Optimization tool of waste management in building deconstruction with environmental criteria

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ABSTRACT:

Building demolition is a major issue regarding waste management. In order to encourage companies to improve their practices, European and French laws target a minimal recovery rate of 70% (in mass) for 2020. However, a recovery rate is not enough to study environmental impacts of demolition. Moreover, demolition has gradually headed for a new practice: deconstruction. But this practice is more complex than classic demolition. In order to overcome the complexity, we developed a Multi-Objective Optimization model to help demolition companies with a better waste management.

The Multi-Objective Optimization algorithm considers 4 objectives regarding cost, delays, recovery rate and greenhouse gas emissions. The algorithm integrates 40 waste types, technical and organizational constraints and existing treatment sites network.

The algorithm was tested on a real case study. It shows efficiency by finding a set of optimal trade-offs between economic performance, delays and environmental impacts were found. A solution was chosen as a basis for the deconstruction site and feedback supported the algorithm relevance.

The suggested algorithm allows demolition engineers to better understand and assess environmental aspects of a demolition strategy.

Keywords: Waste management, Decision tool, Multi-objective optimization, Greenhouse gas emission.

1. Introduction

Constant increase of urban population brings on a faster renewal of buildings and infrastructures. Building demolition and renovation are growing. These works produce 35 million tons of waste in France per year [1]. However, waste management still lacks of coordination and efficiency. A large variety of waste can be managed in buildings demolition: concrete, wood, brick, plaster brick, furniture, metals, carpeting, PVC floor, plaster, movable partition, sandwich panel, green waste, asbestos… Unfortunately, in order to reduce work time on site, waste are evacuated unsorted, preventing recovery and causing negative impacts: landfills are overused, recyclable materials are wasted and pollution risks spread.

In order to stimulate better practices, the European Union has set up for the objective of a minimal 70% recovery rate (in mass) for waste from building and public works by 2020 [2]. France has adopted this objective in 2015 [3]. However, recovery rate is not enough to assess environmental impacts. As example, metal and concrete recycling are both attractive regarding recovery rate, but they do not produce the same environment consequences. Metal recycling need far more energy than concrete recycling. In addition to waste treatment, their transport and building demolition also cause environmental impacts. These impacts need to be considered.

Demolition produces a great amount of waste. Yet, few tools or methods help to reduce environmental impacts of demolition works [4–6]. Reducing these impacts is complex. First it requires to allow for the demolition process, because waste treatments depend on site sorting, and on demolition techniques. Then it is necessary to consider global cost, duration to achieve works and environmental impacts. As far as we know, there is no existing tool that optimizes building demolition considering the whole demolition process (from site preparation to waste management) and the different criteria (environmental, economic…).

To reach this objective, we developed a multi-objective optimization tool that will guide demolition companies to a better waste management. We developed the algorithm in partnership with a French demolition company, so that the algorithm would be well adapted for the sector.

2. Demolition work model into a multi-objective optimization problem

2.1. Demolition work with a deconstruction approach

For a couple of decades, demolition has gradually headed for a new practice: deconstruction. Deconstruction can be seen as the reverse of construction. The last installed element during a building construction is the first one removed during deconstruction. Deconstruction stands up for manual work instead of mechanical or explosive work. Deconstruction is less destructive than demolition and eases waste on-site sorting. It is a first step to a better waste management. A waste sorted on site is more easily sent to a recovery plant. Recovery is more difficult if the waste is evacuated in a sorting plant. Sorting plants have a low recovery rate: about 35% for mixed inert waste and 15% for mixed non-hazardous waste [7]. Sorting plants do not allow an efficient waste management. Only deconstruction would enable to reach regulation, i.e. a minimal recovery rate of 70%.

2.2. Building deconstruction phases

The first phase, called installation, is to prepare the site before works. Fence, electricity and water supply and workers rooms are installed. Deconstruction begins with a dismantling phase. Elements inside the building are removed, such as furniture, doors, windows, partition, false ceiling, floor covering… Each element type is removed at the same time, that eases on-site sorting. Workers take off elements manually, with hand tools or with machine like a mini excavator. Technique choice depends on element type and quality, building features, finishing level… Building structure deconstruction is done with the same sorting approach. Roofing is deconstructed first, then structural frame, external walls, pavement and finally foundation. It is usually done with hydraulic excavators. Deconstruction work ends when all waste are evacuated. Waste are gradually loaded into containers. Filled containers are then evacuated by trucks to treatment plants.

