An analytical methodological framework for managing reverse supply chains in the construction industry

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Abstract: - As the growing amount of waste created by the construction industry poses severe environmental challenges, environmentally conscious construction processes have emerged as an issue of increasing importance for both the industry and society at large. The proper management of the construction and demolition waste, which constitutes the major solid waste stream in the European Union (apart from mining and farm waste) appears to be of great merit. Reverse logistics and waste management offer the appropriate contextual framework within which the problem can be tackled comprehensively. Towards this effect, a conceptual framework is presented on the current status and legislation in the field of construction and demolition waste management, as well as on the optimal deconstruction and demolition practices of the end-of-life buildings with the goals of materials' recycling and waste minimization. In addition, a novel integrated decision-making model for the entire construction and demolition supply chain is proposed starting from the deconstruction and demolition decisions till the transportation of the collected materials to potential recyclers/customers and waste disposal sites. Finally, we conclude with a demonstration of the application of the developed model is via a specific case study, and by discussing few interesting managerial insights.

Keywords: - Construction industry; Deconstruction; Recycling; Decision-making; Optimization; Reverse logistics; Waste management

1 Introduction: Basic Concepts and Motivation

Environmentally conscious construction processes have emerged as an issue of increasing importance for both the industry and society at large. The growing amount of waste created by the construction industry poses a severe environmental threat [1]. Construction and demolition waste (C&D) often contains bulky and heavy materials such as concrete, bricks, gypsum, metals, glass, plastics, wood, etc. Thus, the proper management of the C&D waste, which constitutes the major solid waste stream in European Union (apart from mining and farm waste), appears to be of great merit. This is not only due to the environmental concerns and the relevant regulations that favor alternative management processes (e.g. selected deconstruction for material recovery), but also due to its profound financial ramifications [2], [3].

Reverse logistics offer the appropriate contextual framework within which the examined problem can be tackled comprehensively. According to Rogers and Tibben-Lembke (1999) [4] "reverse logistics is the process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal", while Wikipedia [5] defines reverse logistics "as the total of the operations related to the reuse of products and materials". Reverse logistics constitute a rapidly evolving research field. Financial, environmental factors and regulative interventions have provided the incentives for companies to redesign their forward supply chain networks to further incorporate and optimize the relevant recovery and waste management processes (Thierry et al., 1995 [6], de Brito, 2004 [7], Georgiadis et al., 2005 [8], Georgiadis et al., 2006 [9], and Kralj and Markic, 2008 [10]).

In this context, the goal of this manuscript is two-fold: to present a conceptual framework for the C&D waste industry and to provide a novel analytical decision-making model for supporting the relevant reverse logistics processes. The presented contextual framework deals firstly with the legislation in the field of C&D waste management, and secondly with the examination and evaluation of the deconstruction and demolition practices in the

C&D industry with the goals of materials' recycling and waste minimization. On the other hand, the proposed optimization model covers the entire C&D supply chain, starting from the deconstruction and demolition decisions till the transportation of the collected materials to potential recyclers/customers and waste disposal sites.

The research work presented herein, was initially motivated by our involvement with an ongoing four year research grant funded by the General Secretariat for Research and Technology of the Hellenic Ministry of Development, titled 'Information system for demolition waste management - DEWAM' (that started in 2005). The main objective of the project is the development of analytical methodological approaches for the optimization of the recovery/environmental management of the C&D waste of end-of-life (EOL) buildings (old buildings that are to be pulled down, so that new ones can replace them). Additionally, the project deals with the following issues:

- Development of C&D waste management information system.
- Definition of the reusable and recyclable building materials.
- Definition of the demolition and building disassembly processes.
- Separation techniques for C&D waste management.
- Third-party logistics providers for the transportation and storage of C&D waste.
- Certified recipients of C&D waste.
- C&D recovery and waste management cost.

The remainder of this paper is organized as follows. In Section 2 we present a comprehensive literature background on the quantitative and qualitative decision-making research works on C&D reverse logistics and waste management operations. Section 3 deals with the development of a conceptual framework for the C&D waste industry. Section 4 accommodates the development of the proposed integrated decision-making model for the optimization of the reverse logistics and waste management processes of EOL buildings. Section 5, illustrates the applicability of the developed analytical methodology by its application on a specific case study, while managerial insights regarding the behavior of the optimal solution are obtained and discussed. Finally in Section 6, we wrap-up with the main conclusions of the paper and provide directions for future research.

2 Literature Review and Insights

One of the initial works tackling the optimization of the recovery of C&D waste is that of Spengler et al. (1997) [11]. The authors developed a rather simple single period MILP model for the design of optimal recycling techniques and for the transformation of dismantled materials and building components into reusable materials. Peng et al. (1997) [12] proposed a plain econometric model in order to describe the economics of the recycling of the C&D waste. Barros et al. (1998) [13] 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) [14] proposed a spreadsheet-based systems analysis model for assessing the cost-benefit of various C&D waste management scenarios. Duran et al. (2006) [15] presented a sophisticated econometric model for evaluating the financial viability of C&D recycling processes. Hao et al. (2007) [16] proposed a system dynamics simulation model, for obtaining insights on the complexity of information and processes involved in the strategic planning of C&D waste. Based in this work, Hao et al. (2008) [17] provided another system dynamics simulation model for supporting decisions related to the on-site recovery and handling management of C&D waste. Roussat et al. (2008) [18] presented a multi-criteria methodology based on the ELECTRE III decision-aid method [19] 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., 2005 [20], Kralj et al., 2005 [21], Yang et al. 2008 [22], and Kralj and Markic, 2008 [23] presented interesting findings dealing with the environmental issues in construction industry.

Summing-up, the optimization of the C&D waste recovery operations has been addressed inadequately in the relevant literature body. Indeed, there exists only a limited number of papers dealing with examined problem; these works propose both quantitative and qualitative techniques for the evaluation of different C&D waste management plans, as well as techniques for the optimization of the recovery processes.

The present paper builds upon the general concepts that were developed by previous research efforts, while extending them into the area of a generic conceptual and optimization methodological framework for the reverse logistics supply chains and waste management of the C&D waste industry. It is distinguished from the existing research in that it presents an integrated decision-support framework and not merely a new myopic qualitative or analytical model.

3 Conceptual Framework for C&D Waste Industry

The rapid growth of the construction industry worldwide has resulted to the vast increase of the produced C&D waste. In 2000, according to the European Commission, the total amount of C&D waste generated was estimated to be roughly 450 million tones per year (including earth and excavated road material) [1]. Up to recently, the most common and clearly unacceptable practice in the field of C&D waste management was the discarding of all waste materials and debris to sanitary landfills, or even worse to uncontrolled open dumps. The primary goal of C&D waste management is to recover the maximum amount of building materials from the waste stream. Direct reuse that allows for retaining the current economic value of materials (via recycling) has the highest priority, either in new or existing structures [24].

In the following subsections, we first present briefly the current state and the regulatory framework in the field of C&D waste management in several countries of the European Union (EU)-25, as well as in U.S.A. and Japan, and secondly the alternative dismantling practices of EOL buildings for the scope of materials' recovery and waste minimization.

3.1 Regulatory Environment

The EU, in order to remedy the uncontrollable disposal of C&D waste has spearheaded a number of Directives aimed at harmonizing waste disposal policies while ensuring environmental protection. C&D waste are originally included in the general waste Directive 75/442/EEC (as well as all in further amendments to it) that is mandatory for all Member States [25]. 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 production. Lately, Directive 2006/12/EC consolidated and replaced Directive 75/442/EEC on waste. In 2000, the European Commission's Decision 2000/532/EC introduced the European Waste Catalogue, which became effective on January 1st, 2002. Until today, the Catalogue has been amended with Commission Decisions 2001/118/EC and 2001/119/EC, and Council Decision 2001/573/EC.

Furthermore, several European countries have started introducing C&D waste management in their legislation. In Germany the national legislation has implemented the European Waste Catalogue. The amended European Waste Catalogue combines hazardous and non-hazardous wastes in one single list, with hazardous wastes marked with an asterisk. The latter are categorized as "waste requiring special supervision" within the German waste management law. In brief, the demolition contractors in Germany have a special, multi-role responsibility in the C&D waste management process. They provide invaluable service to building owners by taking over responsibility for recovering buildings' EOL materials, processing them and reintroducing waste into the construction market. To accomplish this, deconstruction and recycling contractors need to deconstruct buildings in such a way that material recovery and recycling is made possible. They are bound to do this both due to legal considerations as set out in the regulatory requirements for C&D waste management, as well as for financial benefits. A deconstruction company, which is responsible for the marketing of recovered deconstructed materials, can obtain significant revenue streams through the sale of recovered and recycled building materials. Since the market competitiveness in Germany is relatively high, a local deconstruction company is obliged to offer its services at very low or at absolutely no cost. Even more, in many cases deconstruction companies occasionally pay the building owner, since the value of the recovered materials outweighs their costs for the building's deconstruction or demolition. In this competitive market, the company that can extract the highest possible value from demolition waste is the one that gains the competitive advantage over its competitors [26].

In the United Kingdom there are a number of regulations related to the management, transport, treatment and final disposal of waste. The latter include both C&D waste used in construction and those processed for the production of aggregates. The "Landfill (England and Wales) Regulations 2002" and amendments, implement the Landfill Directive (Council Directive 1999/31/EC), which aims to minimize the negative environmental effects of landfilling. Construction companies which produce waste, have to pay to waste companies for recycling. At the same time waste companies pay the landfill tax for disposal of wastes, which can not be treated [27].

In Scandinavia, the common practice in the field of C&D waste management is quite similar to the policies that have been adopted by the Western European countries. In Sweden, EOL building materials recycling rates were estimated through interviews with contractors and waste enterprises. Around 60% by weight of the overall EOL building materials end-up in landfills, about 10% are incinerated and about 30% are recycled in some form. The relatively high figure for recycling is mainly due to the extensive reuse of stone and sand. In order to avoid legislative action, contractors and building material suppliers opted for joint voluntary recycling programs. They joined a "trade organization", which is known as the "Eco-cycle Council". The Swedish construction and building sector has established an Environmental Program (2003-2010) to reduce the environmental impacts of construction and demolition. The main objectives of this Environmental Program are [28]:

- Halve the volumes of landfill waste from construction works between 2004 and 2010.
- Reduce the use of hazardous substances within the building sector to a minimum by 2010.
- Identify and remediate existing buildings that cause health problems the later by 2010.

In Denmark, it's the municipalities that are responsible for collecting C&D waste. More than half of Danish municipalities - especially f major cities and towns - have introduced specific regulations on the sorting of this particular stream of waste. Towards the same effect, the Danish Environmental Protection Agency generates waste management plans. The waste strategy for the period 2005-08 was generated in 2004 [29]. Specifically, the main targets of the Waste Strategy 2005-08 for waste from building and construction activities are [30]:

- 90% of the overall building and construction waste to be recycled.
- Consideration from recycling should focus on groundwater resources.
- Introduction of indicators that evaluate environmental initiatives in construction.

In Southern Europe, the state of affairs for C&D waste management is rather complex. In Spain, the 91/156/EEC Directive on Waste was not approved until 1998. This delay in the harmonization with the EU legislation has brought a serious lack of coordination regarding the environmental waste management, while the absence of an adequate legal framework at state level has led to significant differences between the different autonomous communities [31].

C&D waste management in Portugal is not yet of a primary concern. Despite a few legislative interventions the destination of C&D waste has been controlled only in just a few cases. The owners of the construction companies, either public or private, are normally more concerned with costs, ignoring environmental concerns. In addition, during the process of approval for construction projects, some City Councils demand an estimation of C&D waste quantities and an indication of the chosen landfill, as preconditions to deliver the permissions for construction [32].

Outside the EU-25, in the United States, since the vast bulk of materials encountered in C&D waste do not contain asbestos or any other hazardous materials, management requirements for the majority of C&D waste are not covered by federal regulations. Most States have promulgated their own C&D waste management rules, including defining what waste materials are recognized as C&D waste and what components need to be excluded. Requirements for C&D waste management vary from one State to another. These variations are primarily a result of the unique characteristics of each State and include variables, such as annual rainfall, annual temperature range, land availability, geologic stability, as well as perceptions by local policymakers and regulators as to the relative risk that C&D waste poses to human health and the environment. While each State has the autonomy to create regulations to fit its unique status, the lack of federal guidance has led to inconsistent regulations throughout the nation. A C&D waste regulation survey that was conducted lately, revealed a large diversity of requirements and approaches. Twenty-three states were reported to have specific C&D waste disposal regulations, while in other states, C&D waste is regulated under requirements for inert debris landfills, or general solid waste facilities [33].

In Japan, the Construction Material Recycling Law includes quantitative targets in the field of C&D waste management, such as the recycling rate of specified construction materials in 2010 to be 95% and final disposal quantities for specified C&D waste generated in public works to be zero from 2005 and on [34]. The law requires that, when constructing or demolishing buildings, the owner shall notify beforehand the Prefecture government of his plan on sorting and recycling C&D waste. In parallel, the constructor needs to sort C&D waste, recycle specified materials (wood, concrete and asphalt) and report it to the owner of the structure. In order for a company to operate in the demolition business, under Japanese law, it should be registered by the Prefecture government [35].

3.2 Dismantling of EOL Buildings

Generally, there are two practices for dismantling EOL buildings. The first one involves the demolition of the entire structure. The demolition industry has undergone a major transformation within the last 20 years. Traditionally, it has been a low-skill, low-technology, and poorly regulated industry, dealing mainly with the disassembly of simply constructed buildings. However, during the last few years, following the trend of all major industrial sectors, it has been automated by replacing workers with machines. Recently, the demolition industry employs fewer but more highly skilled operators, as well as very expensive highly dedicated equipment. In brief, there is a wide variety of demolition techniques, both regarding their practices, as well as their technology, application, cost and speed. Traditional methods, employing for example the steel ball, are being rapidly replaced by more modern methods, as the emphasis migrates from masonry and brickwork to concrete and steel structures. During demolition the building facilities are demolished and the produced C&D waste is collected in containers, without prior on-site 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 [36].

The second practice for dismantling EOL buildings involves the selective deconstruction of a building piece by piece so that materials can be preserved, separated, reused and recycled. Chini and Bruening (2003) [37], define deconstruction as “the systematic disassembly of buildings in order to maximize recovered materials reuse and recycling”. By using this method, specific materials and components are removed prior to the commencement of the demolition of the building’s main shell. This method of deconstruction attempts to maximize the recovery of materials that can be retrieved within a specific and rational timeframe at the lowest possible cost. The produced waste may be processed on-site or off-site, at specialized processing plants far from the worksite. The application of this technique leads to an extension of the materials’ life cycles [38].

Deconstruction is emerging as an alternative process to demolition globally and has several advantages over conventional demolition. The main advantages of deconstruction are listed below [24], [37]:

- It is an environmentally-friendly technique with high recovery rates of building materials resulting in the reduction of waste landfilled.
- It enables the proper removal and handling of hazardous waste materials.
- It creates new jobs, while the economic development is enhanced since several businesses are needed to support a deconstruction infrastructure.
- It decreases the disposal costs.
- It increases revenues from selling valuable salvaged materials.
- It promotes recycling and remanufacturing.
- It can assist in salvaging important historical architectural features.

4 System Description

4.1 Problem definition

C&D materials recovery management includes the collection of debris generated during the construction, renovation, and demolition of buildings, roads, and bridges (U.S. Environmental Protection Agency) [39]. An interesting problem that has emerged in this field, involves the integrated optimization of the entire C&D waste supply chain. The critical decisions include: (i) the determination of the deconstruction depth before demolition, and (ii) the design of the transportation network for moving deconstruction products and waste from the construction/ demolition site to potential recyclers/ customers and waste disposal sites.

Herein, we consider the case of deconstructing a single EOL building at an economically optimal depth and then transporting the collected material and waste to recyclers and landfills. The deconstruction process occurs in stages. In each stage, we have the option either to recover specific products/materials and demolish the remainder of the building, or to continue the deconstruction process and postpone the demolition of the building for a latter stage. In other words, by determining the depth of the deconstruction process, we also determine the stage in which the demolition will take place.

After the deconstruction processes, 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.

Finally, full containers should be transported to certified recipients/recyclers or landfills. Apart from the obvious environmental benefits of recycling

C&D materials, significant revenues can be also realized, depending on the value of the content of a specific container.

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 by Spengler et al. (1997) [11], we have determined the typical sequence of dismantling activities for an EOL building that applies in our case. Table 1 encapsulates this exact experience and presents the products resulting from each of the proposed six deconstruction stages for a typical block of flats with tiled-roof in South-Eastern Europe.

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 an EOL building (Fig.1). Firstly, we provide the employed indices/sets:

Table 1. Deconstruction products per stage.

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

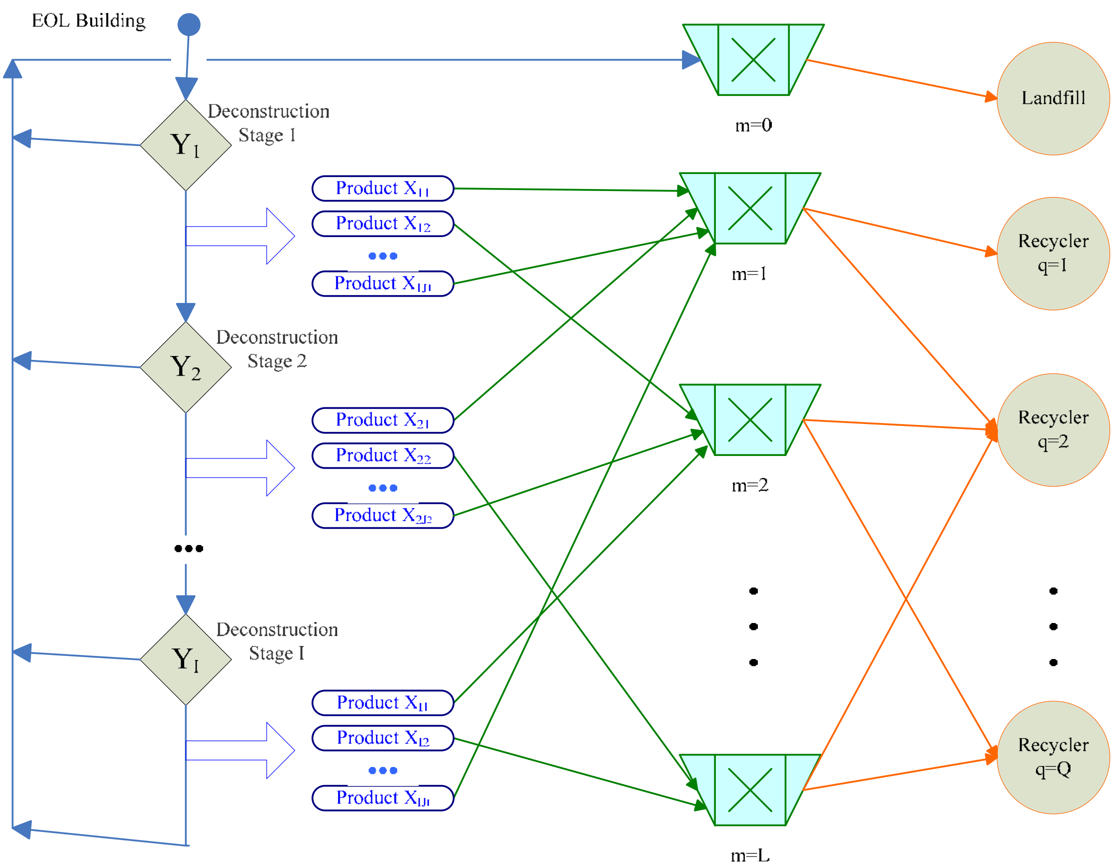

Fig.1 Flow diagram of deconstruction/demolition options for EOL buildings.

$i = 1,\dots, I$: deconstruction stages.
$j = 1,\dots, J_i$: deconstruction products at stage i.
$m = 0,\dots, L$: container contents (single or mixture of materials); the value $m=0$ stands for demolition waste.
$q = 1,\dots,Q$: final recipients of the deconstruction products (landfills and certified recyclers).

The problem decision variables are provided in Table 2:

Table 2. Decision variables.

Variable	Definition
X_{ij} :	quantity (tn) of the j^{th} product to be deconstructed at stage i
V_{mq} :	quantity (tn) of products that are stored in container for material m and end-up to recipient q
Y_i :	binary variables denoting whether deconstruction continues after ($Y_i = 1$) or stops before ($Y_i = 0$) stage
N_m :	integer variables that define the number of containers for material m
Z_{mq} :	integer variables that define the number of containers for material m that end-up to type q final recipient q

Finally, the nomenclature for the cost and general parameters is provided in Tables 3 and 4, respectively.

Table 3. Cost parameters.

Parameter	Definition
c_{ij}^d :	variable cost of deconstructing the j^{th} product of stage i (€/tn)
c_{ijm}^s :	variable cost of separating j^{th} product of stage i, plus loading cost in container for material m (€/tn)
c_q^t :	variable shipping cost of a container to recipient q (€/container)
c^w :	variable cost of handling demolition waste (€/tn)
k^b :	fixed cost of using/renting a container (€)
k_i^d :	fixed deconstruction process cost at stage i (€)
k_0^w :	fixed cost of demolishing the entire building (€)
k_i^w :	fixed demolition process cost at stage i (€)
r_{mq} :	revenues from selling material m to final recipient q (€/tn)

Table 4. General parameters.

Parameter	Definition
a_{ijm} :	percentage ratio of material m in the j^{th} product of stage i in (%)
C_{ij} :	total quantity of j^{th} product collected at the deconstruction stage i (tn)
C_m :	capacity of container for material m (tn)
e :	desired deconstruction ratio of the total weight of the EOL building (%)
M :	an extremely large positive number

Then, the following MILP model is applicable:

Maximize

$$\begin{aligned}
&-\sum_{i=1}^{I}\sum_{j=1}^{J_i} c_{ij}^d \cdot X_{ij} - \sum_{i=1}^{I} k_i^d \cdot Y_i \\
&-\sum_{i=1}^{I}\sum_{j=1}^{J_i} c^w \cdot \left(C_{ij} - X_{ij}\right) - k_0^w \cdot \left(1 - Y_1\right) \\
&-\sum_{i=1}^{I-1} k_i^w \cdot \left(Y_i - Y_{i+1}\right) - k_I^w \cdot Y_I \\
&-\sum_{i=1}^{I}\sum_{j=1}^{J_i}\sum_{m=1}^{L} c_{ijm}^s \cdot a_{ijm} \cdot X_{ij} - \sum_{m=0}^{L} k^b \cdot N_m \\
&+\sum_{m=1}^{L}\sum_{q=1}^{Q}\left(r_{mq} \cdot V_{mq} - c_q^t \cdot Z_{mq}\right)
\end{aligned} \tag{1}$$

Subject to:

$$Y_{i+1} \le Y_i,\ \forall i = 1,\dots, I-1 \tag{2}$$

$$X_{ij} \le C_{ij} \cdot Y_i,\ \forall i, j \tag{3}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J_i} X_{ij} \ge e \cdot \sum_{i=1}^{I}\sum_{j=1}^{J_i} C_{ij} \tag{4}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J_i} a_{ijm} \cdot X_{ij} \le C_m \cdot N_m,\ \forall m = 1,\dots, L \tag{5}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J_i}\left(C_{ij} - X_{ij}\right) \le C_0 \cdot N_0 \tag{6}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J_i} a_{ijm} \cdot X_{ij} = \sum_{q=1}^{Q} V_{mq},\ \forall m = 1,\dots, L \tag{7}$$

$$V_{mq} \le M \cdot Z_{mq},\ \forall m = 1,\dots, L,\ \forall q \tag{8}$$

$$\sum_{q=1}^{Q} Z_{mq} = N_m, \ \forall m = 1,\ldots,L \tag{9}$$

$$X_{ij}, V_{mq} \in \mathbb{R}^{+},\ N_m, Z_{mq} \in \mathbb{N}_0,\ and\ Y_i\ binary\ variables \tag{10}$$

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 $(Y_i - Y_{i+1}) = 0$ determines the last deconstruction stage before demolishing the rest of the building. Inequalities (2) denote that a deconstruction stage cannot be skipped. 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. Constraint (4) is an environmental/ regulatory type constraint that enforces a lower bound on the ratio of the total weight of the EOL building that should be deconstructed for recovery purposes. Next, constraints (5) and (6) determine for each material m the minimum number of containers necessary to transport the respective volume of the specific material to its final recipients. Equations (7) denote that the total quantity of the deconstruction products should be transported either to landfills and/or to recyclers. 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 will be delivered to an appropriate destination. Finally, in (10) 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, we consider a typical old apartment building with tiled-roof, of a total weight equal to 220 tones. The examined building is to be pulled down, so as a new one can be constructed in its 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 the building, and secondly to optimize the transportation, recycling and disposal processes of the produced C&D materials. The sequence of dismantling activities for an EOL building of Table 1 is adopted.

A number of thirteen (13) possible container configurations are considered regarding their alternative content. More specifically, potential containers could be used for storing and shipping separately the following different contents/materials: demolition waste, wood, glass, aluminum, insulation materials, plastic, metals, copper, inert materials, electrical, heating and sanitary devices, gypsum, 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 undertakes the recovery operations of one or more different materials.

The percentage e of the total weight of the building that is desired to be deconstructed is set to 10%, 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 90 continuous, 84 integers and 6 binary variables, and 131 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 negligible (with an average of three seconds) and the solution performance of the proposed MILP model is obviously satisfactory; something that is quite expectable for single building realizations of the examined problem (MILP models of small to medium scale). The optimal solution prescribes the deconstruction of all the products of the first three stages, while the remainder of the building should be demolished. Furthermore, all containers used for storing deconstruction materials are transported to recycling centers. An interesting finding is that in the under study case the entire process is not profitable, which according to our experience seems to be the case in C&D waste management. Figure 2 illustrates the total system cost for the various alternative deconstruction depths.

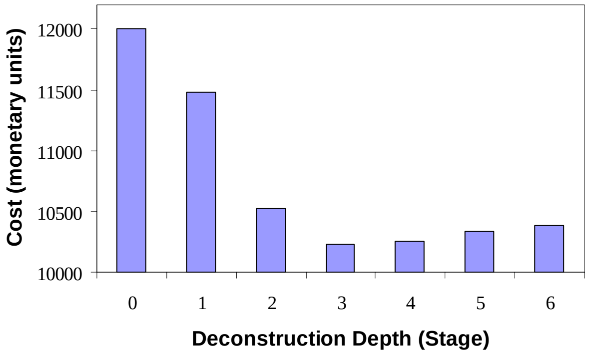

Fig.2 Total cost variation for various deconstruction depths.

Moreover, the environmental/regulative type (4) constraint is marginally satisfied. Given the fact that it is costly to proceed to a higher deconstruction stage, the optimal deconstruction depth is mainly defined from the 'mandatory' constraint. In addition, as the potential revenues from the under recycling deconstruction materials increase, the system moves to a higher deconstruction level.

Next, an interesting investigation appears to be exploring the sensitivity of the optimal solution as few of the cost parameters are altered. Specifically, we consider the cases that all cost parameters are increased or decreased at 20% percent. In the first case, the optimal deconstruction depth is the same with the initial obtained solution. In the latter case, the optimal deconstruction stage is a higher one ($i = 4$), in comparison to the one of the original solution, since it is more cost-effective to recover the constituent materials of the examined building. Finally, the sensitivity analysis can go through the desired deconstruction ratio e. More specifically, we examine values of e ranging from 0% to 100% with a step of 10%. As we move to higher percentages of e (that correspond to higher deconstruction stages) the total cost is an increasing function of e. For values of e larger than 60%, approximately, it is optimal to deconstruct fully the building and recover its materials, as the weight of the deconstruction products of the last stages is considerably higher than the products of the first stages.

