Modelling the upgrade of an urban waste disposal system

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A B S T R A C T

The waste intermodal station of Clyde, in the city of Sydney, Australia, is in the heart of a complex network of terminals connected by road and rail to transport urban waste from its first collection to its final disposal. The amount of waste the network is projected to handle in 2015 will increase from about 340,000 tonnes/year in 2006 up to about 1.5 million tonnes/year, following population and consumption raise. The paper proposes a discrete-event model to represent Clyde Transfer Station (TS) and its relations with the other terminals. Such a model allows one to evaluate the effects of different expansion plans of the station structures as well as different policies of the collection service. The results show that, as often happens, a careful consideration of management alternatives can decrease the necessity of structural enlargement, which is normally much more expensive, if at all possible.

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1. Introduction

The worldwide expansion of the urban population and the parallel improvement of lifestyles make the disposal of urban wastes a critical problem in both developed and developing countries. Furthermore, most urban wastes are still disposed into landfills which have a finite capacity and were originally located relatively close to the urban areas. They are now approaching their planned capacity and their expansion is almost forbidden by the enlargement of residential areas and by the augmented concern of citizens with respect to environmental issues.

The situation can be partially compensated by the improvement of production processes to reduce the amount of wastes “from cradle to grave”, i.e. during all the life cycle of products from their design, to production, to packaging, to use and disposal, and by an enhancement of recycling and reuse practices. All over the world, legislation is pushing in this direction and the situation in Australia is no exception.

Projections for the whole Australia foresee for the next decades an increase in the total amount of generated urban wastes (disposed and recycled) from 31.6 million tons per year in 2002/03 up to 57 million tons per year in 2022/23 (ABS, 2006a; DEH, 2006). In particular in New South Wales (NSW) urban solid waste to dispose is projected to rise every year reaching 8.1 million tons per year in 2014 (NSW DECC, 2006), while the related waste legislation asked at least to hold its level for 5 years from the release of Waste Strategy 2003, when it was around 6 million tons, and it set other thresholds for the remaining six years.

Similar guidelines dealing with waste generation, transport and disposal have been suggested by the European Directive 2006/12/EC as well (codified version of the previous Directive 75/442/EEC).

The above figures explain why the region of NSW has been taking an increasing interest to the waste management issue. It is understood that a more sustainable transport, recovery and disposal of waste have to be pursued in order to reduce the considerable pressure on the environment (Beavis et al., 2006). Waste management policy needs to suggest a new interpretation of products handling, seeking to optimize outcomes against a range of economic, environmental and social objectives across all stages of a product’s life, rather than being concerned only with the final disposal. NSW has recently updated the current guidelines, introducing the Waste Avoidance and Resource Recovery Strategy in 2006 developed under the Waste Avoidance and Resource Recovery Act 2001 (NSW DECC, 2006). Action needs to be taken in order to fulfil the objectives defined by this new strategy.

To tackle this situation, the scientific literature has addressed on the one side the classical problem of designing the expansion and management of disposal facilities (e.g., Cheremisinoff, 2003), and, on the other side, the optimal location of facilities on a given territory which also entails an optimal planning of waste collection (see, for instance, Abou Najm and El-Fadel, 2004 and the literature review presented therein). While the first point of view concentrates on...
a single plant and mainly requires a continuous time modelling to evaluate, for instance, the impact of a landfill on underground water quality or the combustion dynamics in an incinerator (e.g. Astrup et al., 2004; Lobo García de Cortázar and Tejero Monzón, 2007; Huai et al., 2008), the second approach is normally non-dynamic, utilizes classical operation research tools as integer programming and network optimization, and is presently evolving towards an integrated assessment of the complete waste production and disposal cycle (e.g. Tchobanoglous et al., 1993; Everett and Applegate, 1995; Björklund et al., 1999; Tchobanoglous and Kreith, 2002; Costi et al., 2004; Salhofer et al., 2007).