2.3. Objectives

Four criteria were chosen to assess deconstruction strategies: deconstruction duration in days, deconstruction cost in euros, recovery rate in mass % and GHG (Greenhouse gas) emission in kg CO_2 eq.

The first two criteria, duration and cost, are common for construction and demolition companies. The objective is to minimize them. Cost represents the deconstruction cost, including waste transport and treatment, and potential profit from recoverable material sale. Duration corresponds to duration of the whole deconstruction work.

The third criterion, recovery rate, enables to assess the strategy with the regulatory objective of 70%. Treatments for recovery are reusing, recycling, backfilling and composting of green waste. Waste incineration is not considered, even if energy is produced. Hazardous waste and soil recovery is not considered, as requested in regulation [2]. We wish to maximize this criterion. However, to ease the implementation, this objective is modeled in a opposite way. The criterion is then reversed into a landfill rate, that reflects rate of waste that could not be recovered. The optimization algorithm will try to minimize the landfill rate.

The fourth and last criterion is completely environmental. GHG emission of a deconstruction strategy is obtained by multiplying consumed or treated amount by emission factor; for instance, fuel liters by 3.17 kg CO_2 eq for one fuel liter combustion [8] and steel tons for recycling by 938 kg CO2 eq for one steel ton recycling [9]. GHG comes from energy consumption by machine use, workers daily travels, equipment and waste transport, machines production and waste treatment. Machines production is distributed on each deconstruction work according to machine use duration. A recovered waste becomes a secondary material that can replace a raw material in a new production process. Then raw material production is avoided. We assume the avoided raw material type for each secondary material. For example, recycled concrete into road gravel avoids non treated gravel production. Avoided emissions are obtained by multiplying recovered amount by emission factor of the avoided raw material production. For example, tons of recycled concrete are multiplied by emission factor of one non treated gravel ton production. It is still an estimation, not a sure result. Reality is more complex because a secondary material does not have the same characteristics than a raw material. As an example, gravels from recycled concrete have lower mechanical characteristics than classic gravels. Then a secondary material can not completely replace a raw material. Avoided emissions should be considered as “potentially avoided emissions”. Several studies are used to adapt GHG emission calculation for deconstruction [8,10,11]. GHG emissions from workers life on the working site (rooms, heating, food) are negligible. It is not included in the calculation.

2.4. Variables

The optimization algorithm uses three kinds of variable: decision, knowledge and building variables. Decision variables are directly linked to the deconstruction strategy: demolition type, human and mechanical resources, container type, waste treatment, treatment plants. The strategy is achieved according to demolition type (deconstruction or classic demolition), number and type of workers and equipment. Container type is for waste transport. Waste treatment is described by treatment plants (where waste are evacuated) and their treatment. Sorted waste amount depends on the demolition type. A classic demolition is completely done by a hydraulic excavator, which does not enable to sort as much as a deconstruction. A strategy is characterized by 77 decision variables. Relationships between decision variables and objectives are presented in the Figure 1.

Knowledge variables are constant regarding different demolition cases. Knowledge variables are removing efficiencies, workers and equipment daily costs, waste transport and treatment costs, recovery rates and GHG emission factors. Removing efficiency of a building element, estimated by the professional experience, is used to compute demolition duration. Resources daily cost (e.g. excavator daily cost) impacts the strategy cost. Treatment plants around the building are characterized by accepted waste type, available treatments and cost per ton. Territorial grid of treatment plants is significant for waste management. Some waste treatments are well implanted in France, like concrete recycling in road gravels, wood recycling into particle board, metal recycling… But other treatments are still in a research phase or only available in specific areas like recycling of glass wool [12] or PVC floor [13]. In France, concrete recycling into structural concrete is still at a research level, but recent studies give hope for an upcoming industrial use [14,15]. Recovery rates per waste and per treatment come from bibliography or field studies. GHG emission factors per activity are used to assess deconstruction case emission [6,8,9,16].

