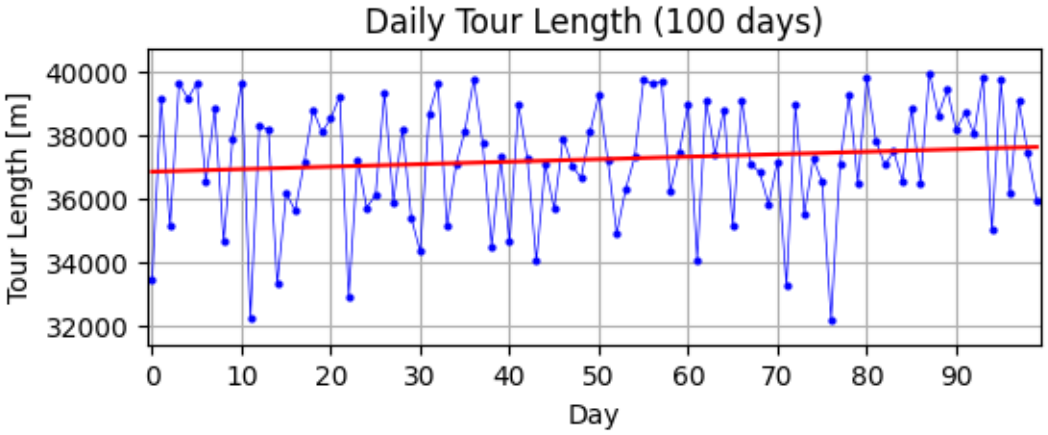

Parcels Daily Left-Overs (100 Days)
Number of Parcels
800
600
400
200
0
0
10
20
30
40
50
60
70
80
90
Day

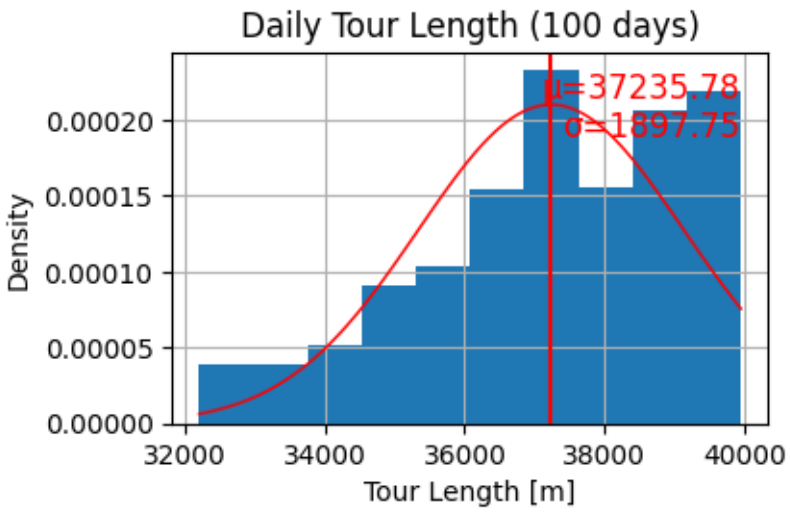



```
Simulating delivery of 2478 parcels over 100 days to 100 customers
Delivery Centre Inventory at the end of last day: 1219 parcels
Simulation Results saved in: rec/SimRec p=0.25 C=100 days=100.pickled
```

