Reverse logistics processes of multi-type end-of-life buildings/construction sites: An integrated optimization framework

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Abstract: - A significant problem that has emerged in the field of construction and demolition waste management (C&D), involves the integrated optimization of the entire C&D waste supply chain. The critical decisions to be made include among others: (i) the determination of the optimal deconstruction depth for each EOL construction site before the demolition process, and (ii) the design of an effective transportation and recovery network for shipping deconstruction products and waste from deconstruction/demolition sites to potential recyclers/customers and waste disposal sites. In this context, we propose a novel integrated model for optimizing the reverse logistics processes of multi-type end-of-life buildings/construction sites in a single planning period. An additional innovative feature of the proposed methodological approach is that the final recipients/recyclers may provide different pricing policies in a stepwise manner, depending on the quantity of materials that they receive. Finally, a specific case study is presented in order to demonstrate the applicability of the proposed decision-making model, while few interesting managerial insights regarding the behavior of the optimal solution are obtained and discussed.

Keywords: - Construction and Demolition Waste Management; Reverse Logistics; Mathematical Programming; Multiple Construction Sites; Different Types of End-of-Life Buildings; Single Planning Period; Stepwise Pricing Policies

1 Construction and Demolition Waste Industry

The construction industry constitutes one of the most significant sectors of the world economy. A huge number of construction, renovation and demolition activities of buildings, utilities, structures and roads take place all over the world in a continuous basis. These activities result to the generation of a huge amount of construction and demolition (C&D) debris, with profound financial and environmental ramifications.

The majority of C&D debris is made up of non-hazardous, uncontaminated materials such as bricks, concrete, soil, rock, wood, wall coverings, plaster, drywall, plumbing fixture, roofing shingles and other roof coverings, glass, plastics, metals, etc. On the other hand, C&D debris may also contain hazardous materials, such as asbestos and heavy metals that should be separated and disposed of according to each nation's hazardous waste regulations. According to Fatta et al. (2003) [1] the hazardous materials can be categorized in three groups: (i) C&D waste fractions that are hazardous because the materials originally used are hazardous themselves (e.g. lead, asbestos, tar, paint), (ii) materials that become hazardous due to the environment they have existed for years, and (iii) C&D waste fractions that become hazardous due to the fact that they are in contact or mixed with hazardous materials.

In general, the type and quantity of C&D waste produced depends on various heterogeneous factors such as:

- the type and size of the project,
- the year of construction,
- the location of the project,
- the materials used in the project, and
- the construction/demolition practices.

Materials resulting from the deconstruction and demolition processes of end-of-life (EOL) infrastructure and buildings constitute one of the most important solid waste streams [2], while natural disasters such as floods, earthquakes, and hurricanes may greatly increase these percentages. The efficient and effective management of these materials in an environmentally sound and economic feasible manner appears to be of high importance.

Up to recently, the most common and clearly not attractive international practice in the field of C&D waste management has been the discarding of all the waste materials and debris to sanitary landfills, or even worse to uncontrolled open dumps in some countries. To remedy this, European Union has adopted a number of Directives aimed at harmonizing waste disposal policies, while ensuring environmental protection. C&D waste management has been originally included in the general waste Directive 75/442/EEC (as well as in all further amendments to it) that is mandatory for all Member States. In September 2005, the European Commission proposed an overhaul of the 1975 Directive, mostly in order to lay down rules on recycling and to require Member States to draw up binding national programs for cutting waste. Regarding the hazardous C&D waste, European Union has adopted Directive 91/689/EEC that established the list of criteria to be used when the hazardous of waste is determined. This hazardous list was subsequently published as Council Direction 94/904/EEC and seven years later revised by the Commission Decision, 2001/118/EC.

In this contextual framework, the goal of this manuscript is to present a mixed-integer linear programming (MILP) model that addresses the optimization of the entire C&D supply chain examining multiple EOL buildings/constructions of different type that have to be dismantled in a single-period. The C&D supply chain starts from the deconstruction and demolition decisions till the transportation of the collected materials to potential recyclers/customers and waste disposal sites. Tackling the multiple EOL buildings/constructions problem appears to be of great merit, since the synergies and the resulting economies of scale from the simultaneous dismantling of buildings/ constructions can be exploited in a cost-effective manner. For instance, a subcontractor may provide discounts in order to undertake the dismantling processes of more than one EOL building/ construction or a recycler may provide better pricing policies so as to receive the aggregate quantity of a specific material gained from more than one EOL building/construction (achieving in this way economies of scale in his/her recycling processes).