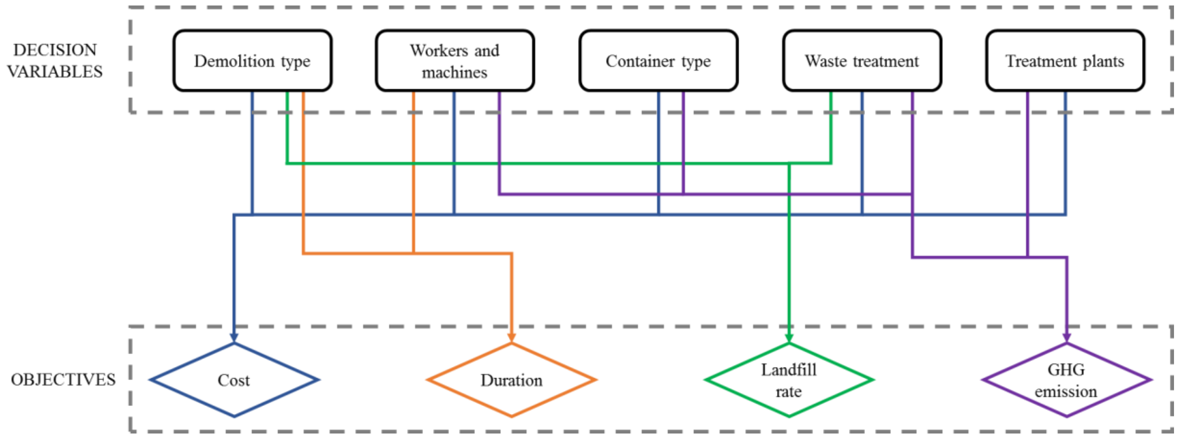

Fig. 1 Decision variables influence on the algorithm objectives

Building variables belong to the study case. The case is characterized by floor area, net floor area, waste amount from the building to deconstruct (type, mass and volume) and constraints that can hinder the works. For instance, a building in the city center, with a limited access for trucks, is a constraint. Up to forty waste types are treated by the model. Reusing inert waste on site and maximum number of workers, which depends on the building size, are also considered. A professional assesses these variables thanks to experience and building documents, like plans and inspection reports.

2.5. Problem-solving method: multi-objective optimization

The demolition optimization is a complex problem. Objectives oppose themselves, decision variables are numerous (that can create billions of feasible solutions for one study case) and relationships between variables and objectives are non-linear. In order to solve this complex problem, we use a metaheuristic search algorithm, i.e. an iterative stochastic algorithm that uses several methods to find a global optimum. The algorithm samples a population (i.e. solutions group) and makes the population evolve copying natural processes like Darwinian evolution and ant colony. The search algorithm tries to find optimal solutions in Pareto meaning, i.e. a solution "x* is Pareto optimal if there exists no feasible vector x which would decrease some criterion without causing a simultaneous increase in at least one other criterion" [17]. Numerous search algorithms exist but no one is the most efficient for each optimization problem because of the "No free lunch theorem" [18]. Nevertheless, DBEA (Decomposition-Based Evolutionary Algorithm) [19] suits for our demolition problem [20]. Then we chose this search algorithm. The optimization algorithm was implemented in JAVA with the Opensource library MOEA [21].

3. Application on a real case study

3.1. Case context

In order to validate the suggested tool, the algorithm is used on a real case study. Four little French houses need to be demolished. Waste mass is 74% of concrete, 19% of plaster bricks, 3% of wood, 2% of bricks, 1% of miscellaneous inert waste like tiles and 1% of miscellaneous non-hazardous waste like glass wool. Inert reuse on site is not possible. The case is located in a small town, far away from big cities and from their large grid of waste treatment plants.

Concrete is the largest part of the waste amount for this case. However, waste like plaster bricks and glass wool complicate demolition. A careful demolition is necessary so that recoverable materials will not be polluted. In France, plaster brick has been considered as an inert waste until leaching risks on the environment have been discovered. Therefore, plaster brick became a non-hazardous waste. Some inert residues are acceptable in concrete recycling, but non hazardous residues such as plaster bricks are forbidden. This problem happens with the study case: plaster bricks are against concrete walls and are used on false ceiling and partitions. With a demolition without dismantling, waste are mostly mixed and recovery would not be possible.

3.2. Results and interpretation

We run the optimization algorithm for this case study. Demolition type has been restricted to deconstruction, because of plaster bricks as wall doubling. 20 optimal solutions (i.e. deconstruction strategies) have been found in less than 3 mn (Figure 2). Strategies have a close duration, between 14 and 16 days. Duration objective will not be significant to compare strategies. Figure 3 shows the Pareto front (i.e. group of optimal solutions) given by DBEA for cost and landfill rate objectives. All solutions have a recovery rate above regulatory objective, which means less than 30% for landfill rate. Two groups of strategies are identified regarding landfill rate. The first group has a landfill rate between 6 and 8% whereas the second group has a landfill rate between 25 et 26%.

