Closed-loop oriented project management in construction

An approach for sustainable construction management

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Abstract

Up to now, the construction industry is mainly characterized by open-loop material systems. Considering that dumping capacities are limited, land for landfill is reduced and natural resources have to be preserved, it is obvious that closed-loop material systems have to be established. Following the maxims of sustainability, these closed-loop systems have to respect technical, ecological and economic principles. Although much effort has been undertaken to develop recycling techniques for construction materials in the past years, the construction and recycling industry, especially the housing sector, still suffers from a lack of innovation in terms of sustainability.

In this paper we show how the construction industry, as a major representative of the engineer-to-order industry, can make use of recovery concepts already widely spread in the manufacturing industry, e. g. reuse, refurbishing or recycling. Additionally, we reveal how advanced project management can be performed with respect to these recovery strategies by extending current project management approaches, which have mainly addressed time and cost efficient objectives in theory as well as in practice so far. In particular, we develop an approach for advanced construction management that integrates targets beyond time and cost to enable closed-loop material systems in the construction sector. By exemplarily showing how this approach can be applied to deconstruction processes we reveal how it contributes to sustainable, high performance buildings.

Keywords

Project management, construction industry, sustainable objectives, closed material loops, recycling

1 Introduction

Research about sustainability in construction has up to now mainly focused on design aspects and materials in buildings considering, e. g. their ability to efficiently use natural resources such as sun light and water, their potentials of avoiding harmful or hazardous emissions as well as their suitability for reuse. Considering the life cycle of a building it becomes obvious that the design of a building is important, but it solely concentrates on the first phase in the life span of a construction. Looking further, not only the design of a building has to meet criteria of sustainability, but also the phases of construction, use and deconstruction. Taking into account the rapid increase of the building stock this becomes even more obvious. In Europe for example, the major portion of the buildings has been erected during the last 5 decades. During this time the main purposes for construction were often rather practical than ecological ones. In particular, for buildings built shortly after World War II in Germany the aim was merely to provide dwellings for the population. Nowadays, many of these residential buildings are vacant[1] and face either a replacement with new ones or a transition into high performance buildings. Thus, there is a need not only to foresee and plan the future of construction, but also to reflect on methods how to integrate the present building stock into sustainable construction concepts. Consequently, sustainable principles should be far more integrated into construction processes.

Up to now, the transition of the present building stock into high performance buildings is still characterized by open-loop material systems. Closed-loop systems with full materials recovery do not exist at present, partially due to a lack of technology, partially due to poor product design, partially due to thermodynamic reasons and partially due to the lack of adequate economic incentives (Kibert and Schultmann, 2005). Taking into account that dumping capacities are limited, land for landfill is reduced and natural resources, e. g. wood, metal and natural gravel, have to be preserved, it becomes obvious that closed-loop material systems have to be established. Thus, one aim of advanced construction processes should be to keep as much construction materials in closed-loops as possible, respecting technical, ecological and economic principles. The material accumulated at the end-of-life of buildings can be brought back into the material flow in the same or different condition and functionality after recycling or recovery to serve as input for new high performance houses.

Even though, much effort has been undertaken to develop recycling techniques for construction materials in the past years, the construction and recycling industry still suffers from a lack of innovation in terms of closed-loop systems. In other industries closed-loop material systems are triggered by product recovery and reuse approaches, like refurbishment, recycling or cannibalization.

In this paper we first reflect on how these approaches can be adapted for processes in the construction industry as a major representative of the engineer-to-order sector. We particularly concentrate on the preservation of natural resources and the establishment of closed-loop material systems in the construction industry. Additionally, we reveal, how advanced project management can be performed with respect to recovery strategies. For this purpose we extend current project management approaches, which have mainly addressed time and cost efficient objectives in theory as well as in practice so far. This results in a sophisticated approach for advanced construction management that integrates targets beyond time and cost.