6 Conclusions

Recovery of deconstruction and demolition materials has emerged as an environmentally and economically meaningful practice for the construction industry. The development of new approaches aiming at the selective deconstruction of buildings, instead of pulling them down, has been gaining increased attention. However, only few methodological approaches for planning, scheduling and optimizing the C&D waste management are available. In this context, we proposed a novel MILP integrated model for supporting the decision-making from the point of optimally determining the deconstruction depth of an EOL building, till the transportation of the deconstruction and demolition waste to recyclers and landfills for recovery and waste minimization purposes. The proposed methodological approach contributes towards a comprehensive and integrated construction and demolition waste management strategy. Moreover, we provided an illustrative case study demonstrating the applicability of the proposed model, through which managerial insights regarding the optimal solution are obtained. Future research directions could include the expansion of the provided model by adding additional meaningful financial, environmental, regulatory and technological constraints. Finally, problems that appear to have great research merit, include problems studying the stochasticity of the considered parameters (e.g. fluctuated market values of recycled materials), and problems aiming for the comprehensive optimization of C&D waste management for multiple types and number of construction/ demolition sites.

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References:

[1] European Commission, *Management of Construction and Demolition Waste*, Directorate - General Environment, ENV.E.3 Waste Management, 2000.

[2] Kralj, D., and Markic, M., Processes Innovation and Sustainable Development, *WSEAS Transactions on Environment and Development*, Vol.4, No.2, 2008, pp. 99-108.

[3] Kralj, D., Recycling and Environmental Waste Management in Constructions, *WSEAS Transactions on Environment and Development*, Vol.4, No.5, 2008, pp. 389-398.

[4] Rogers, D.S., and Tibben-Lembke, R.S., *Going Backwards: Reverse Logistics Trends and Practices*, Reverse Logistics Executive Council, Pittsburgh, 1999.

[5] http://en.wikipedia.org/w/index.php?title=Special:Cite&page=Reverse_logistics&id=248975204, Wikipedia (last accessed on 10th November 2008).

[6] Thierry, M., Salomon, M., van Nunen, J.A.E.E., and van Wassenhove, L.N., Strategic Issues in Product Recovery Management, *California Management Review*, Vol.37, No.2, 1995, pp. 114-135.

[7] de Brito, M.P., *Managing Reverse Logistics or Reversing Logistics Management?*, PhD Thesis, Erasmus University Rotterdam, 2004.

[8] Georgiadis, P., Besiou, M., Vlachos, D., and Iakovou, E., A Comprehensive Methodological Framework for Sustainable Supply Chains, *IASME Transactions*, Vol.2, No.4, 2005, pp. 569-574.

[9] Georgiadis, P., Iakovou, E., Vlachos, D., and Besiou, M., Ecological Motivation and Sustainability for Reverse Logistics: A Systems Dynamics Modeling Approach, *WSEAS Transactions on Systems*, Vol.1, No.5, 2006, pp. 48-55.

[10] Kralj, D., and Markic, M., Sustainable Development Strategy and Product Responsibility, *WSEAS Transactions on Environment and Development*, Vol.4, No.2, 2008, pp. 109-118.

[11] Spengler, T., Püchert, H., Penkuhn, T., and Rentz, O., Environmental Integrated Production and Recycling Management. *European Journal of Operational Research*, Vol.97, 1997, pp. 308-326.

[12] Peng, C.L., Scorpio, D.E., and Kibert, C.J., Strategies for Successful Construction and Demolition Waste Recycling *Operations, Construction Management and Economics*, Vol.15, 1997, pp. 49-58.

[13] Barros, A.I., Dekker, R., and Scholten, V., A Two-Level Network for Recycling Sand: A Case Study, *European Journal of Operational Research*, Vol.110, 1998, pp. 199-214.

[14] Wang, J.Y., Touran, A., Christoforou, C., and Fadlalla, H., A Systems Analysis Tool for Construction and Demolition Wastes Management, *Waste Management*, Vol.24, 2004, pp. 989-997.

[15] Duran, X., Lenihan, H., and O'Regan, B., A Model for Assessing the Economic Viability of Construction and Demolition Waste Recycling - The Case of Ireland, *Resources, Conservation & Recycling*, Vol.46, 2006, pp. 302-320.

[16] Hao, J.L., Hills, M.J., and Huang, T., A Simulation Model Using System Dynamic Method for Construction and Demolition Waste Management in Hong Kong, *Construction Innovation: Information, Process, Management*, Vol.7, No.1, 2007, pp. 7-21.

[17] Hao, J.L., Hills, M.J., and Shen, L.Y., Managing Construction Waste On-Site through System Dynamics Modeling: The Case of Hong Kong, *Engineering, Construction and Architectural Management*, Vol.15, No.2, 2008, pp. 103-113.

[18] Roussat, N., Dujet, C, and Mehu, J., Choosing a Sustainable Demolition Waste Management Strategy Using Multicriteria Decision Analysis, *Waste Management*, to be published: doi:10.1016/j.wasman.2008.04.010.