The research work presented herein, was originally motivated by our four-year involvement (originating in 2005 till the present time) with a research grant funded by the General Secretariat for Research and Technology of the Hellenic Ministry of Development, entitled ‘Information system for demolition waste management - DEWAM’. The main goal of the project is the development of analytical methodological approaches for the optimization of the recovery/environmental management of C&D waste of EOL buildings.

The remainder of this paper is organized as follows. In Section 2 we present a comprehensive literature review on the relevant to our paper quantitative and qualitative decision-making research works, by focusing on the C&D reverse logistics and waste management operations during the construction and demolition phase of EOL buildings/constructions. In Section 3 we present a dismantling waste management plan and analyze alternative dismantling practices. Section 4 accommodates the development of the proposed decision-support optimization methodology, while in Section 5 we illustrate its applicability on a specific case study and provide interesting managerial insights regarding the behavior of the optimal solution. Finally, we conclude this work and provide useful directions for future research.

2 Literature Background and Insights

The optimization of reverse logistics processes, by taking into consideration financial, environmental and regulatory issues, constitutes a rapidly evolving research field [3], [4]. The existing research efforts focus mainly on the design of reverse logistics networks, distribution planning, and inventory control problems of EOL electric and electronic products and waste paper. On the other hand, optimization of the C&D waste recovery operations has been so far addressed inadequately in the relevant literature body. The research efforts in this field can be divided into two categories: evaluation of C&D waste management plans (i) in the construction and (ii) in the deconstruction/ demolition phase of the project.

Regarding the construction phase of the project, a significant number of research works explores the appropriate construction waste management practices on jobsite, as a part of an integrated waste management plan [5], [6], [7], [8]. Many papers focus on the calculation of the quantity of construction waste generated on construction sites. McGrath (2001) [9] introduced “SMARTWaste”, a software tool that can be used to audit, reduce and target waste arisings on a construction site. Cochran et. al. (2007) [10] presented a methodology for defining the economics, the sources of generation, and the composition of building-related construction waste at a regional level. The application of this methodology is illustrated by the authors through a real-world case study for the region of Florida, United States. Kofoworola and Gheewala (2009) [11], proposed a mathematical model for estimating the quantities of construction waste generated in Thailand from 2002–2005, in order to promote: (i) the development of an integrated waste management system, and (ii) the implementation of policies for managing construction waste in Thailand.

On the other hand, in the deconstruction phase of a project, there is only a small number of papers dealing with the optimization of the waste recovery operations. These works propose both quantitative and qualitative techniques for the evaluation of different deconstruction waste management plans, as well as techniques for the optimization of the relevant recovery processes. One of the initial works dealing with the economics of the recycling of the generated C&D waste is that of Peng et al. (1997) [12], who proposed a plain econometric model. Spengler et al. (1997) [13] developed a single period MILP model for the transformation of the dismantled materials and building components into reusable materials and for the design of optimal recycling techniques. In the same period, Barros et al. (1998) [14] developed a single-period, cost minimization MILP model for the configuration of an optimal sand recycling network, in which the sand originates from the demolition and reconstruction of old buildings. Following these efforts, Wang et al. (2004) [15] proposed a spreadsheet-based systems-analysis model for evaluating the cost-benefit of various deconstruction waste management scenarios. More recently, Roussat et al. (2009) [16] presented a multi-criteria methodology (based on the ELECTRE III decision-aid method [17]) in the context of choosing a sustainable demolition waste management strategy, while taking into consideration economic aspects, environmental ramifications and social issues of the examined problem. Additionally, Kralj et al. (2005a) [18], Kralj et al. (2005b) [19], Kralj and Markic (2008) [20] and Yang et al. (2008) [21] presented also interesting findings dealing with the environmental issues in construction industry.

