Table of Contents

1. Prelude

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

2. Utilities (as before)

2.1. Points and Distances

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

2.2. PlotMap

In [3]:
```
def plotMap(G, T=[], P=[], W=None,
            style='r-o', lw=1, ms=3,
            styleT='go', msT=5,
            styleP='b-o', lwP=3, msP=1,
            stylePT='go', msPT=7,
            styleW='bo', msW=9,
            text=None, grid=False):
    fig = plt.gcf()
    fig.set_size_inches(6, 6)
    V, E = G

    if not grid:
        plt.axis('off')
    plt.plot( [ p[0] for p in V ], [ p[1] for p in V ], 'ro', lw=lw, ms=ms)
    for (p, q) in E:
        plt.plot( [ p[0], q[0] ], [ p[1], q[1] ], 'r-o', lw=lw, ms=ms)
    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:
        maxX = max([p[0] for p in V])
        plt.text(0.8*maxX, 0, text)
    if grid:
        plt.grid()
    plt.show()
```

2.3. Add Targets

In [4]:
```
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 Warehouse Location

In [5]:
```
def generateWarehouseLocation(M):
    V, _ = M
    W = random.sample(V, k=1)[0]
    return W
```

2.5 Time Handling

Convention: In this project we measure 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`

In [6]:
```
def timestamp(t):
        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(math.floor(t))
        t = int(math.floor((t - secs)*10))
        return f"[{day:2d}] {hour:02d}:{mins:02d}:{secs:02d}.{t:1d}"
```

In [7]:
```
timestamp(24*3600*3+17*3600+615.1)
```

Out[7]:
```
'[ 3] 17:10:15.0'
```

In [8]:
```
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
```

In [9]:
```
def day(now):
    return int(now//(24*3600))
```

2.6. Plotting Routines

In [10]:
```
import scipy.stats as stats

def histplot(data, title="", xlabel="",
```

```
            width=None, height=None):

    minx = min(data)
    maxx = max(data)
    μ = np.mean(data)
    σ = 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=μ, scale=σ).pdf(p) for p in x]
    ax.plot(x, y, lw=1, color='red')
    ax.axvline(x=μ, color='red')
    maxy = max(max(y), max(hist[0]))
    ax.text(maxx, maxy,
            f'μ={μ:2.2f}\nσ={σ:2.2f}',
            ha='right', va='top',
            color='red', fontsize=12)
    ax.grid(True)
    plt.show()
```

In [11]:

```
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(-1, days)
    ax.set_ylim(ymin, ymax)
    ax.grid(True)

    ms = 2 if len(data)>100 else 5
    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)

In [12]:
```
def dist(p1, p2):
    (x1, y1) = p1
    (x2, y2) = p2
    return int(math.sqrt((x1-x2)**2+(y1-y2)**2))
```

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

In [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 Shortest Delivery Route (as before)

4.1. Iterative Integer Programming

In [15]:
```
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
```

In [16]:
```
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)
```

In [17]:

```
import time

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

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

    D, P = createTables(M, T)   # These are the distances between customers and war

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

    n = len(T)

    if n==1:
        return 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
    # initialise solver
    solvers = pulp.listSolvers(onlyAvailable=True)
    solver = pulp.getSolver(solvers[0], msg=0)
    prob.solve(solver)

    if timing:
        print(f"Solver:         {time.time()-last_time:6.2f}s {constraints:6,d} Con
        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
        prob.solve(solver)

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

        trips = roundtrips(x, n)

    trip = trips[0]
    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
```