2 Closed-loop material flows in the construction industry

Efforts to closed-loop material flows in the construction industry have mainly focused on the recycling of waste material from underground engineering. In this sector, recycling strategies have already been implemented successfully in many countries. However, problems occur with the handling of waste material from the building construction sector resulting from deconstruction, modification or renovation of buildings. These problems mainly arise because of the long time-lag between the beginning (construction) and the end (deconstruction) of the life cycle of the buildings. Moreover, the uncertainty about the composition of buildings at the end of their life hampers a proper recycling (Schultmann, 2003c). Rarely any concept exists for the circuitry of these material flows, especially as building waste usually consists of a heterogeneous mixture of different, partly contaminated materials which hampers a high quality recovery of the material (Schultmann, 2003a).

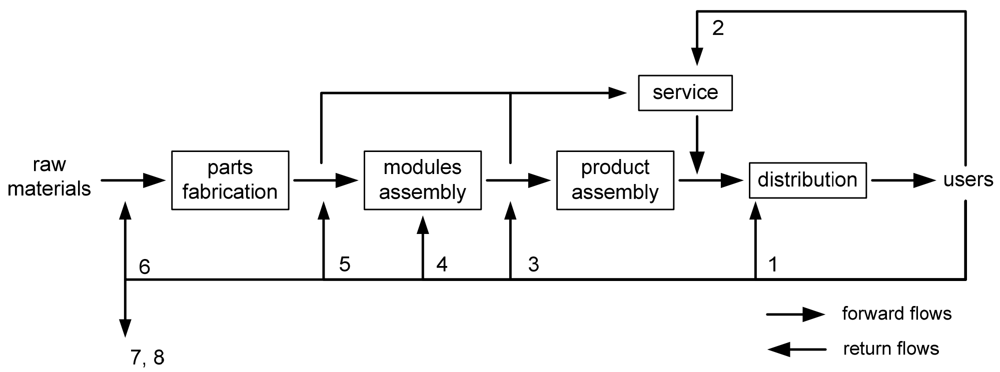
As resources and dumping capacities are limited, as well as the production of building material consumes a lot of energy and produces emissions and hazardous substances the aim of sustainable construction should be to strive for closed-loop material flows, i. e. recover deconstructed material (Thormark, 2001). To encounter this situation concepts and techniques are necessary which enable the circuitry of building material and building waste throughout the life cycle of a building. Following the principles of construction ecology (cf. Kibert et al., 2002), an approach for building materials recovery has to be developed which considers the renovation, modification as well as deconstruction processes or buildings. This especially includes techniques and strategies which explicitly consider the deconstruction process of buildings where contaminated material as well as different valuable materials classes can be separated from each other. This can be achieved with a selective deconstruction of buildings by a partly or complete dismantling of a building in its modules and parts, which can be reused, recovered or disposed. While the amount of recoverable material is determined by the design of the building, the amount and quality of the recoverable material can be influenced by the technical organization of the deconstruction process (Schultmann, 2003b). In comparison to the construction of a building the deconstruction process is characterized by a reverse process structure; i. e. whereas the construction of a building represents a convergent process where a number of different prefabricated materials, parts and modules are assembled on-site, the deconstruction of a building is a divergent process where, generally, a number of material, parts and modules simultaneously emerge from a building (Schultmann, 2001). To each of these components and materials a recovery option can be assigned, unless it is disposed.

Concepts for the recovery of products and material have already been studied extensively for the manufacturing industry, e. g. the automobile industry (see for example Schultmann et al., 2006). However, as already revealed, up to now the building construction sector is not using its full potentials of product and material recovery to build up closed material loops. Hence, in the following section it is demonstrated how recovery strategies already wide spread in the manufacturing industry can be adapted to the construction sector in order to enable an environmental friendly deconstruction as well as a proper management of deconstructed components and materials.

2.1 Recovery strategies in the manufacturing industry

Recovery strategies for material or components are the focus of product recovery management (PRM). PRM aims to recover as much of the economic as well as ecological value of a product and its components as possible and thereby to reduce the amount of waste at the end of a product’s life cycle as well as to avoid or at least to reduce the rate of the depletion of resources (Thierry, 1995; Lambert, 2005). Hereby, the need for PRM might be imposed by governmental actions or by customers, expecting companies to operate environment-friendly (Ofori, 1992).