The current work is specifically based on three particular research papers. In the first one, Aidonis et al. (2008a) [22] presented a model that addresses the optimization of the deconstruction depth of an EOL building. In the second work, Aidonis et al. (2008b) [23] proposed an analytical model that covers the entire C&D supply chain for a single EOL building, starting from the deconstruction and demolition decisions till the transportation of the collected materials to potential recyclers/customers and waste disposal sites. In the third one, Aidonis et al. (2009) [24] presented an analytical model that covers the entire C&D supply chain for multiple EOL buildings of a similar type. The present paper builds upon the general concepts that were developed by these research efforts, while extending them on the multiple EOL buildings/constructions of different type case. In addition, a further new feature is that the final recipients/recyclers may now provide different pricing policies in a stepwise manner, depending on the quantity of materials that they receive.

3 Dismantling Waste Management Plan of EOL Buildings

The dismantling process is regarded as the last stage of a building's lifecycle, following the stages of design, construction, use and maintenance. Dismantling activities result to enormous quantities of waste that need to be treated in a proper way.

The most common practice in the field of dismantling waste management until recently has been the discarding of all the waste materials and debris to sanitary landfills. This practice is clearly non-optimal, since most of the waste materials can be reused in their existing form or recycled for future use.

In order to manage properly the generated waste from dismantling activities, it is crucial to develop a dismantling waste management plan. This plan will assist the entire process by defining the appropriate methods in order to recover the maximum amount of building materials from EOL buildings/ constructions. Prior to beginning any dismantling process with the structure itself, it is important to carry out a building assessment. The building assessment consists of the following six stages:

1st Stage: Assessment of the EOL building and its materials.
2nd Stage: Investigation of the permitting issues.
3rd Stage: Conduct of cost analysis.
4th Stage: Task scheduling including transportation procedures.
5th Stage: Assessment of field safety.
6th Stage: Preparation of the jobsite.

During the task scheduling, one of the main decisions is the employment of the appropriate method for the dismantling of the structure. Nowadays, dismantling waste management employs two different methods in order to recover the maximum amount of building materials from the EOL buildings. The first method involves the demolition of the entire structure. During the demolition process the building facilities are demolished and the produced waste is collected in containers, without prior on-site separation and selection of the materials. Then, waste is transported to recycling plants for selection and special processing. More rarely, a preliminary manual selection of waste is carried out on-site, following the demolition of the building [25].

The second, and more environmentally-friendly, method for dismantling EOL buildings involves the selective deconstruction. The process of deconstruction is the exact opposite of constructing a new building [26], [27]. Selective deconstruction seeks to maximize the value gained from the materials of an EOL building, in a manner that it allows the reuse or efficient recycling of the materials that comprise the structure. The main advantages of the deconstruction process over conventional demolition are listed in Table 1, while in Table 2 the main barriers of employing the deconstruction method are presented

Table 1. Main advantages of deconstruction over demolition process.

Advantages of Deconstruction Process
• Enhanced environmental protection • Reduced disposal costs • Salvage of important historical architectural features • Revenues from selling salvaged materials • Reduction of waste landfilled • Economic development • Creation of new jobs • High recovery rates for building materials • Removal and proper handling of hazardous waste materials

4 System Definition

4.1 Problem description

A significant problem that has emerged in the field of C&D waste management, involves the integrated optimization of the entire C&D waste supply chain. The critical decisions to be made include among others: (i) the determination of the optimal deconstruction depth for each EOL construction before the demolition process, and (ii) the design of an effective transportation and recovery network for shipping deconstruction products and waste from deconstruction/demolition sites to potential recyclers/customers and waste disposal sites.

More specifically, we consider the case of deconstructing multiple EOL buildings of different/various construction types for the scope of recovering their constituent materials, within a single planning period. In each deconstruction stage of each EOL building/construction, we have the option either to recover selected products/materials and demolish the remainder of the building or continue the deconstruction process and postpone the demolition of the building/construction for a later stage. In other words, by determining the depth of the deconstruction process, we also determine indirectly the stage in which the demolition will take place.

Table 2. Main barriers on applying deconstruction process.