A third, intermediate approach is however possible, though rarely used (Čerić and Hlupić, 1993; Lu et al., 2006; Johansson, 2006). It looks at the waste disposal system as a classical industrial activity where wastes reach the plants in discrete lots at certain (almost random) time instants and plants perform a number of “transformations” on incoming wastes (actions required for the final disposal) using given resources and requiring a certain time. The modelling paradigm normally used in these cases is based on discrete events and is particularly suited to explore the trade-offs between an increase in the capacity of the waste disposal system (an action that, as already mentioned, may not be easy for technical and social reasons) and other non-structural changes (Humphries, 1986; Ballis and Golia, 2001), such as a modification of the collection schedule, that may be undertaken more rapidly and economically, as pointed out also by Wilson et al. (2002).

This type of modelling is used in this paper to analyze future scenarios of the Great Sydney Urban Waste disposal system and determine the required retrofit as well as possible management actions to improve its performance.

The present and future conditions of the system are described in the next section, while the third presents in more details the Clyde intermodal transfer station. Section 4 shows how a model for the systems was developed and verified, recalling also some basic ideas about discrete event systems and queuing theory. The following section defines the scenarios that have been simulated and the optimization performed and, finally, Section 6 shows the results obtained and highlights the trade-offs determined between facility expansion and management improvements.

2. Great Sydney Urban Waste disposal system

The studied region includes the central core of the city of Sydney, NSW, and the expansion around it, shown in Fig. 1. Currently municipal solid waste is collected from households by trucks and transshipped to landfill sites (solid circles in the same figure) for disposal, with collection of landfill gas for generation of electricity. At present, four landfill sites for municipal waste are in operation: Belrose and Eastern Creek, placed respectively in the northern and western area of the city; Jacks Gully and Lucas Heights, located south. These landfills accept only specific components of waste to disposal (WSN, 2006).

Municipal waste from suburbs to the North of the Paramatta river and a fraction of waste collected in the southern councils of the region is trucked to the transfer station of Clyde, where it starts its journey by rail to be disposed in a much larger landfill at Woodlawn site, close to the transfer station of Goulburn, located about 250 km south-west of the city of Sydney (not shown in the map).

Within the next ten years, the four landfills close to the city will exhaust available space and will become unavailable for waste disposal, thus requiring a major revision of the municipal waste treatment and disposal network.

The current plans are that the transfer stations of Artarmon and Ryde, along with the Belrose site, when the landfill will be definitely closed, will be used as satellite stations to Clyde TS. Therefore waste, after being collected at the kerbside, will be gathered at the satellite facilities and then sent to Clyde station for transportation by rail to the final disposal in Woodlawn. Two sites (Eastern Creek and Jacks Gully) hosting the old landfill facilities will process a fraction of the solid waste on their own with alternative technologies in order to reduce the total amount diverted to Clyde TS, which will have to dispose in practice all the waste produced in the city except for that continuing to go to Lucas Heights landfill from the southern suburbs in the region.

3. Clyde Intermodal transfer station

Clyde Intermodal Terminal, located in the geographic centre of the Sydney region, is the core of the network and it is rather unique, because it is so far the only station in Australia in which mixed solid waste is compacted in standardized containers (ITU) subsequently loaded on a train, and daily dispatched to the disposal location in Woodlawn. All other transfer stations are single modal road/road TS.

Currently Clyde TS receives approximately 342,000 tonnes of waste to dispose per year. Woodlawn Bioreactor, its associated final disposal site, is a landfill with a long estimated lifetime (about 40/50 years), and facilities for efficient recovery of waste and production of compost and energy.

Waste gets to the entrance of the transfer station as mixed solid waste fraction carried by collection trucks and leaves it in compacted form on the train loaded with ITU containers.

Trucks arrive all day long, carrying different loads of waste: from a few tonnes up to 20 tonnes can be unloaded from each of them. The loads and rate of arrival of trucks differ during the 24 h and the days of the week.

All collection vehicles pass through the gate where they are weighed, then they drive, through the approach ramp, to the dumping floor (see Fig. 2). Here each driver backs up his collection vehicle, emptying its contents.