4.2. Heuristic Algorithm

In [18]:
```
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
```

In [35]:
```
def createLoopH(M, T, timing=False):

    def makeLoop(L):
        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)

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

    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"createLoopH:    {time.time()-start_time:6.2f}s")

    return makeLoop(L)

def shortcut2(roundtrip):
    #Attempt to shorten the route by reversing segments of the route.
    n = len(roundtrip)
    best_route = roundtrip[:]
    for i in range(n - 1):
        for j in range(i + 2, n):  # ensure at least one node between i and j
            new_route = roundtrip[:i+1] + list(reversed(roundtrip[i+1:j+1])) + roun
            if calculate_total_distance(new_route) < calculate_total_distance(best_
                best_route = new_route
    return best_route

def shortcut3(roundtrip):
    #Attempt to improve the route by repositioning nodes.
    n = len(roundtrip)
    best_route = roundtrip[:]
    for i in range(1, n - 1):
        for j in range(n):
            if j != i and j != i + 1:  # Prevents index errors and unnecessary swap
                new_route = roundtrip[:i] + roundtrip[i+1:]
                new_route.insert(j, roundtrip[i])
                if calculate_total_distance(new_route) < calculate_total_distance(b
                    best_route = new_route
    return best_route

def calculate_total_distance(route):
```

```
    #Calculate the total distance of a route using the dist function.
    return sum(dist(route[i], route[i + 1]) for i in range(len(route) - 1))
```

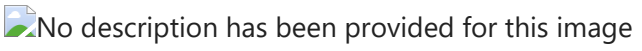
5. Class Recorder

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.

In [20]:
```
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

        self.timing = timing
        self.start_time = time.time()
        self.last_time = self.start_time
        self.cum_timer = {}

        Customer.REGISTER = []
        Parcel.REGISTER = []

        # 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 timer(self, s):
        t = time.time()
        Δt = t-self.last_time
        if self.timing:
            print(f"==== t: {t-self.start_time:6.2f}s "
                  f"Δt: {Δt:6.2f}s [{s:s}]")
        if s in self.cum_timer:
            self.cum_timer[s] += Δt
        else:
            self.cum_timer[s] = Δt
        self.last_time = t

    def reportTimer(self):
        print(f"==== t: {self.total_time:6.2f}s Total")
        for k in sorted(self.cum_timer, key=lambda x: self.cum_timer[x], reverse=Tr
            print(f"==== ΣΔt: {self.cum_timer[k]:6.2f}s "+ k)

    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.total_time = time.time()-self.start_time
        self.daily['working time'] = (self.daily['end work at']-self.daily['begin w

    def histWorkingTime(self):
        histplot(self.daily['working time'],
                 xlabel='Working Time [min]',
                 title='Daily Working Time')

    def plotWorkingTime(self):
        dailyPlot(self.daily['working time'],
                  ylabel='Working Time [min]',
                  title='Daily Working Time')
```

6. Class Parcel



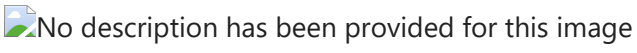
Parcels follow through a sequence of states:

- processing
- in transit (From manufacture to distribution centre)
- arrived in distribution centre
- out for delivery
- customer not present
- retured to distribution centre
- delivered

In [21]:
```
class Parcel:

    REGISTER = []

    def __init__(self, rec, i, cust, custIndex):
        self.rec = rec
        self.i = i  # row index in data frames of input data
        self.dest = cust.location
        self.custIndex = custIndex
        self.status = [ 'processing' ] # status record and
        self.timing = [ self.rec.env.now ]      # timing
        assert(len(Parcel.REGISTER)==i)
        Parcel.REGISTER += [ self ]
```

```
    # factory method ensures that there is only
    # one Parcel per location
    def getParcel(rec, i, location, custIndex):
        for p in Parcel.REGISTER:
            if p.i == i:
                return p
        return Parcel(rec, i, location, custIndex)


    def __str__(self):
        return f"Parcel: {self.i:3d} ({self.custIndex:3d})"

    def index(self):
        return self.i

    def destination(self):
        return self.dest

    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')
```

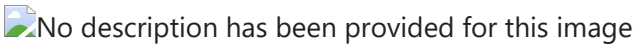
7. Class Customer



In [22]:
```
class Customer:

    REGISTER = []

    def __init__(self, rec, location):
        self.rec = rec
        self.location = location
        self.i = len(Customer.REGISTER)
        Customer.REGISTER += [ self ]
        self.atHome = True
        self.answersDoor = False
        self.parcelsReceived = []
        rec.env.process(self.process())

    def __str__(self):
        return f"Customer: {self.i:2d} {str(self.location):s}"

    # factory method ensures that there is only
    # one customer per location
    def getCustomer(rec, location):
        for c in Customer.REGISTER:
            if c.location == location:
                return c
        return Customer(rec, location)
```

```
    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:
            yield self.rec.env.timeout(random.expovariate(1/AVERAGE_TIME_ANSWER_DOO
            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(str(self)+" not at home")

    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()
            yield self.rec.env.timeout(nextHour(self.rec.env, 18))
            self.returnHome()
            yield self.rec.env.timeout(nextHour(self.rec.env, 8))
```