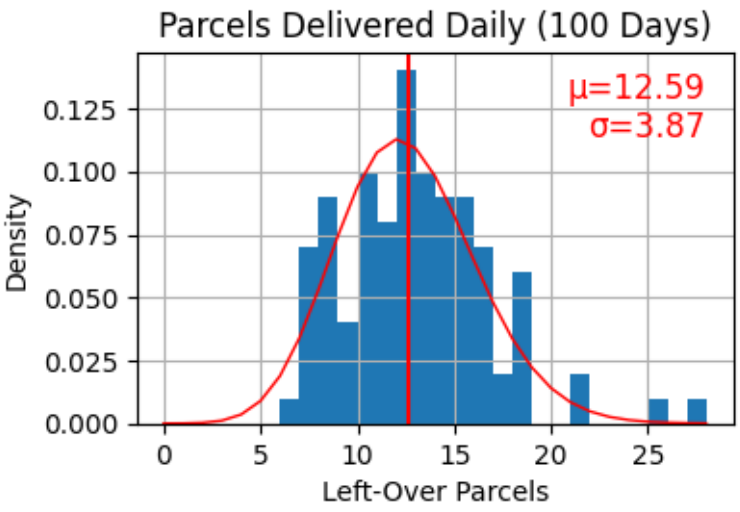


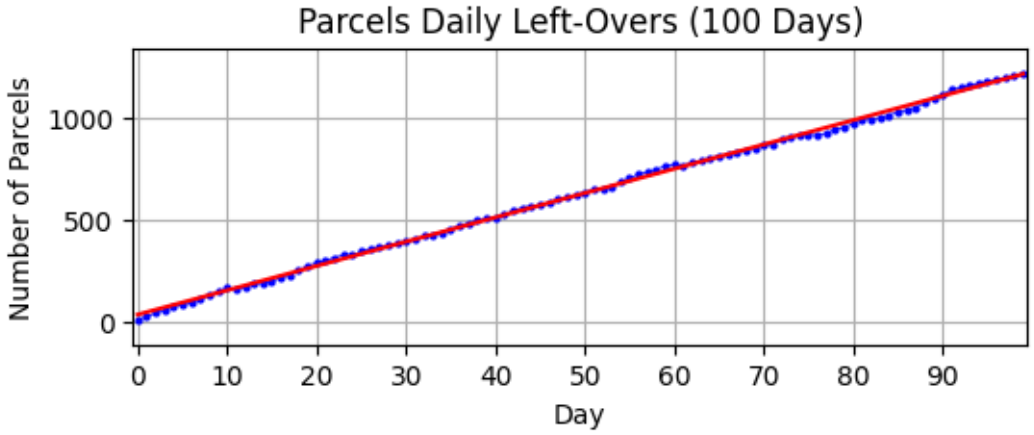

Daily Working Time (100 days)
μ=188.61
σ=2.15
Density
0.0
0.1
0.2
0.3
182
184
186
188
190
192
194
Working Time [min]

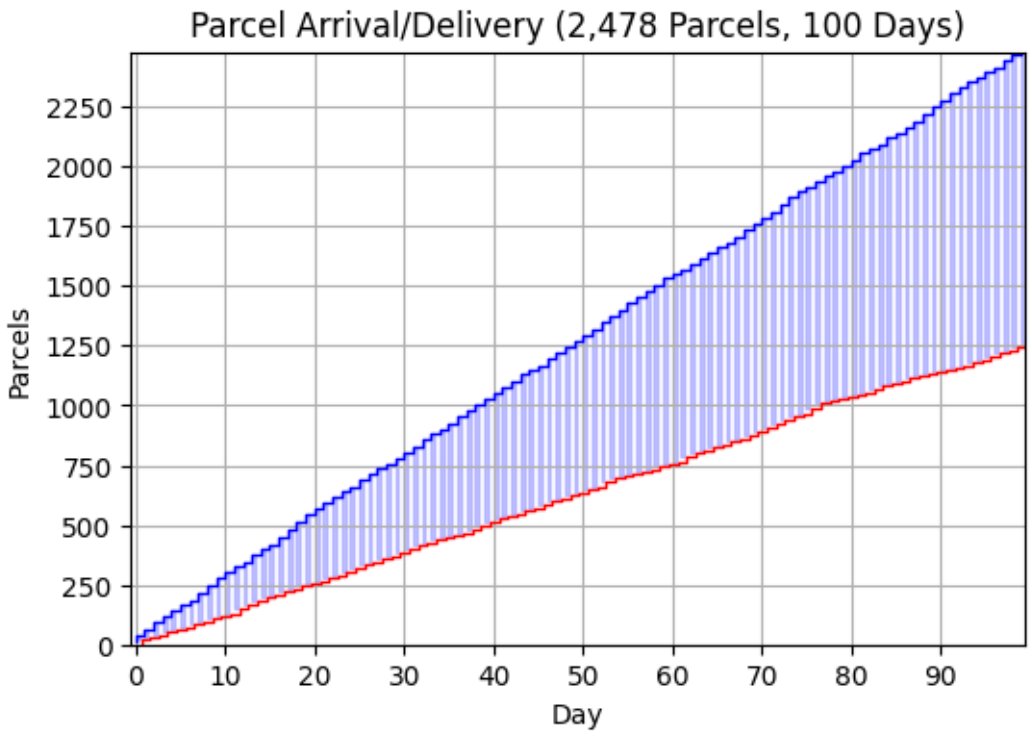

Daily Tour Length (100 days)
Tour Length [m]
32000
34000
36000
38000
40000
0
10
20
30
40
50
60
70
80
90
Day


Daily Tour Length (100 days)
μ=37235.78
σ=1897.75
Density
0.00020
0.00015
0.00010
0.00005
0.00000
32000
34000
36000
38000
40000
Tour Length [m]


Parcels Arrived Daily (100 Days)
μ=24.78
σ=4.24
Density
0.10
0.08
0.06
0.04
0.02
0.00
0
10
20
30
Parcels Arrived


Parcels Delivered Daily (100 Days)
μ=12.59
σ=3.87
Density
0.125
0.100
0.075
0.050
0.025
0.000
0
5
10
15
20
25
Left-Over Parcels


Parcels Daily Left-Overs (100 Days)
Number of Parcels
1000
500
0
0
10
20
30
40
50
60
70
80
90
Day


Parcel Arrival/Delivery (2,478 Parcels, 100 Days)
Parcels
Day
0
250
500
750
1000
1250
1500
1750
2000
2250
0
10
20
30
40
50
60
70
80
90

[ ]: