Simulation Step 5A Working Time

July 7, 2024

1 Prelude

[1]:
```
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="",
             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()

    hist=plt.hist(data, density=True)
    plt.xlabel(xlabel)
    plt.ylabel('Density')
    plt.title(title)

    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)

    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()
```

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()
```

```python
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, days,
                 log=False, plot=False, timing=False):
        self.env = env
        self.M = M
        self.W = W
        self.C = C
        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

    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 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

    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)')
```

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/AVERAGE_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))

    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')

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

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

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 / AVERAGE_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()
            tour, parcels, addresses = self.DC.sendForDelivery()
            if len(parcels)==0:
                self.rec.trace("Nothing to do today")
            else:
                yield self.rec.env.timeout(PREP_TIME_PER_PARCEL*len(parcels))
                self.leaveForDelivery(tour, parcels, addresses)
                while len(self.parcels)>0:
                    # 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(1/10))
                            self.parcels = self.parcels[1:]
                        cust.signOff()
                        yield self.rec.env.timeout(random.expovariate(1/10))
                    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)

                leftOver = len(self.DC.parcels)+len(self.DC.leftOver)
                self.rec.trace(f"{leftOver:d} parcels left for next day")

            yield self.rec.env.timeout(600)

            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):
        self.rec = rec
        self.M = M
        self.W = W
        self.limit = limit

        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()
        if custLoc not in self.dest:
            MT = addTargets(self.M, self.dest + [custLoc])
            SH = createLoopG(MT, [self.W] + self.dest + [custLoc])
            if pathLength(SH)<self.limit:
                self.parcels.append(parcel)
                self.dest += [custLoc]
                self.tour = SH
            else:
                self.leftOver.append(parcel)
```

```
        else:
            self.parcels.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 proportion of customers that for whatever are not at home or return home late

[25]:
```
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

[26]:
```
BIKE_RANGE = 40000
```

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

[27]:
```
AVERAGE_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.

[28]:
```
PREP_TIME_PER_PARCEL = 50
```

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

[29]:
```
RETURN_TIME_PER_PARCEL = 30
```

The average time to answer the door.

[30]:
```
AVERAGE_TIME_ANSWER_DOOR = 40
```

[31]:
```
WAIT_TIME_IF_CUSTOMER_DOESNT_ANSWER_DOOR = 60
```

11.2 Generate Input Data

[32]:
```
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

[33]:
```
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, 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)
    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: {DC.getInventory():d} parcels")

    return rec
```

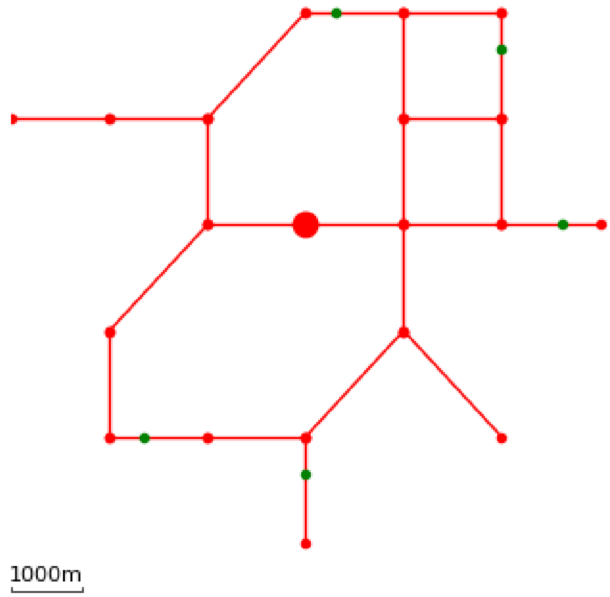
11.4 Test Statistics

11.4.1 Using Simple Data

[34]:
```
import pickle
with open('simpleData.pickled', 'rb') as f:
    M, C = pickle.load(f)
```