After trucks have been unloaded, they go back through the ramp and head towards the exit gate, where they are weighted and the disposal fee is determined.

While unloading activities are performed 24 h a day, the operative activities involving human staff and machinery are executed only during the station working hours (from 06:00 to 22:00). One bulldozer mixes the waste in the dumping area, and alternatively pushes it into one of the two loading hoppers. Waste loaded in each hopper is conveyed to the related compactor and compacted into a 40 ft standard container until alternatively the weight limit of 27.2 tonnes or the maximum length of 26 ft is reached. Containers cannot be filled up to their maximum capacity, because they would become too heavy to be transhipped through the remaining operations in the system (for example, from wagons to trucks for the short journey to the landfill). Containers are thus underutilized at present and this certainly allows for an improvement in efficiency.

Each compacting process takes on average 10 min to be performed and compactors operate alternatively. When the container is full, it is unhooked from the machine, manually closed, lifted with a forklift from the compaction area and put on one of the free wagons standing on the transshipment sidings. If no free wagon is available because the train maximum capacity has been reached, full containers are stored in a specific area within Clyde station, to be transported on the following day. Every working day, a 54-wagons-train (800 m long, weighing 1469 tonnes) is dispatched at 23:00 to Goulburn rail station, taking about 6 h to cover the 230 km of the route. The train may also leave on Saturdays if at least 50 wagons have been loaded.
Constraints on train length and schedule are due to the fact that it must use the only available track going south where passengers’ transportation and freight dispatch are given a higher priority. Thus, during the journey to the landfill, the train carrying waste has to use sidings to stop (about 900 m long), each time a faster train has to overtake it.

Once in Goulburn, containers are transhipped from wagons to other smaller trucks that drive them to the bioreactor, where waste is removed from the ITU, and recompacted for disposal into the landfill. Trucks then complete their travel going back to Goulburn, carrying empty containers that are put on the same train and sent back to Clyde TS.

4. Model development and validation

Clyde transfer station (as well as other stations working in a similar way) represents a typical example of a discrete event system, characterized by a strong queuing structure (Cassandras and La Fortune, 1999), as can be easily perceived from the description of the operations performed in the station.

Fig. 1. Map of the city of Sydney and present waste disposal facilities. Landfills sites are represented by solid dots; while transfer stations planned to be transformed into satellite stations are shown as circles and include Belrose.

Fig. 2. Map of the dumping floor and trucks access from the ramp, Clyde transfer station.
In Clyde TS, “customers” (anything that arrives at a facility and requires service) are represented by three types of entities: trucks entering the station, unloaded waste mass waiting to be processed and containers to be loaded onto wagon. While “servers” (person or machine which provides the requested service) are represented by truck drivers, bulldozers and compactors, forklifts and related staff (Banks et al., 2005). Note that, despite bulldozers and compactors being separate physical entities, they have been considered together because they operate jointly and no queue is allowed to form between them.

The operations performed inside the station and their reciprocal connections are described by the activity cycle diagram of the system represented in Fig. 3. It shows the interactions among entities, basically constituted by a set of mass balance equations (for instance, the waste on the dumping floor is increased by each truck unloading operation and reduced by each compaction operation).

The maximum number of “customers”, which may be in the waiting line or in the system, defines the system capacity. Since in many cases it might represent a constraint to system performance, system capacity is one of the most important issues when studying queuing systems.

With regard to the degrees-of-freedom available to upgrade Clyde TS, it is possible to identify two main system capacity issues: the dumping floor and the container storage. With respect to the dumping floor, the two important constraints are: the maximum number of trucks that can enter the area at the same time and the maximum mass of waste that can be accumulated onto the area. Containers storage involves in turn two different areas. The first is to store the empty containers that guarantee that all compacted waste can be packed. The second is the storage of full containers and must allow enough space to put the daily overproduction of containers that cannot fit on to the 800 m train. When simulating the station, one sets these capacities to their actual values and verifies if the performance of the model are similar to those recorded in terms, for instance, of mean number of waiting trucks or mean residence time of the waste on the dumping floor. Subsequently, their values can be modified to test alternative design hypotheses.