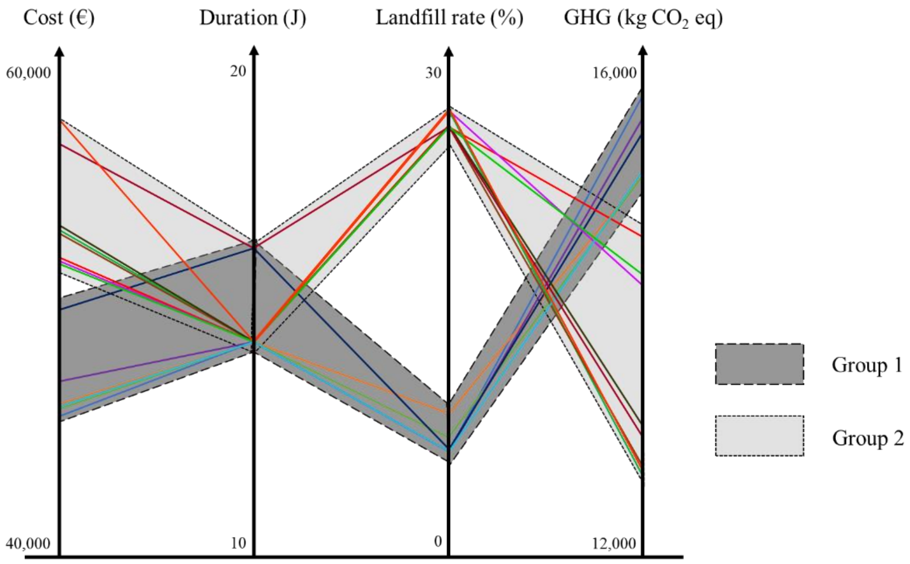

Fig. 2 Optimal solutions given by the metaheuristic search algorithm DBEA for the four objectives: Cost, Duration, Landfill rate and GHG emission

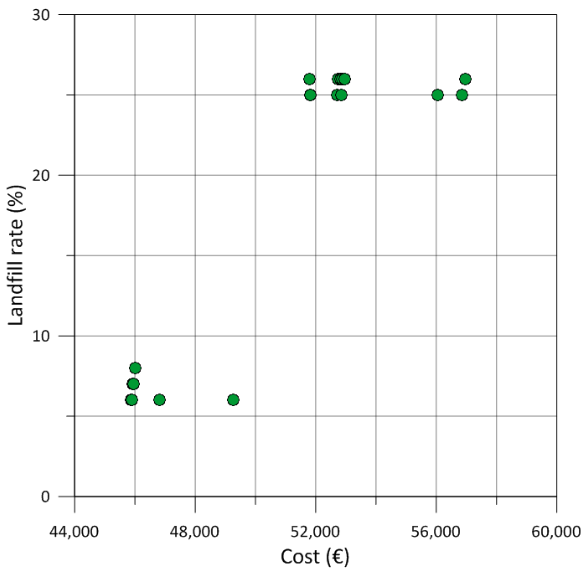

Fig. 3 Optimal solutions given by DBEA algorithm for the two objectives Cost and Landfill rate

Table 1 shows the objectives results of the two groups for the three significant objectives. Duration objective is not included because its variation is low for this case.

Table 1. Results of the two groups for the three objectives Cost, Landfill rate and GHG emission

	Cost (€)		Landfill rate (%)		GHG emission (kg CO_2 eq)	
	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2
Mean	46,539	53,394	7	25	15,189	13,191
Minimum	45,884	51,783	6	25	14,973	12,610
Maximum	49,253	56,956	8	26	15,593	14,504

Solutions with the lowest landfill rate (i.e. the biggest recovery rate) are also the cheapest. However, they emit GHG the most. On the other hand, the second group has a landfill rate greater of 18%, a cost greater of 15%, but GHG emission lower of 13%. Results show that recovery rate is not enough to assess environmental performance of a deconstruction strategy. Our hypothesis is validated. It might not be intuitive, but it can be explained. The main difference between group 1 and group 2 strategies is about plaster bricks treatment. Group 1 suggests to use plaster bricks for gypsum quarries backfilling. This treatment emits more than a sorting plant and is available more than 100 km away from the building. However, backfilling is cheaper and is considered as recovery. Otherwise group 2 suggests to evacuate plaster bricks to sorting plants or landfills. These plants are closer to the building. Cost is greater and recovery rate is lower, but remains above the regulatory objective thanks to the other recovered materials, and GHG emission is reduced.