The handling of used material can be differentiated into the direct reuse, product recovery management and waste management. To enable closed material loops, direct reuse and product recovery strategies have to be followed, as depicted in figure 1.



Waste Management

7: Incineration

8: Landfilling

Product Recovery Management

5: Cannibalization

6: Recycling

2: Repairing

3: Refurbishing

4: Remanufacturing

Direct Reuse

1: Direct reuse/resale

Fig. 1 Handling of used material in supply chains (Thierry, 1995)

According to figure 1, the following options for product recovery management exist depending on the degree of disassembly:

- repairing
- refurbishing
- remanufacturing
- cannibalization
- recycling

The purpose of *repairing* is to return used products to working order by fixing and/or replacing broken parts, whereas the quality is usually less than the quality of new products. Hence, the repair of products or components requires only limited assembly and reassembly and can be easily performed at the customer's location or at manufacturer-controlled repair centers (Thierry, 1995).

Refurbishing raises the quality of used products up to a specified level by disassembling the products into modules, inspecting them and, if necessary, replacing them and reassembling inspected modules into refurbished products. This can be combined with technology upgrading replacing outdated modules, whereas the quality standards for refurbished products are usually less rigorous than quality requirements for new. In comparison to refurbishing, the objective of *remanufacturing* is to bring used products up to specified quality standards which are as rigorous as those for new products. Therefore, products are completely disassembly and all modules and parts are inspected. Worn-out or outdated parts and modules are replaced with new ones and other parts are resold cheaper than new parts but with the same quality and same warranty (Thierry, 1995).

With the recovery strategy of *cannibalization* the used products are selectively disassembled and potentially reusable parts are inspected and used in repair, refurbishing, and remanufacturing of other products and components (Thierry, 1995).

Obviously, refurbishing, repair, remanufacturing, and cannibalization are based on the product level and its main objective is to keep the identity and functionality of used products and their components as much as possible. However, recycling is processed on the material level, while the identity and functionality of the product and/or its components is lost. Hence, recycling begins where used products and components are disassembled into parts and these parts are separated into material categories. The recycled materials are thereafter reused in the production of new parts (Thierry, 1995).

Although different alternatives exist for the handling of used products at the end of their lifetime, the selection of a product recovery option depends on the technical feasibility, the supply with suitable used products, the demand for recovered products or components and materials as well as on the economic and environmental costs and benefits (Thierry, 1995).

2.2 Recovery strategies in the construction industry

Compared with the manufacturing industry, recovery strategies in the construction industry bear much more difficulties, since buildings have to be distinguished from other products by their individuality, i. e. their uniqueness and their wide variety of constituent parts.

2.2.1 Classification of construction materials and construction waste

In comparison to the recovery of products in the manufacturing industry the recovery of building material and components promises an even higher potential to protect the environment. This refers to energy savings by reducing the production of primary materials, the efficient use of virgin materials with a restricted supply as well as to the reduced use of landfill space (Lambert, 2005; Guy, 2002).

Classifying construction materials, it has to be differentiated between constituent parts and components of buildings used for the construction and construction waste. According to Kibert, five general component categories of houses can be distinguished (cf. Kibert et al., 2002):

1. manufactured, site-installed commodity products, systems, and components with little or no site processing (e. g. boilers, valves, electrical transformers, doors, windows, lighting, bricks),

2. engineered, off-site fabricated, site-assembled components (e. g. structural steel, precast concrete elements, glulam beams, engineered wood products, wood or metal trusses),
3. off-site processed, site-finished products (cast-in-place concrete, asphalt, aggregates, soil),
4. manufactured, site-processed products (dimensional lumber, drywall, plywood, electrical wiring, insulation, metal and plastic piping, ductwork),
5. manufactured, site-installed, low mass products (paints, sealers, varnishes, glues, mastics).

At the end of the life cycle of a building, these components represent potentially recoverable materials and parts which are transformed into waste.