In addition, one or more of these same capacities can be seen as objectives, when using the model for planning purposes. Given a rate of arrivals (corresponding for instance to future scenarios) one may ask which is the minimum number of bulldozers and compactors required to maintain the average residence time of waste on the dumping floor below two or three hours.

The software used to implement the model is Powersim Studio (www.powersim.com), a dynamic simulation software, enabling the modelling of both continuous and discrete mechanisms, and offering stochastic simulation and optimization capabilities. It has a GUI based on the standard system dynamics notation (similar to STELLA) and given its ability of simulating hybrid systems, it also implements queues at discrete time steps. This may be computationally inefficient for a purely discrete event simulation, but allows for future expansion of the model including continuous time components and has not been a problem for the current study since, even with a simulation step of 1 min, a monthly run took about 1 min of computer time on a Pentium 4 PC.

4.1. Input and operation data

The model is completed with the definition of the arrival process of waste/trucks and of the working process of each type of server: drivers, bulldozers and compactors, forklifts. The queue discipline is always assumed to be FIFO.

![Fig. 3. System activity cycle diagram.](image-url)
Clyde TS data for a typical month of operation (September 2006) have been carefully analysed. It is immediately evident that they show a strong periodicity at daily and weekly periods. It was thus decided to look at data statistics on an hourly basis, which means assuming statistical stationarity at least in this short interval.

The first analysis concerned the input of trucks and of waste. As is evident from graphs like the one in Fig. 4, they peak in the morning and are strongly correlated: indeed the overall correlation between the number of incoming trucks in each hour and the weight of waste discharged is 0.98 for Mondays and similar for the other days of the week. It was thus assumed that the mean load of each truck was constant during each day, or correspondingly that the mix of loads of the trucks arriving in every hourly period was always the same.

Similarly, the weekly periodicity clearly appears when looking at the number of trucks or to total waste arriving every day: these values are summarized in Table 1. As can be easily noted, Mondays are characterised by a higher amount of incoming waste, because the quantities produced during the weekends are only partially collected then.

Additionally, the hourly distribution of Sunday loads are quite different from that of the weekdays, since the arrivals from restaurants of waste produced during Saturday nights make the peak hour shift to the very early morning. The overall distribution thus becomes bi-modal as shown in Fig. 5.

These analyses allow an assumption of a similar hourly distribution for Mondays, Tuesdays to Fridays, and Saturdays, with different Poisson distribution for each day. Thus, if $p_{hd}(x)$ is the probability of events (truck arrivals) occurring in hour $h$ of day $d$, then

$$p_{hd}(x) = \frac{e^{-\lambda_{hd}}(\lambda_{hd})^x}{x!}$$

where $\lambda_{hd}$ is the average inter-arrival time in hour $h$, day $d$. The inverse of these values (average number of arriving trucks per hour) is shown in some more detail in Table 2.

For waste handling, again a standard assumption was made: the duration of truck unloading, waste mixing and compacting, container filling and moving to the wagons were assumed to be random variables distributed in a truncated Gaussian way, i.e. if $p_0(t)$ is the probability of operation $o$ to take time $t$, then

$$p_0(t) = \frac{1}{\sigma_o \sqrt{2\pi}} e^{-\frac{(t - \mu_o)^2}{2\sigma_o^2}}$$ (2)

where, $\mu_o$ and $\sigma_o$ are the mean and standard deviation of the duration of operation $o$. These distributions where truncated in order to avoid unreasonable short or long durations as shown in Table 3.

On the contrary, the train dispatch has not been considered as a random process since, as already stated, its load and schedule are fixed and some minutes of delay do not change the overall work of the station.

The present capacity constraints of Clyde transfer station are: three trucks can move and unload at the same time on the dumping floor; a stock of up to 200 empty containers is available in a suitable area (empty container storage) to compensate for overproduction; the dumping floor area can accumulate up to 1000 tons; and a maximum of 72 full containers can be piled up in the dedicated storage area.