With GHG emission, we can better take into account environmental impact of demolition strategies. Apart from plaster bricks treatment, solutions show similar characteristics. They suggest to program as many workers as possible, the value is near the authorized maximum. Concrete is recycled with mixed bricks and other inert waste, because of the very small amount of it. Wood is recycled and mixed non hazardous waste are evacuated into sorting plants. Nearest treatment plants are mostly preferred.

GHG results highlights phases with the most impacts. For group 2, the three phases that emit the most are waste treatment at the level of 65%, then structure deconstruction with a hydraulic excavator (21%) and waste transport (11%). For group 1, waste treatment is still the first emitting phase with 54% of total GHG emission. Then comes waste transport at (26%) and structure deconstruction (17%).

3.3. Deconstruction site feedback

Solutions have been shown to the site supervisor. The objective was to submit solutions to an expert. Before that, solutions have been compared to the company solution, done by an engineer. The company solution encouraged cheapest treatment plants, even with a greater distance from the building to deconstruct.

The site supervisor wanted to do deconstruction at least cost. Recycling inert waste and wood was compulsory. Regarding regulation, recovery rate is suitable for groups 1 and 2. Then the second criteria chosen by the site supervisor was GHG emission. Easiest way to reduce GHG emission was to find a balance between recovery and transport. Nearest treatment plants and a local management of plaster bricks have been preferred.

Among the 20 optimal solutions given by the algorithm, one solution shared the site supervisor plan in terms of workers number, waste treatments, container type and treatment plants. Unlike the engineer solution, the chosen solution favors nearest treatment plants. Cost increases slightly, but GHG emission decreases. Deconstruction has been achieved with this solution as a basis. Real results were close to those computed with the model, despite some hazards (e.g. four workers were not present each day on the site). Differences are acceptable: 5% for global cost and 7% for duration. The cost difference comes mostly from a bad estimation of waste amount. Real waste amount was larger than the amount suggested by the engineer. No accurate amount is available because some treatment sites did not have equipment to weigh waste. Waste amount would be larger of 49%, with 83% of inert waste (concrete and miscellaneous), 13% of plaster bricks, 1% of wood and 3% of mixed non hazardous waste. Fortunately, treatment plant for inert waste took waste for free. Recovery rate and GHG emission can not be checked for the real case, because we lacked data like exact fuel consumption for transport trucks.

Comparison brings out that the optimization algorithm is close to a real deconstruction case. Differences between solutions and reality are possible because of reality hazards (e.g. unplanned work to do, non-uniform team on site following the days) and facts that could not be transformed into mathematical formulas (e.g. how to plan mini-excavators number according to workers number). These differences are acceptable. However, the experimentation emphasizes the waste amount estimation importance. This would impact each criterion, e.g. additional cost for waste transport and treatment, additional work days, false recovery rate and additional GHG emission. A good waste amount estimation is critical for the algorithm efficiency.

4. Conclusion

We suggested a multi-objective optimization model for deconstruction. A real study case brought out the algorithm relevance. In comparison with a common study, waste management is better planned and cost and duration are optimized. With the search algorithm DBEA, a high diversity of solutions is found and offers a larger choice for the decision-maker. Deconstruction site feedback accounts for the model accuracy, even if it is aimed at deconstruction studies.

Solutions with a high environmental performance are easily found by studying GHG emission and recovery rate. Recovery rate only considers recovered mass whereas GHG emission takes into account each consequence of a recovery (e.g. a longer distance to evacuate waste, which means more transport emission). Nevertheless, GHG emission has limits because of some emission factors. For example, a landfill emission factor is usually lower than a recovery emission factor, but a recovery is obviously better than landfill regarding recovery rate. If the recovery rate was not in the objectives, the model could have chosen landfill to reduce GHG emission.

Thus, the model helps demolition engineers to optimize a demolition strategy. An expert opinion is still useful, before (good estimation of waste amount, demolition constraints, feasible demolition type…) and after the algorithm use (solutions assessment and choice). The model was developed in a French context, but it can be easily adapted to other contexts.

The developed model is a significant advantage for demolition studies. With GHG emission, a demolition company can properly assess demolition strategies. However, we wish to study environmental impacts of demolition in a more global way. We plan to replace GHG emission by a LCA (Life Cycle Assessment). Actually, demolition does not only impact climate change. Demolition contributes to resource depletion, ozone depletion, loss of recoverable materials… Adding a LCA would strengthen decision on the environmental scale.

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