[35]:
```
W = generateWarehouseLocation(M)
```

[36]:
```
plotMap(M, T=C, w=W, scale=True)
```

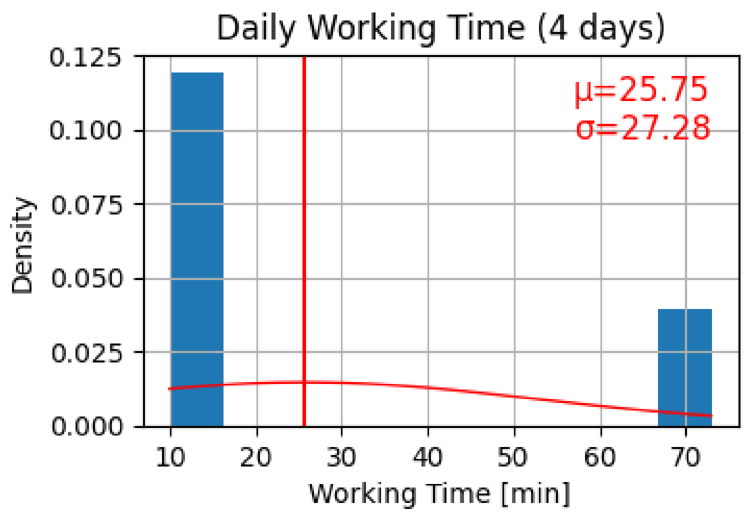


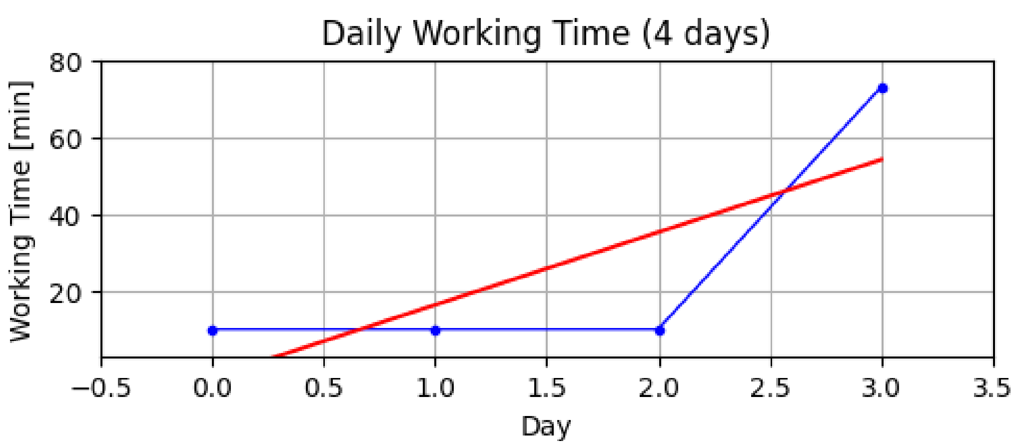
[37]:
```
rec1 = simulation(M, W, C, p=0.15, days=4, log=True)
```

```
Simulating delivery of 2 parcels over 4 days to 5 customers
[ 0] 18:00:00.0 Driver arrives for work
[ 0] 18:00:00.0 Nothing to do today
[ 0] 18:10:00.0 Driver goes home
[ 1] 18:00:00.0 Driver arrives for work
[ 1] 18:00:00.0 Nothing to do today
[ 1] 18:10:00.0 Driver goes home
[ 2] 18:00:00.0 Driver arrives for work
[ 2] 18:00:00.0 Nothing to do today
[ 2] 18:10:00.0 Driver goes home
[ 3] 17:00:00.0 Parcel 0 for cust 2 arr at delivery centre
[ 3] 17:00:00.0 Parcel 1 for cust 4 arr at delivery centre
[ 3] 18:00:00.0 Driver arrives for work
[ 3] 18:00:00.0 Parcel 0 for cust 2 out for delivery
[ 3] 18:00:00.0 Parcel 1 for cust 4 out for delivery
[ 3] 18:01:40.0 Driver leaves for delivery of 2 parcels to 2 customers
[ 3] 18:01:40.0 Length of delivery tour: 14,876m
[ 3] 18:01:40.0 Driver drives to Customer 2 at (4929, 7300)
[ 3] 18:22:21.0 Driver arrived at Customer 2 at (4929, 7300)
[ 3] 18:22:58.8 Customer 2 at (4929, 7300) answers door
[ 3] 18:22:58.8 Customer 2 at (4929, 7300) accepts Parcel 0 for cust 2
[ 3] 18:23:23.2 Customer 2 at (4929, 7300) signs off
[ 3] 18:23:57.2 Driver drives to Customer 4 at (8167, 4500)
[ 3] 18:48:06.3 Driver arrived at Customer 4 at (8167, 4500)
[ 3] 18:48:32.3 Customer 4 at (8167, 4500) answers door
```

```
[ 3] 18:48:32.3 Customer 4 at (8167, 4500) accepts Parcel 1 for cust 4
[ 3] 18:48:52.3 Customer 4 at (8167, 4500) signs off
[ 3] 18:48:55.3 Driver returns to delivery centre
[ 3] 19:03:35.4 Driver arrived at delivery centre
[ 3] 19:03:35.4 0 parcels left for next day
[ 3] 19:13:35.4 Driver goes home
```

[38]:
```python
rec1.histWorkingTime()
rec1.plotWorkingTime()
```

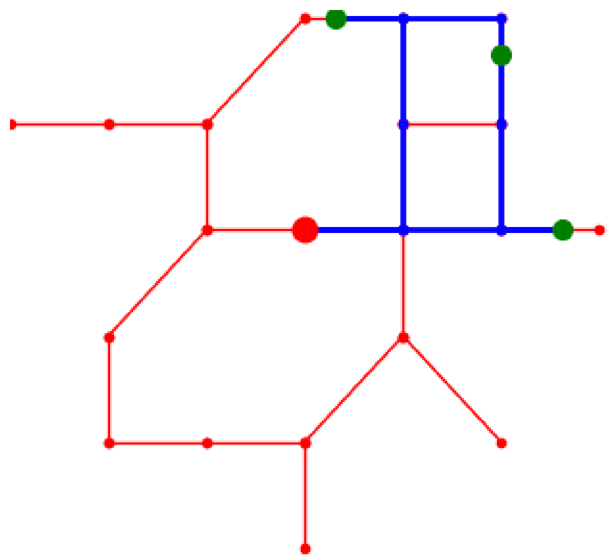




[39]:
```python
rec2 = simulation(M, W, C, p=0.3, days=4, log=True, plot=True)
```

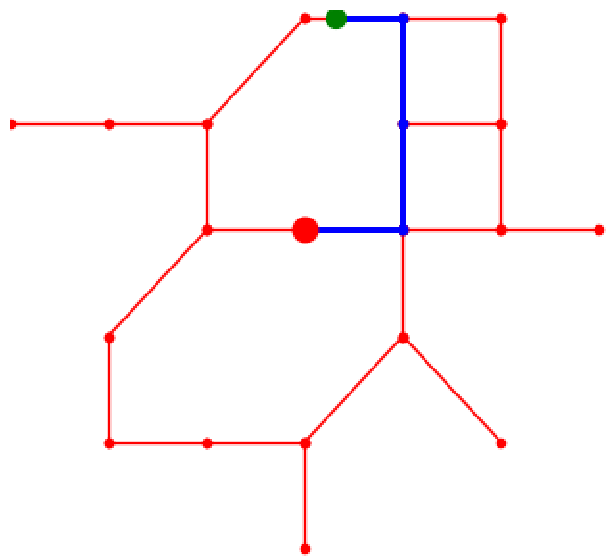
```
Simulating delivery of 5 parcels over 4 days to 5 customers
[ 0] 18:00:00.0 Driver arrives for work
```

```
[ 0] 18:00:00.0 Nothing to do today
[ 0] 18:10:00.0 Driver goes home
[ 1] 17:00:00.0 Parcel 0 for cust 2 arr at delivery centre
[ 1] 17:00:00.0 Parcel 1 for cust 3 arr at delivery centre
[ 1] 17:00:00.0 Parcel 2 for cust 4 arr at delivery centre
[ 1] 18:00:00.0 Driver arrives for work
[ 1] 18:00:00.0 Parcel 0 for cust 2 out for delivery
[ 1] 18:00:00.0 Parcel 1 for cust 3 out for delivery
[ 1] 18:00:00.0 Parcel 2 for cust 4 out for delivery
[ 1] 18:02:30.0 Driver leaves for delivery of 3 parcels to 3 customers
[ 1] 18:02:30.0 Length of delivery tour: 14,876m
```

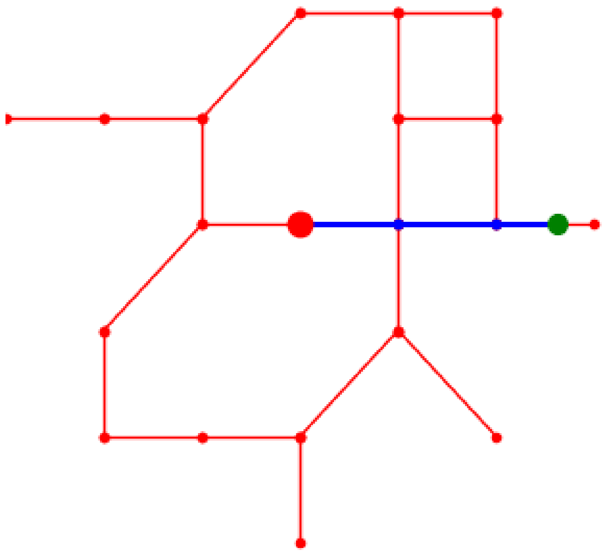



```
[ 1] 18:02:30.0 Driver drives to Customer 2 at (4929, 7300)
[ 1] 18:23:11.0 Driver arrived at Customer 2 at (4929, 7300)
[ 1] 18:23:25.9 Customer 2 at (4929, 7300) answers door
[ 1] 18:23:25.9 Customer 2 at (4929, 7300) accepts Parcel 0 for cust 2
[ 1] 18:23:39.0 Customer 2 at (4929, 7300) signs off
[ 1] 18:24:01.9 Driver drives to Customer 3 at (7300, 6825)
[ 1] 18:35:24.9 Driver arrived at Customer 3 at (7300, 6825)
[ 1] 18:36:11.0 Customer 3 at (7300, 6825) answers door
[ 1] 18:36:11.0 Customer 3 at (7300, 6825) accepts Parcel 1 for cust 3
[ 1] 18:36:17.4 Customer 3 at (7300, 6825) signs off
[ 1] 18:36:18.5 Driver drives to Customer 4 at (8167, 4500)
[ 1] 18:49:04.5 Driver arrived at Customer 4 at (8167, 4500)
[ 1] 18:49:27.3 Customer 4 at (8167, 4500) answers door
[ 1] 18:49:27.3 Customer 4 at (8167, 4500) accepts Parcel 2 for cust 4
[ 1] 18:49:36.8 Customer 4 at (8167, 4500) signs off
```

```
[ 1] 18:50:01.2 Driver returns to delivery centre
[ 1] 19:04:41.3 Driver arrived at delivery centre
[ 1] 19:04:41.3 0 parcels left for next day
[ 1] 19:14:41.3 Driver goes home
[ 2] 17:00:00.0 Parcel 3 for cust 2 arr at delivery centre
[ 2] 18:00:00.0 Driver arrives for work
[ 2] 18:00:00.0 Parcel 3 for cust 2 out for delivery
[ 2] 18:00:50.0 Driver leaves for delivery of 1 parcels to 1 customers
[ 2] 18:00:50.0 Length of delivery tour: 10,342m
```

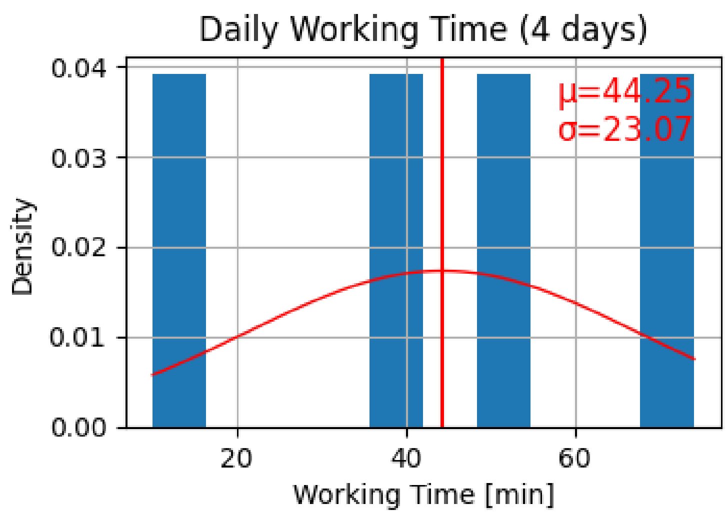


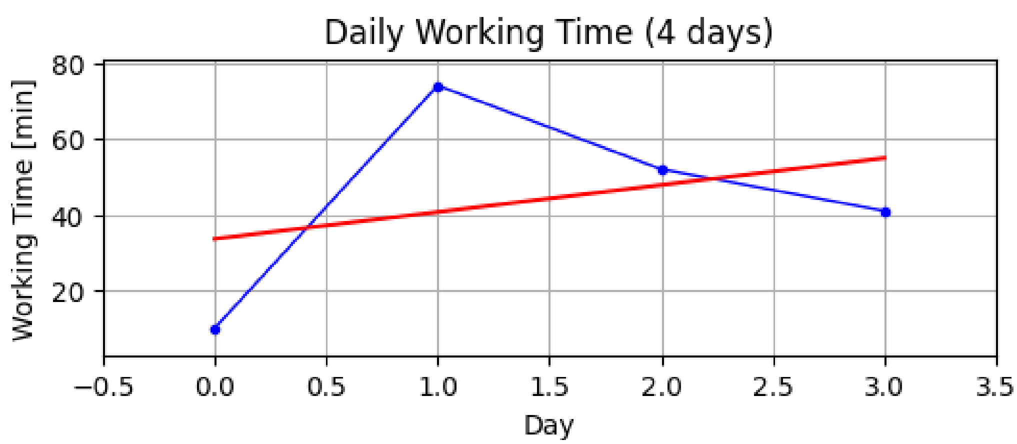

```
[ 2] 18:00:50.0 Driver drives to Customer 2 at (4929, 7300)
[ 2] 18:21:31.0 Driver arrived at Customer 2 at (4929, 7300)
[ 2] 18:22:02.9 Customer 2 at (4929, 7300) answers door
[ 2] 18:22:02.9 Customer 2 at (4929, 7300) accepts Parcel 3 for cust 2
[ 2] 18:22:03.0 Customer 2 at (4929, 7300) signs off
[ 2] 18:22:15.7 Driver returns to delivery centre
[ 2] 18:42:56.8 Driver arrived at delivery centre
[ 2] 18:42:56.8 0 parcels left for next day
[ 2] 18:52:56.8 Driver goes home
[ 3] 17:00:00.0 Parcel 4 for cust 4 arr at delivery centre
[ 3] 18:00:00.0 Driver arrives for work
[ 3] 18:00:00.0 Parcel 4 for cust 4 out for delivery
[ 3] 18:00:50.0 Driver leaves for delivery of 1 parcels to 1 customers
[ 3] 18:00:50.0 Length of delivery tour: 7,334m
```




```
[ 3] 18:00:50.0 Driver drives to Customer 4 at (8167, 4500)
[ 3] 18:15:30.1 Driver arrived at Customer 4 at (8167, 4500)
[ 3] 18:16:30.1 Customer 4 at (8167, 4500) to slow to answer the door
[ 3] 18:16:30.1 Driver returns to delivery centre
[ 3] 18:31:10.2 Driver arrived at delivery centre
[ 3] 18:31:10.2 Parcel 4 for cust 4 return from delivery
[ 3] 18:31:40.2 1 parcels left for next day
[ 3] 18:41:40.2 Driver goes home
Delivery Centre Inventory: 1 parcels
```