4.2. Simulation of Clyde TS operation

Using the assumptions illustrated above, the behaviour of Clyde transfer station has been simulated 20 times, modifying the seeds of the random number generation and changing the initial values of the queues (trucks and waste on the dumping floor, stocks of empty and full containers) around their mean values, to obtain robust statistics of the system performances. The same approach has been used to compute the results of all the scenarios reported in the following section.

Sample results of a typical simulation are shown in Fig. 6, where both the amount of waste on the dumping floor and the number of full containers ready for being loaded on the train by the forklift are plotted.

The mean waste remaining on the dumping floor is 73.5 t and its mean residence time is 20 min, substantially less than the time required for starting the decomposition with the related adverse environmental consequences, while the mean number of full containers waiting to be transshipped is 10 units.

Undisposed waste peaks mainly on Mondays, but this does not represent a real problem since the maximum values are well below the floor capacity of 1000 t. Accordingly, the residence time is always below 8 h. It must be noted that these peak values have no statistical meaning, since they simply represent the maximum...
values obtained in a number of random simulations. A more correct expression of these results would be that the estimated probability of exceeding the value of 1000 t is negligible. Obviously, an event with zero probability may still occur and this is why we cannot rigorously speak of maximum values. Indeed, interpolating, for instance, with a continuous exponential distribution the empirical values plotted in Fig. 7, one may estimate the (very low) value of the probability of exceeding any threshold.

A full 54-container train is loaded in all weekdays and the mean number of remaining full containers is 10, peaking again on Mondays with values around 35 containers, much smaller than the storage area capacity.

These results were judged to represent closely enough the present observed behaviour of the transfer station, thus validating the model, and confirmed that Clyde station can manage quite well the current normal workload.

5. Future waste production and disposal scenarios

Before presenting the future scenarios that have been simulated, it is important to note that Clyde (and any other station on the network) will (continue to) work as a transfer station and thus, if the input values do increase in terms of mass of waste, the output must increase in the same way, on the average. This means that, if the monthly input goes from 28,500 tons in 2006 to 127,000 tons after 10 years, there must be enough capacity on trains to move it to Goulburn. Again, given the problem already outlined on the use of the track, the dispatching of the necessary trains will not be considered a stochastic process, but they will be scheduled in a precise deterministic way.

All the scenarios reported below assume the monthly mass of waste input equals the value foreseen for 2015, computed under the hypotheses of an average annual per capita GDP growth at 1.88% and an average annual population growth of 1.13% (ABS, 2006b). The present time distribution of collected waste is however preserved, which means that the average production in each day of the week is increased in the same proportion as the monthly total.

5.1. Scenario 0: Present structure of Clyde TS

The future input cannot be sustained by the present structure of the station. Even adding one or two more trains per day, the queue of trucks waiting for unloading and also the number of containers waiting for handling tend to infinity. These aspects are in fact the bottlenecks of the system.

Though infeasible, this scenario pointed out two interesting facts: the present capacity of the accumulation area (1000 t) appears to be very large and the train capacity is a tight constraint.

To improve the situation, it has already been proposed to replace the 40 ft containers (sized 40 ft \times 8 ft \times 8'6" ft) with 20 ft (sized 20'ft \times 7'9"ft \times 8'6"ft) ones. Two of them can be loaded on each wagon, but they can be filled up to their maximum capacity of 18 tons per container (with an average bulldozer plus compactor time decreased to 7 min), without causing problems in the unloading and truck operations at Goulburn TS/Woodlawn landfill. This change increases the capacity of a train to 1944 tons, and obviously double the number of containers that can be accommodated in the storage areas. Since it is already under consideration, this change will be assumed for all the following scenarios.

5.2. Scenario A: Enlarged facilities

One possibility to deal with the increased input is to considerably empower the station facilities. Given what has already been said about the ample availability of storage for waste on the dumping floor, the facilities to modify seem the steering area of the floor to allow more trucks to unload at the same time and the number of bulldozers/compactors and forklifts.