[19] Figueira, J., Mousseau, V., and Roy, B., ELECTRE METHODS, in: Figueira, J., Greco, S., Ehrgott, M. (Eds.), Multiple Criteria Analysis – State of the Art Surveys, *International Series in Operations Research and Management Sciences*, Vol.78, 2005, pp. 134-164.

[20] Kralj, D., Ogrin, U., and Krope, J., Environment Protection Culture as a Part of Innovating of Management in Construction Industry, *WSEAS Transactions on Environment and Development*, Vol.1, No.2, 2005, pp. 234-241.

[21] Kralj, D., Ogrin, U., and Krope, J., Innovating of Management in Construction Industry as Integral Part of Environment Protection, in: *Proceedings of the 1st WSEAS International Conference on Environment, Ecosystems and Development*, Venice, 2-4/11/2005, pp. 72-77.

[22] Yang, S.H., Lin, Z.S., and Huang-Fu, M., Research on the Environmental Burden Evaluation of Building Construction - Comparing with Different Construction Methods, *WSEAS Transactions on Environment and Development*, Vol.4, No.8, 2008, pp. 629-643.

[23] Kralj, D., and Markic, M., Building Materials Reuse and Recycle, *WSEAS Transactions on Environment and Development*, Vol.4, No.5, 2008, pp. 409-418.

[24] Kibert, C., and Languell, L., *Implementing Deconstruction in Florida: Materials Reuse Issues, Disassembly Techniques, Economics and Policy*, Florida Center for Solid and Hazardous Waste Management, 2000.

[25] Symonds Group, *Construction and Demolition Waste Practices and their Economic Impacts*, Final Report, 1999.

[26] http://www.cowam-project.org/cms/Content/download/Germany_CD_Waste.pdf, COWAM Project - Construction and Demolition Waste

Management in Germany, 2006, (last accessed on 10th November 2008).

[27] http://www.cowam-project.org/cms/Content/download/Uk_CD_Waste.pdf, COWAM Project - Construction and Demolition Waste Management in United Kingdom, 2006, (last accessed on 10th November 2008).

[28] http://www.cowam-project.org/cms/Content/download/Sweden_CD_Waste.pdf, COWAM Project - Construction and Demolition Waste Management in Sweden, 2006, (last accessed on 10th November 2008).

[29] http://www.mst.dk/udgiv/Publications/2004/87-7614-249-3/pdf/87-7614-250-7.PDF#, DEPA - Waste Strategy 2005-08, 2004, (last accessed on 10th November 2008).

[30] Montecinos, W., and Holda, A., *Construction and Demolition Waste Management in Denmark - Example of Brick, Wood, Treated Wood and PVC Management*, Project Study, 2006.

[31] Alaejos, P., Sanchez, M., Dapena, E., Vazquez, E., Barra, M., Eteberria, M., Mari, A., Agullo, L., Martinez, F., Fonteboa, B., Polanco, A., Franciso,G., Aleza, F., Parra, J.L., and Burón, M., *Draft of Spanish Regulations for the Use of Recycled Aggregate in the Production of Structural Concrete, Task Force of the Standing Committee of Concrete* , Project Study, 2006.

[32] Sousa, H., Sousa-Coutinho, J., Faria, J., Figueiredo, F., and Sousa, R. *Construction and Demolition Waste in the Region of Porto - Portugal: Management and Survey*, Project Study, 2005.

[33] Clark, C., Jambeck, J., and Townsend, T., A Review of Construction and Demolition Debris Regulations in the United States, *Critical Reviews in Environmental Science and Technology*, Vol.36, 2006, pp. 141-186.

[34] http://www.env.go.jp/en/laws/recycle/09.pdf, Japan for Sustainability - Construction Material Recycling Law, 2006, (last accessed on 10th November 2008).

[35] http://www2.kankyo.metro.tokyo.jp/kouhou/env/eng/environment08.html, Tokio Metropolitan Government - Environmental White Paper, 2006, (last accessed on 10th November 2008).

[36] Seemann, A., Schultmann, F., and Rentz, O., Cluster Analysis for the Recycling of Building Elements, in: *Proceedings of the R'02 6th World Congress on Integrated Resource Management*, Genva, 12-15/2/2002, pp. 31-46.

[37] Chini, A., and Bruening, S., Deconstruction and Materials Reuse in the United States, *International e-Journal of Construction, Special Issue article in: The Future of Sustainable Construction*, 2003.

[38] Crowther, P., Developing an Inclusive Model for Design for Deconstruction, *Deconstruction and Materials Reuse: Technology, Economic, and Policy*, CIB Publication 266, Wellington, New Zealand, 2001.

[39] http://www.epa.gov/epawaste/conserve/rrr/imr/cdm/index.htm, U.S. Environmental Protection Agency (last accessed on 23rd of September 2008).