[40]:
```
rec2.histWorkingTime()
rec2.plotWorkingTime()
```

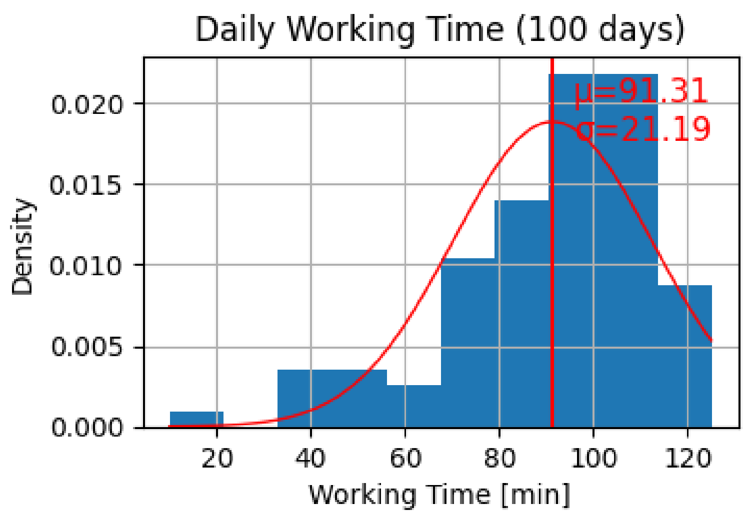


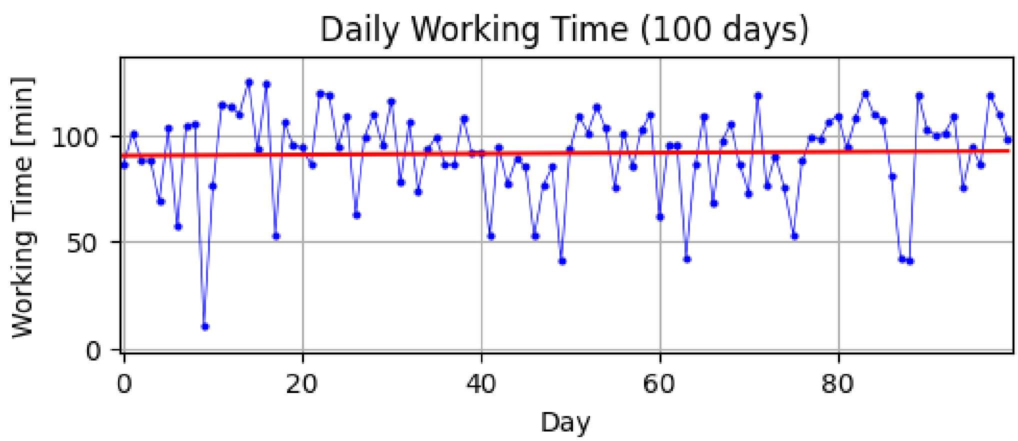


[41]:
```
rec3 = simulation(M, W, C, p=0.6, days=100)
```

```
Simulating delivery of 289 parcels over 100 days to 5 customers
Delivery Centre Inventory: 4 parcels
```