From a formal point of view, one would have to solve a minimization problem of these variables subject to the sustainability constraints that the average lengths of the queues (waiting trucks, backlog of waste on the dumping floor, stored containers to be transhipped) is stationary and other feasibility constraints like the

### Table 1

<table>
<thead>
<tr>
<th>Day</th>
<th>Average truck arrivals</th>
<th>Total mass (tonnes)</th>
<th>Average mass/truck (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monday</td>
<td>187</td>
<td>1339.01</td>
<td>7.16</td>
</tr>
<tr>
<td>Tuesday</td>
<td>173</td>
<td>1247.99</td>
<td>7.20</td>
</tr>
<tr>
<td>Wednesday</td>
<td>179</td>
<td>1196.80</td>
<td>6.90</td>
</tr>
<tr>
<td>Thursday</td>
<td>159</td>
<td>1060.43</td>
<td>6.12</td>
</tr>
<tr>
<td>Friday</td>
<td>172</td>
<td>1060.88</td>
<td>6.12</td>
</tr>
<tr>
<td>Saturday</td>
<td>117</td>
<td>572.28</td>
<td>4.89</td>
</tr>
<tr>
<td>Sunday</td>
<td>55</td>
<td>363.74</td>
<td>6.61</td>
</tr>
</tbody>
</table>

All the scenarios reported below assume the monthly mass of waste input equals the value foreseen for 2015, computed under the hypotheses of an average annual per capita GDP growth at 1.88% and an average annual population growth of 1.13% (ABS, 2006b). The present time distribution of collected waste is however preserved, which means that the average production in each day of the week is increased in the same proportion as the monthly total.

**Fig. 5.** The hourly distribution of truck arrivals on Sundays at Clyde TS.
average waiting time of the waste on the floor and the mass conservation equations. However, there is obviously no sense in increasing the capacity of one facility, say for instance the number of trucks unloading in parallel, without increasing the other facilities on the chain. Additionally, the decision variables (that represent also the problem objectives) are integer and their optimal values are presumably of few units. This allows an extensive search to be performed without using a specific optimization algorithm.

The minimum set of facilities that guarantees a sustained handling is: a steering area allowing for ten unloading trucks in parallel, two bulldozers and two compactors to operate simultaneously, and two forklifts as well.

Two trains must be scheduled every day: the added one leaving the station with a delay of 12 h. However, for the most critical days another train is required: on Mondays and Tuesdays a new train should depart at 06:00.

Though feasible, this solution implies a consistent (and expensive) empowerment of the station also for the dumping floor since, in the simulations, the maximum backlog of waste overpasses 2000 tons. Such a huge upgrade conflicts with the impossibility of physically enlarging the yard, located within a rail track intersection.

5.3. Scenarios B: Trade-offs between operating time and structures

Given the infeasibility of some of the structural changes implied in the preceding scenario A, it is interesting to explore how the situation can be improved by non-structural actions. Clearly, a better management of the station will allow for a reduction of the physical facilities and vice versa. In the following, the number of working hours of the station has been assumed to represent the “working force” cost and the dimension (square meters) of the dumping floor has been used as an indicator of the structures needed to sustain the workload. This indicator is thus the sum of the area for truck steering (around 210 m² per vehicle) and waste accumulation (0.84 m³ per ton). The storage of empty and full containers, on the contrary, has never appeared to be a bottleneck, provided the smaller ones are used and their number is thus doubled. For this reason, the container storage has not been considered as a decision variable for the new design.

The efficiency of a certain time schedule does not depend only on the number of opening hours, but also on the specific day and night shifts. The best results of this analysis are shown by curve B in Fig. 8, where also the preceding scenario (point A) is plotted for comparison, together with the present dimension of the dumping floor (dashed vertical line). They show that, if all the other assumptions on trucks, load and facilities are kept at the same values as in scenario A, there is an almost linear trade-off between opening hours and dimension of the dumping floor around the present condition and a 25% reduction of structural requirements can be attained just by setting the work shifts of the station in a better way (even without increasing the opening hours).