Apart from the deconstruction, this waste, sometimes named Construction and Demolition Waste (C&D-Waste) (European Commission, 1999), also arises during the erection of buildings. These materials can be classified according to the European Waste Catalogue (EWC) (European Comission, 2002). The EWC contains a number of different waste descriptions, e. g. for wastes from inorganic chemical processes, waste from the photographic industry as well construction and demolition wastes (including excavated soil from contaminated sites).

Table 1 shows an extract of the classification of C&D-Waste from the construction industry with the EWC-Code 17 which lists contaminated as well as non-contaminated materials.

Tab. 1 Construction and demolition wastes according to the EWC

EWC Code	Description
17 01	**concrete, bricks, tiles and ceramics**
17 01 01	concrete
17 01 02	bricks
17 01 03	tiles and ceramics
17 01 06	mixtures of, or separate fractions of concrete, bricks, tiles and ceramics containing dangerous substances
17 01 07	mixtures of, or separate fractions of concrete, bricks, tiles and ceramics other than those mentioned in 17 01 06
17 02	**wood, glass and plastic**
17 02 01	wood
17 02 02	glass
17 02 03	plastic
17 02 04	glass, plastic and wood containing or contaminated with dangerous substances
17 03	**bituminous mixtures, coal tar and tarred products**
17 03 01	bituminous mixtures containing coal tar
17 03 02	bituminous mixtures other than those mentioned in 17 03 01
17 03 03	coal tar and tarred products
17 04	**metals (including their alloys)**
17 04 01	copper, bronze, brass
17 04 02	aluminium
17 04 03	lead
17 04 04	zinc
17 04 05	iron and steel
17 04 06	tin
17 04 07	mixed metals
…	…

2.2.2 Deconstruction and product recovery

After classifying construction materials and construction waste, the focus is shifted to the applicability of product recovery strategies known from the manufacturing industry (cf. section 2.1) and their adaptation to the construction industry.

Generally, the deconstruction process of a house consists of several phases[2]. In each phase of the process different components of the building are deconstructed, either by partly or complete dismantling or by demolition. Each of the components itself consists of different parts and materials. The adaptation of the material flows and recovery strategies from manufacturing industry (as depicted in figure 1) to the construction industry is illustrated in figure 2. Overall, this depicts an open-loop system. However, it can be divided into closed-loop subsystems.