[42]:
```
rec3.histWorkingTime()
rec3.plotWorkingTime()
```





11.4.2 Using Test Data

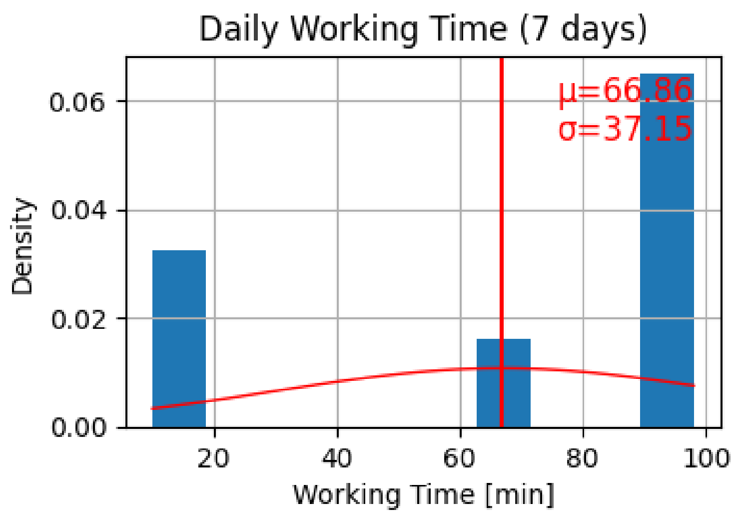
[43]:
```
import pickle
with open('testData.pickled', 'rb') as f:
    MX, CX = pickle.load(f)
```

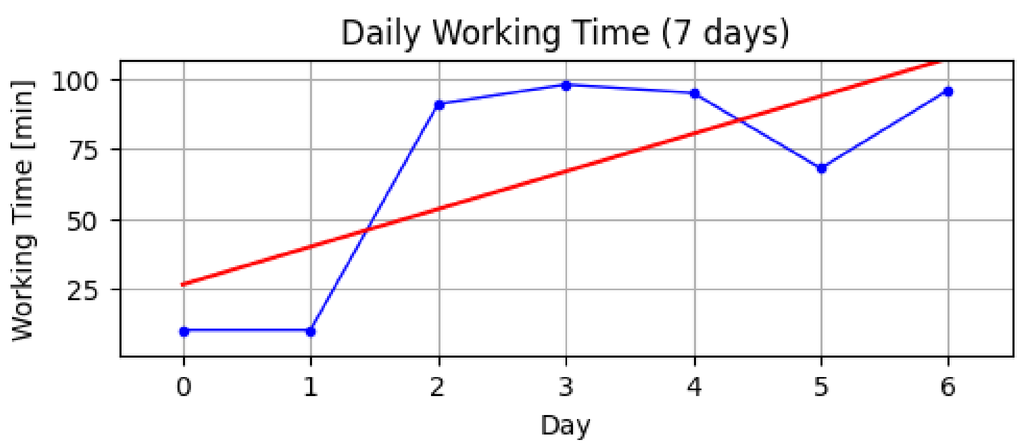
[44]:
```
WX = generateWarehouseLocation(MX)
```

[45]:
```
rec4 = simulation(MX, WX, CX, p=0.15, days=7)
```

```
Simulating delivery of 14 parcels over 7 days to 20 customers
Delivery Centre Inventory: 2 parcels
```