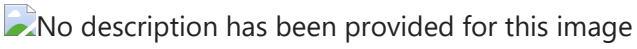
8. Class Driver



In [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.recordDriverBeginsWork()

    def leaveForDelivery(self, tour, parcels):
        self.tour, self.parcels = tour, parcels
        self.rec.trace(f"Driver leaves for delivery " \
                       f"of {len(parcels):d} parcels")

    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 = self.DC.sendForDelivery()
            yield self.rec.env.timeout(PREP_TIME_PER_PARCEL*len(parcels))
            self.leaveForDelivery(tour, parcels)
            while len(self.parcels)>0:
                # drive to customer
                custLocation = self.parcels[0].dest
                cust = Customer.getCustomer(self.rec, custLocation)
                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].dest:
                        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].dest:
                        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)
            yield self.rec.env.timeout(600)

            self.rec.recordDriverEndsWork()

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

9. Class Delivery Centre



In [24]:
```
class DeliveryCentre:

    def __init__(self, rec, M, W):
        self.rec = rec
        self.M = M
        self.W = W
        self.limit = 40000

        self.leftOver = []    # list of parcels
        self.parcels = []     # list of parcels scheduled for delivery
        self.dest = []        # list of unique customer destinations
        self.tour = None      # tour planned for delivery

    def __accept(self, parcel):
        custLoc = parcel.dest
        if custLoc not in self.dest:
            MT = addTargets(self.M, self.dest + [custLoc])
            self.rec.timer("addTarget")
            SH = createLoopH(MT, [self.W] + self.dest + [custLoc],
                             timing=self.rec.timing)
            self.rec.timer("createLoopH")
```

```
            if self.tour is None and pathLength(SH)<self.limit:
                self.parcels.append(parcel)
                self.dest += [custLoc]
            else:
                S = createLoop(MT, [self.W] + self.dest + [custLoc],
                               timing=self.rec.timing)
                self.rec.timer("createLoop")
                if pathLength(S)<self.limit:
                    self.parcels.append(parcel)
                    self.dest += [custLoc]
                    self.tour = S
                else:
                    self.leftOver.append(parcel)
        else:
            self.parcels.append(parcel)

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

    def sendForDelivery(self):
        parcels = []
        if self.tour is None:
            MT = addTargets(self.M, self.dest)
            self.rec.timer("addTarget")
            self.tour = createLoop(MT, [self.W] + self.dest,
                                   timing=self.rec.timing)
            self.rec.timer("createLoop")
        tour = self.tour
        addresses = self.dest

        # 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.dest == dest and p not in parcels:
                    parcels += [p]
                    p.outForDelivery()

        # arrange the left overs
        L = self.leftOver
        self.tour = None
        self.parcels = []
        self.leftOver = []
        self.dest = []
        for p in L:
            self.__accept(p)

        if self.rec.plot:
            plotMap(self.rec.M, T=addresses, P=tour, W=tour[0],
                    text=f"Day {day(self.rec.env.now):2d}, {pathLength(tour):,d}m")

        return tour, parcels

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

```
        self.__accept(parcel)

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

10. Simulation

10.1. Parameters from Specification

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

In [25]:
```
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.

In [26]:
```
PREP_TIME_PER_PARCEL = 50
```

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

In [27]:
```
RETURN_TIME_PER_PARCEL = 30
```

The average time to answer the door.

In [28]:
```
AVERAGE_TIME_ANSWER_DOOR = 40
```

In [29]:
```
WAIT_TIME_IF_CUSTOMER_DOESNT_ANSWER_DOOR = 60
```

10.2. Generate Input Data

In [30]:
```
def generateDeliveryData(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.
    np.random.seed(seed)
    R = np.random.poisson(lam=len(C)*p, size=days)
    D = [ sorted(list(np.random.choice(range(len(C)), size=i))) for i in R ]
    return D
```

In [31]:
```
def generateInputData(D, log=False):