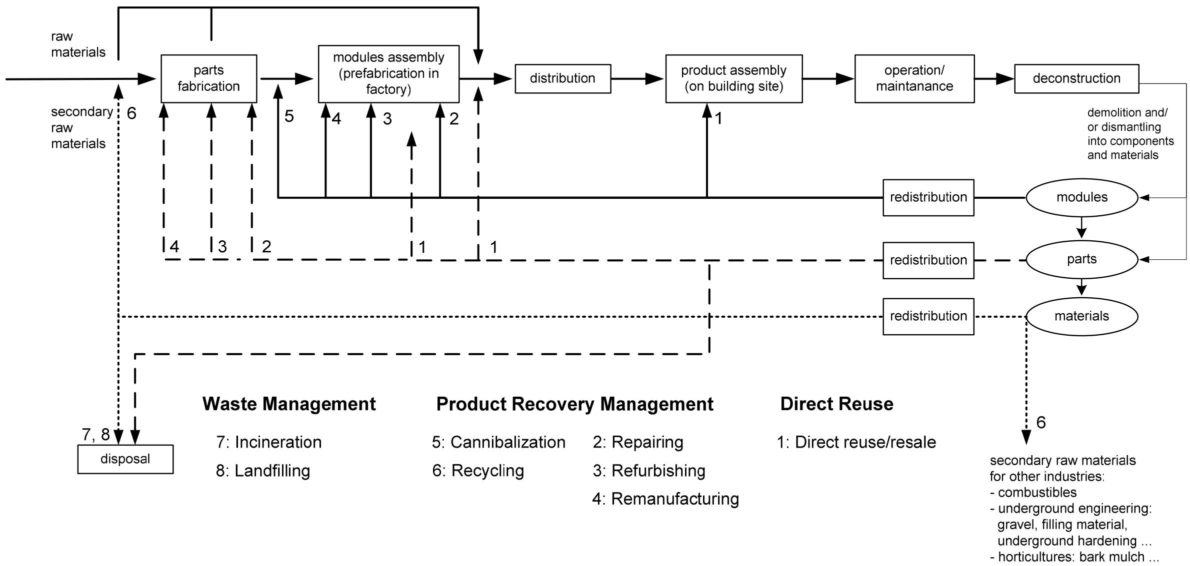


Fig. 2 Material recovery strategies in the building construction sector

In the closed-loop subsystem of component and material flows direct reuse (1) appears when modules are redistributed into the product assembly and are site-installed or site-assembled again, e. g. structural steel, wood or metal trusses. Additionally, direct reuse can be processed with parts that are either redistributed into the product assembly (e. g. bricks) to become a direct part of the building or into the modules assembly to become part of a module (e. g. doors, windows).

Repairing (2), refurbishing (3), and remanufacturing (4) occur on the modules level, when modules are redistributed to the modules assembly, where they are either repaired, refurbished or remanufactured, e. g. boilers, valves, windows. Analogous to the modules level, parts (e. g. metal and plastic, piping, ductwork) can be repaired (2), refurbished (3), or remanufactured (4) in the parts fabrication.

Cannibalization (5) can only be processed on the modules level and not on the parts level as parts are assumed to be the smallest possible unit of equipment of a house.

Recycling (6) is solely possible on the materials level. Hence, modules have to be dismantled into parts and parts have to be dismantled into materials before recycling can be processed. Afterwards, the recycled materials can be used as secondary raw materials in production and manufacturing processes of new parts. Additionally, interfaces exist to other industries, where the recycled material is not used in its original purpose, e. g. as secondary combustibles. Parts and materials (including often contaminated low mass products, e. g. paints, sealers or varnishes), which are neither recovered in the closed-loop system nor used in other industries, leave the material flow and are disposed either by incineration (7) or by land fill (8), whereas modules are usually disassembled into parts and materials in order to reduce disposal costs.

However, the recovery and recycling will not be possible, if the building is completely demolished or only possible after a time consuming selection and separation of valuable material from rubble. In order to gain modules, parts and components in a high degree of diversification, selective deconstruction can help to raise the quality of materials under the focus of sustainability. The sustainability of a construction or a deconstruction project, respectively, can be measured with a figure, called *reuse and recovery potential (RRP).* The RRP describes the portion between the whole mass of a building and the mass of components and parts which can be reused without pre-treatment as well as recovered with the strategies repair, refurbishing, remanufacturing, and recycling. In section 3 it is shown how the RRP can be integrated in a planning approach for sustainable construction.

2.2.3 Limitations of product recovery in the construction industry

The implementation of reverse flows in the construction industry as depicted in figure 2 offers promising opportunities and positive environmental impacts of advanced and sustainable construction planning. However, its realization is still subject to several ecological as well as economic restrictions.

Ecological impacts can both be positive or negative and vary considerably with the type of the recovery process and the type of material chosen. Benefits result among others from saved energy in the production process of new input materials and less environmental pollution. Negative impacts include additional energy consumption as well as environmental burdens. As an example, emissions to air, water and soil can be traced back to deconstruction processes, to transports of components and materials from the place of material and waste accumulation to the recovery facilities as well as to recovery processes itself. For an evaluation of the environmental impacts caused by industrial processes it is referred to the well known approaches from Life Cycle Assessment (LCA) and Eco Balancing, especially with respect to energy consumption during recycling and transport (Brandon and Lombardi, 2005; Thormark, 2001). Nevertheless, from the ecological point of view, the reuse and recovery of building components and materials is “advisable” provided that it results in a positive eco balance by not increasing the gross sum of energy use (energy saved by using recovered modules, parts and material compared to producing it and energy used to transport and recover used components).

In addition to the negative ecological impacts of deconstruction projects, economic objectives might also hamper the realization of a sustainable deconstruction and recovery of components and materials. To decide, whether a recovery of material, which goes along with costs for selective dismantling, transport of components and material as well as costs for the recovery itself, is economically justifiable these factors have to be known in advance and become part of the project planning (Schultmann, 2005).

With respect to a necessity to shift the focus to sustainable production and construction processes triggered by environmental constraints or legal instruments, but simultaneously following organizational objectives, such as budgetary and temporal constraints, an approach for sophisticated construction project management is developed in the next section considering ecological as well as economic aspects. This is done by integrating recovery options for different materials and components into planning procedures in the construction industry. The approach pays respect to the fact that the supply with end-of-life modules and parts of buildings is a necessary condition to take advantage of the recovery management options already described. In order to follow the purpose of deconstruction, i. e. to recover as much components, modules and materials of a building for reuse or recycling as possible, companies involved in the deconstruction process have to become suppliers of components and materials (Guy, 2002). Only with the supply of used parts and modules it is possible to benefit from the high potential of further resource preservation as well as emission and waste avoidance.

3 Construction project scheduling in closed-loop environments

Projects are characterized by a defined objective, uniqueness, complexity, temporally existence, especially assigned resources as well as by a usually high degree of uncertainty.

The scheduling of these projects aims at the development of timetables defining in which periods project activities shall be processed (Klein, 1999). Project scheduling in practice, especially in the construction industry, is very often conducted with simple techniques such as Gantt charts, the critical path method (CPM) as well the Programme Evaluation and Review Technique (PERT) and network diagrams when activity durations and precedence relations are known and deterministic. These scheduling procedures have in common that they assume an unlimited availability of personnel and resources over the planning horizon, i. e. the analysis is based on the time requirements of the activities neglecting the resource demand. However, problems arise in most of the real-world projects when activities require resources that are only available in a limited amount and the demands of parallel activities cannot fully be satisfied.

Therefore, these methods can merely be used to calculate feasible time windows for project activities within their release and due date (Schultmann, 1998). Additionally, they do not allow an integration of sustainable aspects into the project management. However, the objective of sustainable project scheduling should be to enable the deconstruction of a building such that reusing or recovering components and materials up to a high degree is possible.

Quantitative methods for project scheduling generally compensate the lack of appropriate time and capacity planning in project planning approaches. Moreover, the integration of environmental aspects into these methods is possible (Schultmann, 2002b). They can support the project organization in a way that a large number of modules and parts are supplied in a quality which facilitates a further recovery and, hence, help to reduce the negative environmental impacts of the construction industry. However, these methods have not yet been paid much attention to in the construction industry. Hence, in the following a sophisticated quantitative planning approach for sustainable construction project scheduling is developed.

Basis for the quantitative model is an activity-on-node network of a construction project. For our approach we chose the example of a deconstruction project, depicted in figure 3. It shows the activity-on-node network of a house with two floors and a basement. The nodes represent the construction, respectively deconstruction activities j (also known as jobs) of the project and the arcs represent the technological order of the activities, also referred to as precedence relations. Additionally, the network contains a unique source “project start” and a unique sink “project end”. For each activity a duration (e. g. 7 days) as well as a resource consumption (e. g. 2 workers, 2 pneumatic hammers) is assigned, whereas the duration and the resource consumption of the source and sink activity are zero.