5.4. Scenarios C: Coordination of Clyde TS and satellite stations

An even more interesting possibility is to utilize Clyde TS in coordination with the present landfill sites transformed into satellite transfer stations. The waste collected in each council may be temporarily accumulated in the (small) satellite stations and shipped from there to Clyde TS in a scheduled way in order to reduce the daily variability of the input. The queuing structure of Clyde TS acts in fact as a reservoir which transforms the time variable random input into the regular train output. This means that the more variable is the input the larger has to be the station capacity to dampen its variation. A careful scheduling of the input may thus reduce the dimension of the facilities needed to handle it in a sustainable way (Ballis and Golias, 2004).

Three types of scenarios have been simulated to evaluate the outcome of the coordination of the station network. The first two assume that all present landfill sites become satellite stations, each handling the waste of its own collection basin while Clyde TS continues to receive the waste from its collection area with the present time pattern. This means that, in the areas served by each satellite station, solid waste will be transported from the kerbside to the station itself, from where it will be sent to Clyde TS following a uniform, deterministic schedule; while in the natural catchment of Clyde TS, arrivals would still be represented by a Poisson distribution.

Under this assumption, if one still supposes that the arriving trucks are loaded in the same way as today, point C1 in Fig. 8 can be obtained. It shows that, if the station works 24 h a day, the structures can be reduced to about half of those required without satellite stations. Additionally, considering that the existence of the satellite stations may allow for a better loading of the trucks, even without compaction, one may obtain the trade-off shown by curve C in Fig. 8. The structure required in this hypothesis is down to one third of that without coordination, when maintaining the present opening time, and the other performance indices are quite acceptable: less than 2 min average truck waiting time with an average queue of less than two vehicles, less than 20 tons of waste on the dumping floor with a dwelling time below half an hour.

The third type of scenarios is depicted by curve C4 in the same figure and assumes the almost utopian hypothesis that also the input from Clyde TS collection trucks may be scheduled in perfect coordination with all the trucks coming from the satellite stations. While this perfectly uniform input is almost infeasible in practice, this scenario is interesting because it shows how much a careful management would allow to spare in terms of physical structures; again at 18 h of opening time, the dumping floor may go down to one fourth of that required without coordination.

6. Concluding remarks

The discrete-event model developed in this work has allowed us to analyse the behaviour of Clyde TS under a number of different assumptions and to provide clear indications for its future development.

First of all, the current structure of Clyde TS will not be sufficient to face the increased load of waste foreseen for 2015 following population and consumes growth and will require a combination of structural and management changes. Infrastructure enlargements alone will in fact not guarantee a sufficient reliability. Though the
station may appear to be able to stand a regular flow of waste, the random variations which are normal in the waste production and collection activities, may easily bring it to an unsustainable situation.

On the other hand, management changes, which also can be easily tested with the proposed model, can be easier to implement in practice and have proved to be very powerful. For instance, extending the working hours of the TS may strongly reduce the necessity of a larger dumping floor.

In particular, the most effective management change seems to be a precise scheduling of collection activities. A more uniform arrival of the trucks may definitely improve the performance of the TS. In other words, it seems much more efficient to try to modify the station input instead of intervening on the station structure assuming the input as given. Clearly, a perfect scheduling of the waste collection is impossible, but the model has shown the limit of performance that the station can reach, thus providing a useful benchmark to the decision-makers.

A more uniform distribution of the waste input can indeed be obtained by planning the co-ordination of Clyde TS with all the satellite stations and may be further enhanced by implementing some compaction activity there. This would in fact mean that both the truck arrivals and loads are somehow controlled. While this possibility has not been analysed in this paper, it would be easy to replicate a discrete-event model such as that proposed for Clyde TS for all the satellite stations and thus describe the complete waste managing network: most discrete-events software tools, including that adopted in the present study, allow the construction of a hierarchy of sub-models that can be linked in any desired way. In
particular, a model of the complete transhipment network would allow the analysis of other impacts of the system, such as the traffic of trucks between stations and related air pollution emissions, corresponding to alternative management options.

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