Barriers of Deconstruction Process
• Existing buildings have not been designed for dismantling • Economic and environmental benefits from the C&D waste management are not well-established • Additional time is required • Lack of markets for a wide variety of C&D waste products • High costs for C&D collection and recovery processes (e.g. additional labor costs) • Low cost to dispose of C&D materials to landfills • Difficulty to break into the established markets that are dominated by virgin materials • Lack of ample space in deconstruction sites

After the deconstruction process, the generated products are separated on site and stored in containers, one for each type of recyclable material. Thus, a container can be used for storing either a single material, e.g. aluminum or wood, or a mixture of different materials (e.g. bricks and cement) that can be recovered and reused jointly. Full containers from each deconstruction site are transported to certified recipients/recyclers or landfills. It is also assumed that each recipient/recycler may accept the materials generated during the deconstruction process if and only if the quantity of the materials received is above a minimum acceptable bound for each type of materials. These lower quantity bounds per type of material can be recipient-specific and are directly related to the desired economies of scale from the recipients' side. Through this basic assumption the deconstruction synergies among the examined multiple EOL buildings are systematically taken into account. For instance, it is preferable to derive a specific type of material from that building/construction in which the necessary deconstruction process is simpler and less expensive and may yield larger quantities from the examined material.

A further innovative feature of the proposed decision support methodology is that the final recipients/recyclers may provide different pricing policies in a stepwise manner. In particular, the larger the volume of a specific material that the recyclers receive, the better is the price that may offer (according to quantity specific stepwise thresholds). The economies of scale that stem from the larger volumes of materials to be recycled, give the option to recycler to offer better pricing policies. Generally, if we exclude both minimum acceptable quantities and stepwise pricing policies features, then the proposed methodology is relaxed to the case of multiple EOL buildings/constructions that are independently examined.

4.2 Model formulation

In this subsection, we present the structure of the proposed mixed-integer linear programming model (MILP) that addresses the optimization of the integrated C&D waste management of multiple EOL buildings of different type in a single planning period (Fig.1).