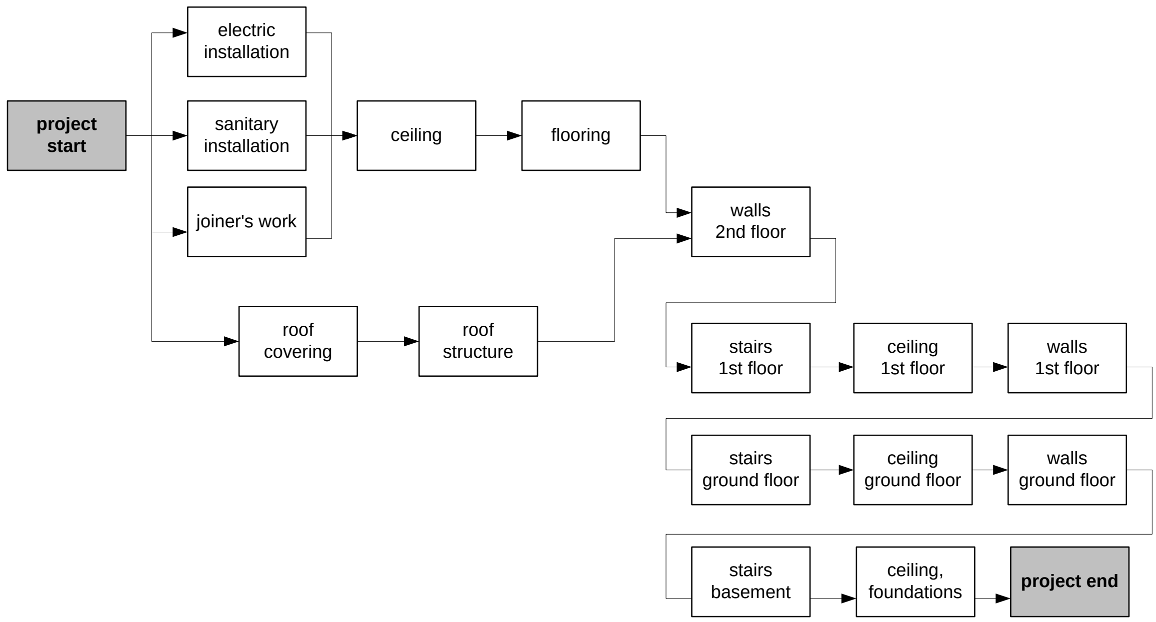


Fig. 3 Activity-on-node network of a deconstruction project (simplified)[3]

A mixed-integer formulation for project planning with the decision variable s_{jt} can be depicted as follows:

$$\text{MIN} \quad \sum_{t=1}^{T} t \cdot s_{Jt} \tag{1}$$

subject to

$$\sum_{t=1}^{T} s_{jt} = 1 \qquad j = 1,\ldots,J \tag{2}$$

$$\sum_{t=1}^{T} t \cdot s_{it} \le \sum_{t=1}^{T} (t - d_j) \cdot s_{jt} \qquad j = 1,\ldots,J\,;\ i \in P_j \tag{3}$$

$$\sum_{j=1}^{J} q_{jr} \sum_{z=t}^{t+d_j-1} s_{jz} \le Q_r \qquad r = 1,\ldots,R\,;\ t = 1,\ldots,T \tag{4}$$

$$s_{jt} \in \{0,1\} \qquad j = 1,\ldots,J\,;\ t = 1,\ldots,T \tag{5}$$

with

t time period, $t = 1,\ldots,T$

j deconstruction activity of a project, $j = 1,\ldots,J$

d_j duration of deconstruction activity j of a project

r renewable resource type r, $r = 1,\ldots,R$

q_{jr} resource consumption of activity j of the renewable resource type r

Q_r resource availability of the renewable resource type r

s_{jt} decision variable

$$s_{jt} \begin{cases} 1, & \text{if activity j ends in period t} \\ 0, & \text{else} \end{cases}$$

The objective function (1) minimizes the project finishing time with T being the end of the planning horizon. Constraints (2) ensure that every job is processed once. Constraints (3) are precedence constraints of jobs with P_j denoting the set of immediate predecessors of job j. The duration of job j is represented by d_j. Constraints (4) limit (for each resource type) the resource demand of the jobs which are currently processed in order not to exceed the constant resource availability per period Q_r with q_{jr} defining the demand of the renewable resource r. Finally, constraints (5) define the decision variable as binary.

The objectives of common project management models are usually time and cost oriented (cf. objective function (1)). However, with the RRP introduced in section 2 it is possible to define and operationalize some sustainable objectives. For instance, the maximization of the quota of recoverable components and materials of a building, e. g. claimed by legal instances. By doing so, each job has to be assigned an individual RRP ε_j which is defined as follows:

$$\varepsilon_j = \frac{\sum_{k \in K_r} a_{jc}}{\sum_{k \in K} a_{jc}} \tag{6}$$

with

ε_j reuse and recovery potential of activity j

a_{jc} mass of material c deconstructed by activity j

K_r number of materials for further reuse or recovery;

$K_r = \{c \in K \mid c \text{ to be reused or recovered}\}, K_r \subseteq K$

K number of all materials

Usually, an activity can be processed in several alternatives[4], which are modeled as mode m $(m = 1, \ldots, M_j)$. Hence, the decision variable s_{jt} hast to be altered into s_{jmt} defining whether a job j in mode m ends in a specified period or not, whereas the source and sink activity can only be processed in one mode. Each alternative represents a deconstruction technique determining the resource consumption and duration of the activity in the defined mode m. Additionally, each alternative realizes a different RRP ε_{jm} (Schultmann, 2005).