[46]:
```
rec4.histWorkingTime()
rec4.plotWorkingTime()
```

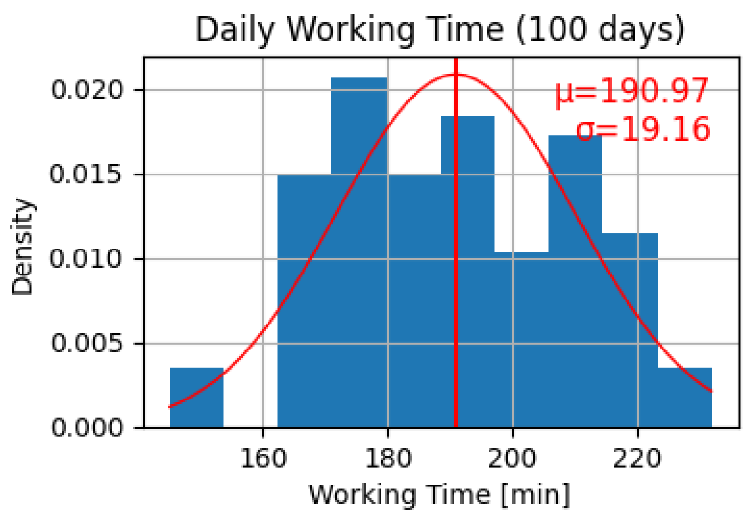


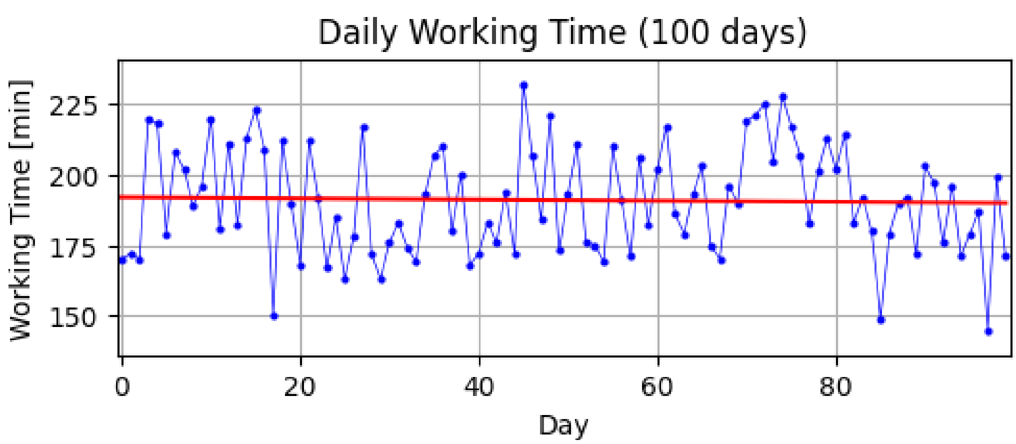


[47]:
```
rec5 = simulation(MX, WX, CX, p=1.2, days=100)
```

```
Simulating delivery of 2342 parcels over 100 days to 20 customers
Delivery Centre Inventory: 7 parcels
```

[48]:
```
rec5.histWorkingTime()
rec5.plotWorkingTime()
```



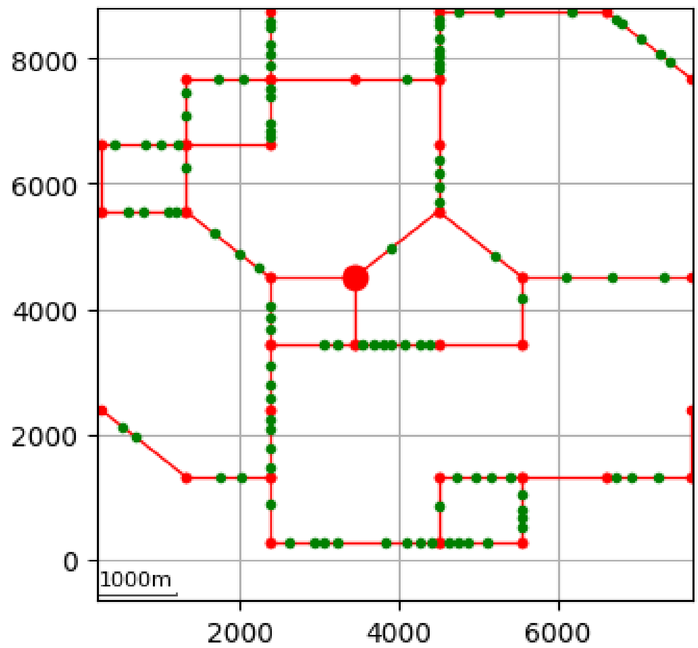


11.4.3 Using Full Data

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

[50]:
```
WW = generateWarehouseLocation(MM)
```

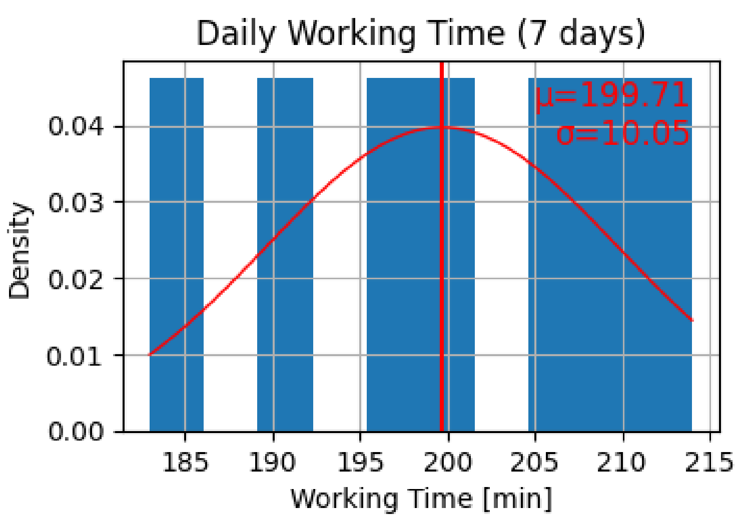
[51]:
```
plotMap(MM, T=CC, w=WW, scale=True, grid=True)
```