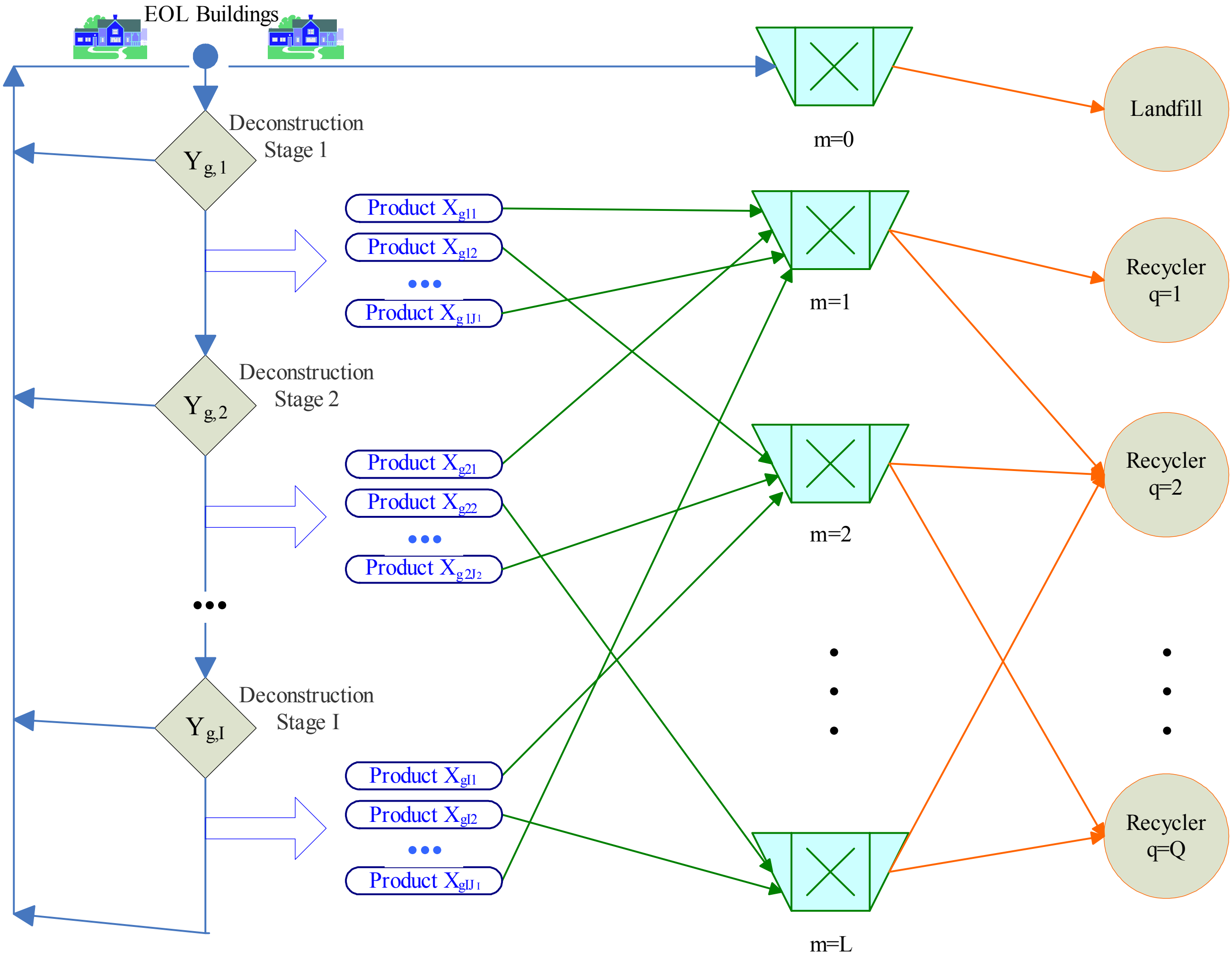

Fig.1 Flow diagram of deconstruction/demolition options for multiple EOL buildings [23].

Firstly, we provide the employed indices/sets:

$g = 1,\ldots,G$: deconstruction sites.
$i = 1,\ldots,I_g$: deconstruction stages of deconstruction site *g*.
$j = 1,\ldots,J_{gi}$: deconstruction products at stage *i* of deconstruction site *g*.
$m = 0,\ldots,L$: container contents (single or mixture of materials); value $m=0$ stands for demolition waste.
$p = 0,\ldots,P_{mq}$: stepwise pricing policy of final recipient *q* for material *m*; value $p=0$ stands for the lower quantity bound (tn) of the first part in each case pricing policy
$q = 1,\ldots,Q$: final recipients of the deconstruction and demolition products.

The problem decision variables are provided in Table 3, while the nomenclature for the cost and general parameters is provided in Tables 4 and 5, respectively.

Table 3. Decision variables.

Variable	Definition
N_{gm}:	integer variables that define the number of containers for material *m* used in deconstruction site *g*
U_{mqp}:	binary variables denoting whether recipient *q* receives containers filled with material *m* under pricing policy *p* ($U_{mqp} = 1$) or not ($U_{mqp} = 0$)
V_{gmqp}:	quantity (tn) of products that are stored in container for material *m* (generated in deconstruction site *g*) and end-up to recipient *q* under pricing policy *p*
X_{gij}:	quantity (tn) of the j^{th} product to be deconstructed at stage *i* in deconstruction site *g*
Y_{gi}:	binary variables denoting whether deconstruction continues after ($Y_{gi} = 1$) or stops before ($Y_{gi} = 0$) stage *i* in deconstruction site *g*
Z_{gmq}:	integer variables that define the number of containers for material *m* (generated in deconstruction site *g*) that end-up to type *q* final recipient

Table 4. Cost parameters.