With the introduced RRP the objective function (1) of the project management formulation is replaced with:[5]

$$\text{MAX} \quad \varepsilon = \frac{\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{k \in K_r} a_{jc}}{\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{k \in K} a_{jc}} \tag{7}$$

Whereas objective function (1) guaranties a *time* optimal solution by minimizing the project finishing time, objective function (7) maximizes the recovered amount of *material* in a deconstruction project by assigning finishing times to jobs in a selected mode ensuring that precedence (equation (3)) and resource constraints (equation (4)) are not violated. However, simply maximizing the RRP of the project without regarding time and cost oriented objectives might result in economic unfavorable solutions. Hence, both objectives functions should be considered and, if possible, optimized simultaneously. However, simultaneous optimization of objective functions (1) and (7) might cause problems because of possible conflicts between the objectives. These conflicts can be solved by applying approaches from multi objective decision making like goal programming or scoring models by assigning weights to different objectives.

Following the approach of scoring models, the objective function (1) first has to be transformed into a maximization problem (8):

$$\text{MAX} \quad -\sum_{t=1}^{T} t \cdot s_{Jt} \tag{8}$$

The multi-objective function maximizing the RRP as well as minimizing the project finishing time can now be described as follows:[6]

$$\text{MAX} \quad w_1 \cdot \left(-\sum_{t=1}^{T} t \cdot s_{Jt} \right) + (1 - w_1) \cdot \frac{\sum_{j=1}^{J} \sum_{m=1}^{M} \sum_{k \in K_r} a_{jc}}{\sum_{j=1}^{J} \sum_{m=1}^{M} \sum_{k \in K} a_{jc}} \qquad 0 \le w \le 1 \qquad (9)$$

The weight assigned to objective function (1) is declared as w_1. The weight for objective function (7) results in $1 - w_1$. The weights of the objectives reflect the importance with that the objective is pursued from the standpoint of the decision maker. Therefore, the responsibility for the appropriateness of the assigned weights remains in the “hands” of the decision maker or decision making units.

4 Conclusion and outlook

In this paper we have highlighted how recovery strategies for used products that are well established in the manufacturing industry can be adapted to the construction industry. Additionally, we developed an approach for construction project management that considers economic as well as ecological aspects. Bearing in mind that, up to now, sustainable aspects in construction project management are still neglected, we introduced a model for project planning which allows scheduling a project in order to gain best possible recovery quotas under consideration of time objectives. Hence, the optimization approach introduced allows moving a step towards closed-loop material flows in the construction industry.

Nevertheless, our model only covers parts of the sustainable requirements made by different stakeholders of the construction industry, e. g. the government, residents, interest groups for environmental preservation as well as the general public. Thus, future work will address the definition of sustainable objects in dependency on different stakeholders of constructions projects. This might include the implementation of pollution as well as of noise regulations in our model.

Endnotes

[1] Mainly because of the demographic development as well as the migration of people from the cities to the outskirts of metropolises.

[2] For a collection of approaches to model the deconstruction process of buildings see (Schultmann, 1998).

[3] With variations taken from (Schultmann, 2002a).

[4] For instance, the deconstruction of a wall can be performed either by using pneumatic hammers, a grabbing bucket or by demolishing it (Schultmann, 2002a).

[5] Note, that also the constraints (2) – (5) have to be amended to be valid for the multi mode case. For an example see (Schultmann, 2001).

[6] Mathematically it has to be respected that the objective function remains so-called regular in order to find optimal solutions. This is subject to our current research.

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