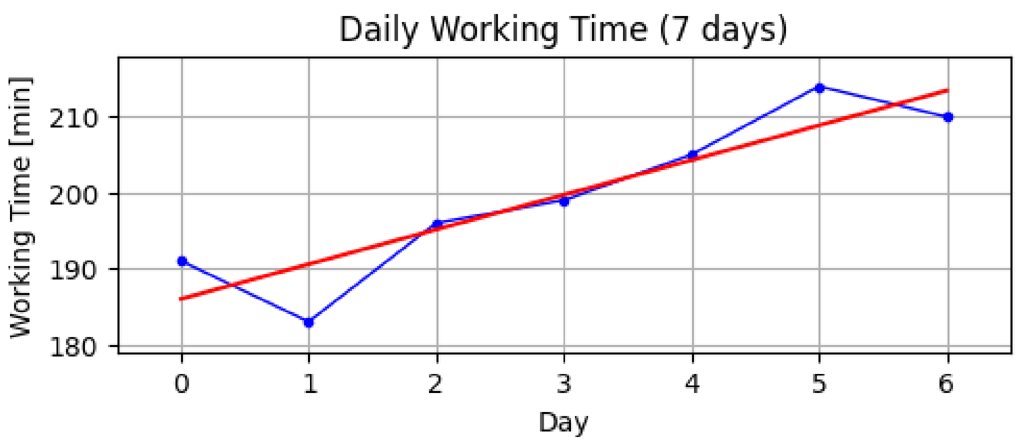


[52]:
```
rec6 = simulation(MM, WW, CC, p=0.15, days=7)
```

```
Simulating delivery of 105 parcels over 7 days to 100 customers
Delivery Centre Inventory: 16 parcels
```

[53]:
```
rec6.histWorkingTime()
rec6.plotWorkingTime()
```

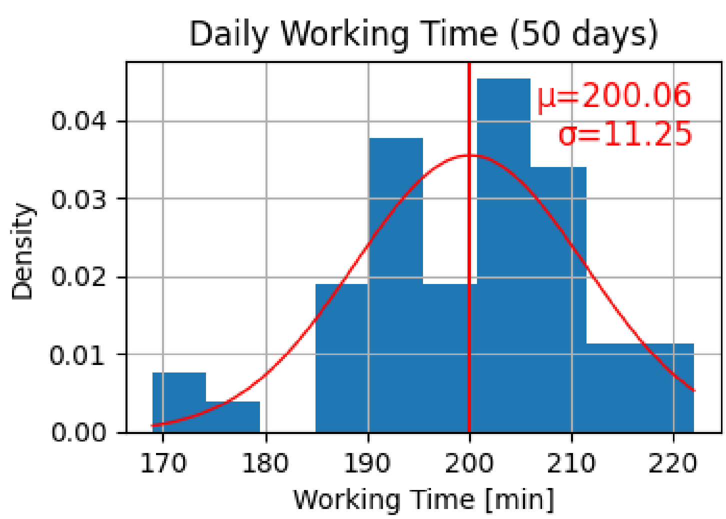


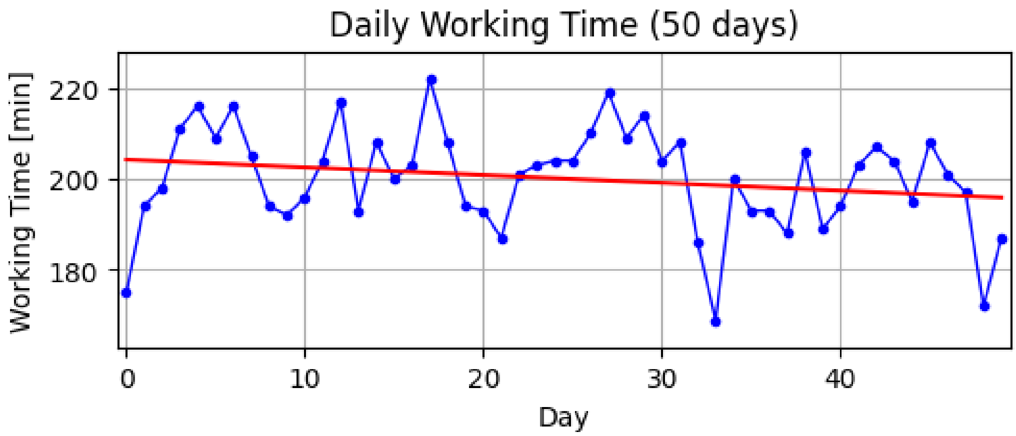


[54]:
```
rec7 = simulation(MM, WW, CC, p=0.15, days=50)
```

```
Simulating delivery of 761 parcels over 50 days to 100 customers
Delivery Centre Inventory: 12 parcels
```

[55]:
```
rec7.histWorkingTime()
rec7.plotWorkingTime()
```




Daily Working Time (50 days)
Working Time [min]
220
200
180
0
10
20
30
40
Day

```
[ ]:
```