Parameter	Definition
c^d_{gij} :	variable cost of deconstructing the j^{th} product of stage *i* (€/tn) in deconstruction site *g*
c^s_{gijm} :	variable cost of separating j^{th} product of stage *i* in deconstruction site *g*, plus loading cost in container for material *m* (€/tn)
c^t_{gq} :	variable shipping cost of a container from deconstruction site *g* to recipient *q* (€/container)
c^w_g :	variable cost of handling demolition waste (€/tn) in deconstruction site *g*
k^b :	fixed cost of using a container (€)
k^d_{gi} :	fixed deconstruction process cost at stage *i* (€) in deconstruction site *g*
$k^w_{g,0}$:	fixed cost of demolishing the entire type *g* building (€)
k^w_{gi} :	fixed demolition process cost at stage *i* (€) in deconstruction site *g*
r_{mqp} :	revenues from selling material *m* to final recipient *q* (€/tn) under pricing policy *p*

Table 5. General parameters.

Parameter	Definition
a_{gijm}:	percentage ratio of material *m* in the j^{th} product of stage *i* (%) in deconstruction site *g*
C_{gij}:	total quantity of j^{th} product collected at the deconstruction stage *i* (tn) in deconstruction site *g*
C_m:	capacity of container for material *m* (tn)
D_{mqp}:	upper bound quantity (tn) for pricing policy *p* of type *m* materials for recipient *q* and simultaneously the lower bound quantity (tn) for $p+1$ pricing policy; D_{mq0} stands for the minimum acceptable quantity of type *m* materials for recipient *q*
e:	desired deconstruction ratio of the total weight of each EOL building (%)
M:	an extremely large positive number

Then, the following MILP model is applicable:

Maximize

$$
\begin{aligned}
& -\sum_{g=1}^{G}\sum_{i=1}^{I_g}\sum_{j=1}^{J_{gi}} c^d_{gij}\cdot X_{gij} - \sum_{g=1}^{G}\sum_{i=1}^{I_g} k^d_{gi}\cdot Y_{gi} \\
& -\sum_{g=1}^{G}\sum_{i=1}^{I_g}\sum_{j=1}^{J_{gi}} c^w_{g}\cdot\left(C_{gij} - X_{gij}\right) \\
& -\sum_{g=1}^{G} k^w_{g,0}\cdot\left(1 - Y_{g,1}\right) \\
& -\sum_{g=1}^{G}\sum_{i=1}^{I_g-1} k^w_{gi}\cdot\left(Y_{gi} - Y_{g,i+1}\right) - \sum_{g=1}^{G} k^w_{g,I_g}\cdot Y_{g,I_g} \\
& -\sum_{g=1}^{G}\sum_{i=1}^{I_g}\sum_{j=1}^{J_{gi}}\sum_{m=1}^{L} c^s_{gijm}\cdot a_{gijm}\cdot X_{gij} \\
& -\sum_{g=1}^{G}\sum_{m=0}^{L} k^b\cdot N_{gm} \\
& +\sum_{g=1}^{G}\sum_{m=1}^{L}\sum_{q=1}^{Q}\left(\sum_{p=1}^{P_{mq}} r_{mqp}\cdot V_{gmqp} - c^t_{gq}\cdot Z_{gmq}\right)
\end{aligned}
\tag{1}
$$

Subject to:

$$Y_{g,i+1} \le Y_{gi},\ \forall i = 1,\ldots,I_g - 1,\ \forall g \tag{2}$$

$$X_{gij} \le C_{gij}\cdot Y_{gi},\ \forall g, i, j \tag{3}$$

$$\sum_{i=1}^{I_g}\sum_{j=1}^{J_{gi}} X_{gij} \ge e\cdot\sum_{i=1}^{I_g}\sum_{j=1}^{J_{gi}} C_{gij},\ \forall g \tag{4}$$

$$\sum_{i=1}^{I_g}\sum_{j=1}^{J_{gi}} a_{gijm} \cdot X_{gij} \le C_m \cdot N_{gm}, \forall g, \forall m = 1,...,L \quad (5)$$

$$\sum_{i=1}^{I_g}\sum_{j=1}^{J_{gi}} \left(C_{gij} - X_{gij} \right) \le C_0 \cdot N_{g,0}, \forall g \quad (6)$$

$$\sum_{i=1}^{I_g}\sum_{j=1}^{J_{gi}} a_{gijm} \cdot X_{gij} = \sum_{q=1}^{Q}\sum_{p=1}^{P_{mq}} V_{gmqp}, \forall g, \forall m = 1,...,L \quad (7)$$

$$\sum_{p=1}^{P_{mq}} V_{gmqp} \le M \cdot Z_{gmq}, \forall g, q, \forall m = 1,...,L \quad (8)$$

$$\sum_{q=1}^{Q} Z_{gmq} = N_{gm}, \forall g, \forall m = 1,...,L \quad (9)$$

$$D_{m,q,p-1} \cdot U_{mqp} \le \sum_{g=1}^{G} V_{gmqp} \le D_{mqp} \cdot U_{mqp}, \quad \forall q, \forall m = 1,...,L, \forall p = 1,...,P_{mq} \quad (10)$$

$$D_{m,q,P_{mq}} = M, \forall q, \forall m = 1,...,L \quad (11)$$

$$\sum_{p=1}^{P_{mq}} U_{mqp} \le 1, \forall q, \forall m = 1,...,L \quad (12)$$

$$V_{gmqp}, X_{gij}, \in \mathbb{R}^{+}, N_{gm}, Z_{gmq} \in \mathbb{N}_0, \text{ and } U_{mqp}, Y_{gi} \text{ binary variables} \quad (13)$$

The objective function maximizes the profit from selling/recycling the deconstruction products minus the fixed and variable deconstruction and demolition costs, the separation and transportation costs of the deconstruction products, as well as the fixed cost of using/renting containers. As far as the demolition process is concerned, the minimum value of *i* for which $(Y_{gi} - Y_{g,i+1}) = 0$ determines the last deconstruction stage before demolishing the rest of the building (for each building *g*). Inequalities (2) denote that a deconstruction stage cannot be skipped for each examined building. Inequalities (3) are typical capacity constraints for a MILP model and represent the maximum/available volume of each product that can be deconstructed in each stage for each building *g*. Constraints (4) are environmental/ regulatory type constraints that enforce a lower bound on the ratio of the total weight from each EOL building that should be deconstructed for recovery purposes. Next, constraints (5) and (6) determine for each material *m* and for each building *g* the minimum number of containers that are necessary to transport each type of material to their final recipients. Equations (7) denote that the total quantity of the deconstruction products should be transported either to landfills and/or to recyclers (under any pricing policy). Constraints (8) are necessary capacity constraints that ensure that the transportation and container rental costs are properly calculated. Equalities (9) ensure that all products/containers from all EOL buildings will be delivered to an appropriate destination. Double inequalities (10), which represent in a sense two different types of constraints, give the lower and upper quantity thresholds for each part of the stepwise pricing policy of each material and for every final recipient/recycler. Furthermore, the lower quantity bound of the first in each case part of the pricing policies describes the minimum acceptable quantity of type *m* materials for each final recipient *q*. Equations (11) ensure that V_{gmqp} variables are properly calculated, when the last part of a stepwise pricing policy (with the larger unit revenues) is not the optimal option in a case instance. Constraints (12) ensure that at most a single pricing policy will be followed for each type of material and for each final recipient. Finally, in (13) the trivial non-negativity, integrality and binary constraints are provided.

5 Case Study

A brief and indicative case study is presented in this section for demonstrating the applicability of the proposed model and for obtaining managerial insights for the optimal solution of the problem under study. More specifically, for our case, we consider two different types of buildings, a typical old apartment building with tiled-roof, of a total weight equal to 220 tones and a metal framed nonresidential building of a total weight equal of 160 tones.

Based on our extensive work on the optimum management of construction and demolition waste (see DEWAM in Section 1), as well as on the work of Spengler et al. (1997) [13], we have determined the typical sequence of dismantling activities for the different types of buildings that apply in our case. Hence, Table 6 presents the products resulting from each one of the six deconstruction stages for a typical block of flats with tiled-roof in South-Eastern Europe, while Table 7 presents the products resulting from each one of the nine deconstruction stages for a metal framed nonresidential building. Furthermore, in Fig.2 the composition of C&D waste produced in South-Eastern Europe is accordingly provided.

Table 6. Deconstruction products per stage of an apartment building with tiled-roof [22].

Deconstruction Stage	Products
1	• Heating components • Doors • Windows • Shutters • Sanitary devices • Electrical devices
2	• Floor covering • Roof covering • Wall covering
3	• Electrical installations • Sanitary installations • Plumbing installations • Heating installations
4	• Roof frame
5	• Walls • Insulation materials
6	• Floors • Stairs • Reinforced concrete walls • Foundations

Table 7. Deconstruction products per stage of a metal framed non residential building.

Deconstruction Stage	Products
1	• Heating components • Doors • Windows • Shutters • Sanitary devices • Electrical devices
2	• Floor covering • Roof covering • Wall covering
3	• Electrical installations • Sanitary installations • Plumbing installations • Heating installations
4	• Roof frame
5	• Ceiling frame
6	• Walls • Insulation materials
7	• Floors • Stairs
8	• Metal frame
9	• Foundations

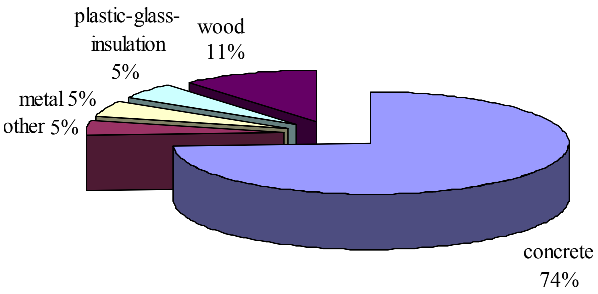

Fig.2: Composition of C&D waste produced in South-Eastern Europe [24].

The examined buildings are to be pulled down, so as new ones can be constructed in their place. The problem for the decision-makers is firstly to find the optimal deconstruction depth to obtain valuable reusable materials before demolishing the remainder of each building, and secondly to optimize the transportation, recycling and disposal processes of the produced C&D materials.

A number of eight (8) possible container configurations are considered to be placed in each deconstruction site, regarding their alternative content. More specifically, potential containers could be used for storing and shipping separately the following different contents/materials: demolition waste, wood, insulation materials, plastic, metals, inert materials (e.g. concrete, glass), electrical, heating and sanitary devices, and hazardous materials. Each container would be either shipped and disposed to a landfill or shipped to a recycler for recovery purposes (with potential revenues). Apart from the option of disposing the C&D waste to a landfill, we consider four different recycling centers. Each recycling center can undertake the recovery operations of one or more different materials under case specific pricing policies. In our case, we consider three different pricing policies for each different material m and for each final recipient q

The percentage e of the total weight of each building that is desired to be deconstructed is set to 15%, a relatively conservative value. Variable costs correspond to operational costs related to the quantity/weight of the specific products/materials, while fixed costs are the sum of the per use cost of specific machines/containers that is charged independently from the quantity of the products/ materials to be processed.

The resulting MILP model consists of 257 continuous, 80 integers and 111 binary variables, and 426 constraints excluding binary, integrality and non-negativity ones. The model was solved on a Pentium 4 computer with 3.6 GHz CPU, and 1GB RAM, via the CPLEX® v.9.1 solver and through the mathematical programming language AMPL®. The computational time is on the scale of few minutes and the solution performance of the proposed MILP model is obviously satisfactory; something that is quite expectable for two building realizations of the examined problem (MILP models of small to medium scale). On the other hand, for the larger ones a polynomial running time behavior is observed.

5 Conclusions

In this paper we present a novel MILP integrated model for supporting the decision-making processes from the point of optimally determining the deconstruction depth of multi-type EOL buildings/ construction sites in a single planning period, till the transportation of the deconstruction and demolition waste to recyclers and landfills for recovery and waste minimization purposes. An innovative feature of the proposed decision-making methodology is that the final recipients/recyclers may provide different pricing policies in a stepwise manner, depending on the quantity of materials that they receive. On the whole, the proposed analytical approach contributes towards a comprehensive and integrated construction and demolition waste management strategy.

Problems that appear to have great future research merit, include problems studying the stochasticity of the considered general and cost parameters (e.g. the recyclability of the deconstructed materials, fluctuated market values and costs, etc.). An additional future research direction could include the expansion of the provided model by adding additional meaningful financial, environmental, regulatory and technological constraints.

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