    R = [ len(d) for d in D ]
    N = sum(R)

    DAY_LENGTH = 24*3600    # measured in minutes
```

```
    DAY_START = 8*3600      # first delivery in the morning
    DAY_END = 17*3600     # last delivery during day time

    x = pd.DataFrame()

    x['iarr'] = [None]*N
    x['time'] = [None]*N
    x['day'] = [None]*N
    x['dest'] = [None]*N

    current_day = 0
    last_time = 0
    i = 0

    for d in D: # for each day

        if log:
            print("generating for day: ",current_day, D[current_day])

        time = current_day*DAY_LENGTH + DAY_START

        for c in d: # for each customer that should get a

            IARR = (DAY_END-DAY_START-2*3600) / len(d)  # estimated average IAT for

            iat = random.expovariate(1.0/IARR)
            new_time = time + iat

            x.at[i, 'iarr'] = round(new_time - last_time,1)
            x.at[i, 'time'] = round(new_time - current_day*DAY_LENGTH , 1)
            x.at[i, 'day'] = current_day
            x.at[i, 'dest'] = c

            i += 1
            last_time = time = new_time

        current_day += 1

    return x
```

10.3. Simulation Routine

In [32]:

```
def simulation(M, W, C, p=0.15, days=25, seed=5640, log=False, plot=False, timing=F

    random.seed(seed)
    D = generateDeliveryData(p, C, days, seed)
    X = generateInputData(D, log=log)

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

    print(f"Simulating delivery of {len(X):d} parcels "
          f"over {len(D):d} days to {len(C):d} customers")
```

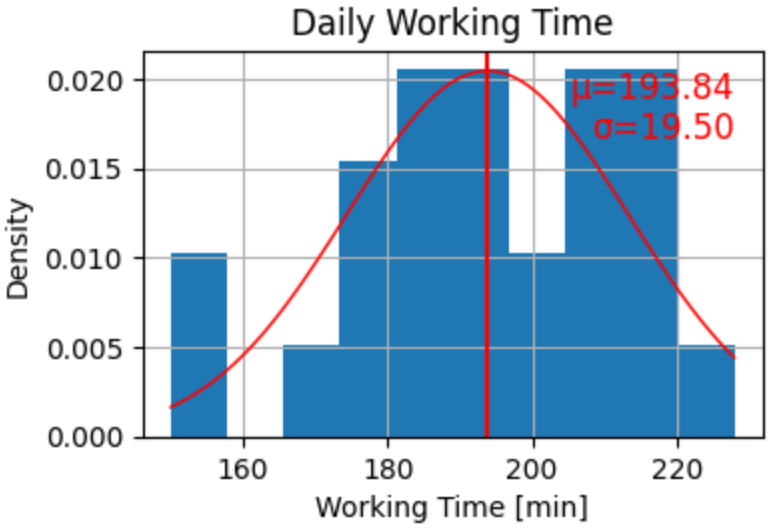
```
    for c in C:
        Customer.getCustomer(rec, c)
    DC = DeliveryCentre(rec, M, W)
    D = Driver(rec, DC)

    def generatorProcess(env):
        # generate the parcels based on input data x
        for i in range(len(X)):
            yield env.timeout(X.at[i, 'iarr'])
            custIndex = X.at[i, 'dest']
            custLoc = C[custIndex]
            cust = Customer.getCustomer(rec, custLoc)
            p = Parcel.getParcel(rec, i, cust, custIndex)
            DC.acceptParcel(p)

    env.process(generatorProcess(env))
    env.run()

    rec.finish()

    if log:
        print(f"Delivery Centre Inventory: {DC.getInventory():d} parcels")

    return rec
```

10.4. Simulation Run

In [33]:
```
import pickle
with open('data.pickled', 'rb') as f:
    M, C = pickle.load(f)
```

In [34]:
```
random.seed(5640)
W = generateWarehouseLocation(M)
rec = simulation(M, W, C, p=0.15, days=25)
rec.histWorkingTime()
rec.plotWorkingTime()
```

```
Simulating delivery of 578 parcels over 25 days to 150 customers
```




Daily Working Time
Working Time [min]
220
200
180
160
0
5
10
15
20
25
Day

In [ ]: