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Efficient waste management in construction logistics: a refurbishment case study

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Abstract Large-scaled construction projects with their complex logistical processes of transport, handling and storage material to site, on site and from site bear significant environmental impacts. Such impacts include use of land, production of waste and emissions. In this paper, we investigate—by using a case study approach—how a well-planed implemented material management can affect efficiency in construction logistics focusing on logistics of disposal. The motivation behind this research is to examine the ecological and economic impact of construction logistics on waste management on site, when construction logistics is planned and determined in the early planning phase of a refurbishment project. We find that the implementation of a waste management plan can reduce environmental impacts, specifically increasing the efficiency of logistics of disposal by approximately 9 %, but it is associated with higher costs. The findings gained from this single case study research lead to case-study-specific recommendations for practitioners and regulators in the construction logistics area.

Keywords Construction logistics · Waste management · Efficiency · Case study research

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1 Introduction

Construction industry has always been struggling for keeping within the time and cost limits defined by the client, within the regulatory measures concerning waste avoidance and material recycling and within social requirements on a low-emission construction site. In practice, many problems occur during site operation which cause unnecessary costs as well as delays in the scheduled completion of a construction project, e.g., delay in delivery of vehicle movements, ineffective storage management, incorrect installation and handling of material on site or a lack of separation of construction and demolition waste [22]. In order to counteract such problems, operation processes that can be integrated in a reliable and transparent manner into any construction project have to be improved to become more efficient [9]. To achieve time- and cost-efficient operation processes, construction logistics is an appropriate tool that has become more and more significant recently for planning and operation activities [9]. This is especially true for inner-city construction projects with special requirements due to their complexity on costs, time and quality. For instance, size and location of the construction project, short construction time and tightly calculated construction costs require from the beginning a plan for construction logistics. Such a plan would ensure smooth supply of materials and recovery of waste in all project phases; would minimize dust, noise and CO_2

emissions caused by site activities; and would maximize the materials that can be reused and recycled profitably.

The alternative improvements of a well-planed construction logistics project in order to secure a smooth material and waste management on site can be very different. For instance, the increasing diversity of building materials and products as well as the recently reinforced used possibilities of industrial prefabrication of such materials and products require new and innovative approaches of construction logistics for an optimal coordination of material flow to site, on site and from site [9]. Similar considerations apply to logistics of disposal, especially for refurbishment, conversion and removal of buildings. Here, an adequate and optimal arrangement of a construction logistics plan is the key for an effective and efficient implementation and operation of material and waste flow on site during construction [9]. The implementation of logistic aspects can help to increase productivity in the construction phase for an efficient supply of materials as well as to ensure an optimal and efficient waste management according to the principles of a closed circle economy.

To the best of our knowledge, there is no research so far for measuring and understanding an implemented construction logistics plan with respect to its efficiency; this applies to construction logistics, in general, as well as, in particular, for the three fields of logistics: logistics of delivery, site logistics and logistics of disposal. This paper is meant as a contribution to fill partially this gap. It focuses on the analysis of waste management on site within the logistics of disposal. The motivation of the research is twofold: first, to introduce an approach for measuring the efficiency of waste management within logistics of disposal. Second, to examine how and why the implementation of an approach for logistics of disposal has an ecological and economic impact on waste management on site. Specifically, in this paper, we use a real case study to measure ecological and economic impact of implementing a waste management plan for the logistics of disposal on site. We also examine how construction logistics of disposal can decrease environmental impacts as well as increase efficiency. We find that the implementation of a waste management plan can reduce environmental impacts, specifically increasing the efficiency of logistics of disposal by approximately 9 %, but it is associated with higher costs.

The paper is organized as follows. First, we present a literature review on construction logistics, waste management and efficiency in waste management. Then, we introduce the case study methodology as the research method used in this paper. Later, we present the case study used that is analyzed concerning its efficiency for the implemented waste management project. The paper concludes with a summary, observations and future prospects for further research.

2 Literature review

2.1 Construction logistics

Construction logistics is the industry-specific characteristics of logistics in construction business and appears more and more often in academic research [6, 13, 23, 26]. The understanding of construction logistics of Schmidt [23] as the supply chain management of material represents the most differentiated approach; however, this approach is not being applied in practice despite growing knowledge of existing strategies, methods and practices for an integrated management of construction logistics material chains [13, 14, 23]. No common definition of construction logistics has been established until today both in the scientific literature and in practice [9]. Based on the definition of [22], construction logistics deals with the planning, operation, and control of materials, personnel and information flows from the point of view of an optimized logistics service regarding schedule, cost and quality while taking into account health and safety as well as environmental aspects. Concerning the different phases of the material flow, three areas have been established: (1) logistics of delivery, (2) site logistics and (3) logistics of disposal [2, 5, 9, 14, 29]. These three areas control the material procurement, the transportation of material to and on site, the provision of materials as well as the recovery and disposal of residual materials on site and from site [2].

2.2 Waste management in construction logistics

The goal of material management within construction logistics is to determine for each resource the best possible supply process, so that the material is in a timely manner, in the right quantity and quality available for every contractor on site. The same applies to waste management within the logistics of disposal. Here, construction logistics must ensure that the disposal of waste and the return of the storage equipment and the residual material are done in a timely manner maximizing the quantity and quality of the materials that can be reused without obstructing the construction process [14]. It must be ensured that already in the early planning stage, the design and implementation of a waste management approach for a construction project is confirmed and that the client together with his planer and main contractors raise awareness of logistics of disposal. The logistics of disposal deals with the construction and demolition waste (CDW) from the source of its generation during construction until its sink at the disposal option [27]. The associated processes have to be linked together so that closed loop systems with recycling activities arise. The aim is to achieve both economic as well as ecological residual flow [27] by guarantying a smooth construction process and the efficient reuse and material recovery of CDW.

In reality, main- and/or subcontractors involved on site are responsible for an optimal and contractual disposal of CDW. They are obliged to prepare a separate waste management approach, to control the separation of material according to the individual waste groups and waste fractions and to organize the transport according to the regulatory measures. However, in practice, a waste management approach may not be implemented within the logistics of disposal. The results are increasing costs and environmental impacts [15, 16]. Small quantities of waste quickly grow to mountains of waste for which nobody wants to be held responsible for [13]. Within the logistics of disposal, well-planed and successfully implemented processes as well as a clear organizational and accountability structure that optimize unpopular logistic process and minimize total costs are missing. The following features characterize the disposal process [16]:

- High requirements for construction logistics due to structural tightness in the inner city
- High daily volume of waste caused by a short construction time
- Deadline pressure imposed by the owner to the contractor favoring supply of new materials compared to the recovery of waste that may increase the reuse of materials
- Professional and legal requirements affecting the collection and separation of CDW
- High-risk potential linked with improper waste disposal
- No integrated waste management system available within the construction industry so far
- Weak regulatory framework for monitoring the disposal of CDW during the construction process

Due to these characteristics of waste management on site, an alternative organizational structure is often chosen: the centralized waste management approach usually managed by an independent service provider. While in the decentralized approach, the disposal of waste during the operation phase remains in the responsibility of every individual contractor on site, and the centralized option sets up an interdisciplinary approach for waste management, in which the waste flow is centrally controlled and the contractors involved on site are connected contractual to a logistics service provider [15, 16]. He coordinates and supports the logistics-related duties of the involved contractors to the client. Usually the service provider plans and regulates to the contractors all conditions and procedures to achieve an optimal supply and disposal to the site as a representative of the client.

2.3 Measuring efficiency in waste management

Efficiency generally means that a given goal is achieved by minimizing the effort. Hence, an activity is more efficient than another if the same result is achieved with less effort [21]. Efficiency is defined using “productivity” since it refers to the ratio of production results (output) and one or more or all factors of production employed [10].

A concept where economy and ecology are equally valued is eco-efficiency. Eco-efficiency is the ratio of an economic and an ecological value and can be defined as resource-friendly business that brings both economic and environmental benefits [19]. Therefore, an eco-efficient company improves its working methods, replaces problematic materials, leads to clean technology and products and makes efforts for a more efficient use and recycling of resources [10]. This idea can be applied to the construction industry also, particularly concerning the efficient disposal of CDW on construction site: An eco-efficient logistics of disposal improves and subs problematic disposal processes, introduces clean technologies for waste management and recycling on site and makes efforts for a more efficient recovery of construction waste and materials from the site way back into the economic cycle.

The main objective of logistic activities within waste management on site concerning the disposal processes is their effective, but especially efficient design with respect to ecological, economic, social and technological goals. The ecological objective concentrates both on minimizing the use of resources including materials, soil, minerals or water and on minimizing environmental impacts such as emissions (including air pollution, emission of sulfur dioxide or the degradation of water quality and noise pollute) and the generation of waste for incineration and landfill [3, 18, 24]. The economic objective is it to minimize the construction logistics costs for waste management taking into consideration the complexity of the logistics of disposal as associated with the size of site and the construction time [3, 21, 27]. The social objective lies in minimizing the health impact and the noise and traffic nuisance of site and logistic activities [3]. The technological objective is it to minimize the damage caused by logistical processes, by at the same time maximizing the utilization of capacity building logistics processes, maximizing the performance level of construction logistics processes and maximizing the potential productivity of construction logistics processes [3].

In this paper, we focus our research on the study of the economic and environmental impacts of logistics of disposal on construction site. Therefore, we restrict our further consideration on how the economic and environmental objectives can be operationalized in terms of eco-efficiency.

In order to measure eco-efficiency, appropriate criteria and indicators have to be chosen. For this purpose, there are different approaches and criteria in scientific literature [11]. According to [19, 20], we suggest to use the amount of costs for the logistics of disposal and the amount of construction logistics services considering the achieved recycling rate in percentage by weight as indicators for measuring the efficiency of waste management on site. The cost of the logistics of disposal consists of the costs for providing services of logistics on site as well as the cost fees for each waste fraction that is collected and separated on site for further recovery and disposal. In order to compare the costs for the logistics of disposal for different construction sites, they must be put into perspective and in relation to performance capacity. We propose to take as reference the total amount of waste generated during the chosen observation period.

Generally, the assessment of construction logistics services depends on the quality of the disposed waste fractions at the place of origin and their subsequent removal on and from site to their disposal facilities. The service components of disposal time, reliability, texture and flexibility are formed [27]. These components, however, have to be extended to one important aspect: From the point of view of ecological issues, the main objective of an optimal and successful waste management approach on site is to provide an optimal material recycling approach for the actual amount of waste. Therefore, we form a key figure that takes this point into account: the "reuse and recycling rate." The rate considers the share of pre-sorted CDW which is directly recovered from construction site for reuse or material recycling in relation to the total amount of CDW.

Based on the previous observation, the implementation of a waste management plan can be considered and evaluated for any construction project from the viewpoint of eco-efficiency, both in relation to other construction projects and within one construction project, e.g., by assessing separately the success and productivity of logistics of disposal for the construction of supporting structure, finishing and tenant expansion.

3 Methodology

In this paper, we use case study methodology as our research method. In general, case study methodology is used to explain and explore a complex phenomenon of interests [12] and makes use of various quantitative and qualitative methods of data collection [8]. Case study research is excellent for theory building, for describing "best practices" in details and for providing a greater understanding of the data gathered [8]. It enables the researcher to answer "how" and "why" type of questions, while taking into consideration how a phenomenon is influenced by the context within which it is situated [1]. The methodology should be carefully planned in advance and should support systematic gathering of data required to address the research questions of interest [8]. A thorough literature review would exceed the extent of this paper; thus, we refer at this point to academic literature on case study methodology that is given, for instance, by [7, 12, 17, 28].

For our research, we use the definition of [17] who defines a case study as a method that "… typically uses multiple methods and tools for data collection from a number of entities by a direct observer in a single, natural setting that considers temporal and contextual aspects of the contemporary phenomenon under study, but without experimental controls or manipulations …."

Depending on the objectives, we can distinguish 3 groups of case study research: descriptive case studies purely describe a specific environment, exploratory case studies contribute to theory building and explanatory case studies verify/falsify a theory [7]. Furthermore, case studies examine either one special case (single case) or multiple cases (multi-case) [7].

Our paper presents an explorative single case study. The aim is to identify the factors that affect the successful implementation of waste management and its efficiency for a single construction project. Thus, we want to suggest a hypothesis on the influencing factors and internal conditions for a fruitful logistics of disposal on construction site. Therefore, we use Eisenhardt's [7] approach of building theory from case study research combined with the proposal of Baxter, Jack [1] on the methodology for qualitative case study research (see Fig. 1).

First of all, defining the research question is important in building theory from case study research. Here,

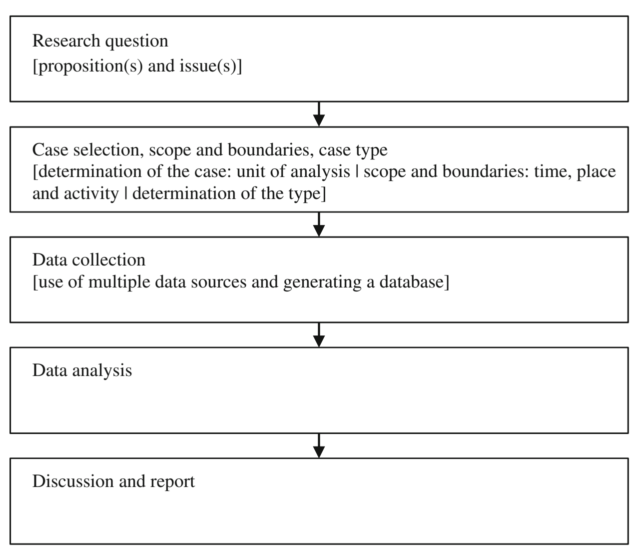

Fig. 1 Approach of exploratory case study research

propositions and the issue of the research are necessary elements as both lead to the development of a conceptual framework that guides the research. The next steps are the determination of the case itself, the consideration about the scope and boundaries, and the determination of the type of the case study. Furthermore, an important step in case study research is the use of multiple data sources and to organize data effectively in a database so that raw data are available for independent inspection. An important limitation of our research arose by using a single case study. The next step is the data analysis using different techniques for analysis as pattern matching, linking data to propositions, explanation building, time-series analysis, logic models or cross-case synthesis ([1] with reference to [28]). Subsequently, the results from data analysis have to be prepared and questioned, in order to shape hypotheses that have to be compared with conflicting and similar literature as well as related practical examples, too. Finally, the results of the case study have to be critically discussed and reported in a concise manner.

4 Single case study

4.1 Research question

Our research question in this paper is the following: Which is the ecological and economic impact of implementing a waste management plan for the logistics of disposal on site? Specifically, we want to know whether using a logistics service provider can decrease environmental and economic impacts as well as increase efficiency of logistic processes of disposal on site. Hence, we form the following propositions:

(a) why the different actors in the case study decided to use a logistics service provider responsible for the successful implementation of the waste management on site,
(b) how the actors implemented this strategy by different alternatives within the operation phase and which was the impact of each alternative and
(c) what quantitative results could be achieved from ecological and economic perspectives.

4.2 Case selection, scope and boundaries, case type

The project chosen for this case study is a single high-rise building refurbishment in the inner city of Frankfurt am Main, Germany. As one of greatest refurbishments of a building in Europe, the site area had a space of 13,000 m^2 with a building gross floor space of about 122,000 m^2 and a rental area of 75,000 m^2. The building owner renovated and modernized the building from December 2007 to February 2011. The gutting work started in December 2007, while the demolition work in part of the building took place from June 2008 to November 2008. The construction work started in June 2008 and ended with the reoccupation of the building in February 2011.

To address the research question and propositions defined in Sect. 4.1, we outline the scope and system boundaries. The scope and system boundary include the investigation of the material stream on site from the place of waste generation within the building to the collection, separation as well as transport and handling of the waste on site and to the continuing utilization of the waste to its recovery or disposal option. Here, we want to prepare the research from the point of view of the most important actors on site with respect to the logistics of disposal: the owner, the main contractor and the logistics service provider. The temporal system boundaries for the qualitative research relate to the whole construction period. However, the quantitative research is based (a) both on a complete set of data of the whole construction period provided by the building owner, the main contractor and the logistics service provider in order to analyze ecological issues and (b) on a sample set of data from April 2009 to March 2010 which were made available only by the logistics service provider in order to analyze both economic issues and efficiency of the implemented waste management concept.

4.3 Data collection

The project was monitored during the construction period, starting in April 2009 and ending in February 2011, while the qualitative and quantitative data were collected for the complete demolition and construction work from December 2007 to February 2011. The propositions and data collection method are presented in Table 1.

In the beginning of the observation and monitoring period in April 2009, the gutting and demolition activities were already finished and the construction work in form of finishing was taking place. The data collection effort included regular contact with many actors involved in the refurbishment project. Concerning the research question and its propositions, the information on the research topics was collected by a researcher (first author of the paper) by (1) direct observation of site activities and (2) interviews of responsibilities from the different parties both on site and within the companies, in order to find answers to propositions (a) and (b). Additionally, we collected and screened secondary data for the whole project period from the building owner, main contractor and logistics service provider, in order to find answers to proposition (c). In order to answer the research question of ecological and economic impacts of implementing a waste management plan, we analyzed a sample set of secondary data to ecological and

Table 1 Information sources used to answer the propositions

Proposition	Information sources
Why did the different actors decide to use a logistics service provider responsible for the successful implementation of the waste management on site?	Interviewing the building owner and his project management
	Interviewing the main contractor
	Interviewing the logistics service provider
How did the actors implement the waste management strategy by different alternatives within the operation phase and which was the impact produced by each alternative?	Direct observation of the construction site from April 2009 until February 2011 by the researcher
	Screening documentations:
	Waste management approach provided by the main contractor and logistics service provider
	Logistical handbook provided by the logistics service provider
	Reports of the qualitative preliminary results from the waste management plan, LEED Certification and DGNB Certification
What quantitative results could be achieved from ecological and economic perspective?	Interviewing the logistics service provider
	Collecting, preparing and analyzing quantitative data:
	Secondary data concerning the amounts of waste, its quality and quantity, provided by project management, the main contractor and the logistics service provider
	Secondary data concerning the costs for the logistics of disposal provided by the logistics service provider

economic issues from April 2009 to March 2010 provided by the logistics service provider.

5 Results

5.1 Overview

This section is structured according to the qualitative and quantitative results of the case study research. The first subsection gives information about the qualitative results we got from interviews, direct observations and screening documentation: the challenges of the construction project the building owner, the companies and the society had to deal with and, additionally, information about the specific planning and implementation of the waste management approach.

Based on the findings of the literature review, in this paper, efficiency is measured through eco-efficiency by calculating the reuse and recycling rate in relation to the costs of logistics of disposal. Thus, in the second subsection, the results of ecological assessment and the results of the economic assessment are presented.

5.2 Qualitative results

5.2.1 Challenges

In the early planning phase of construction projects, the planners have to deal with a wide range of uncertain requirements and conditions that are burdened with high risk. At the same time, construction logistics is expected to be flexible and efficient. Under these conditions, the logistics service provider of the case study was expected to implement a logistic plan to coordinate and optimize all logistical processes. However, the other actors involved (and especially the building owner, the construction companies on site and the society) had also to deal with specific challenges from the beginning of the project.

The main goal of the building owner was to get a certification for the finished construction building in accordance with LEED platinum [25] and DGNB gold status [4]. They expected that the refurbishment project should contribute to a sustainable construction industry and should, thus, attract worldwide attention as a flagship project. Therefore, they decided to use a logistics service provider that would support not only the logistics activities of the project during the demolition and construction phase but also its marketing. Furthermore, the logistics service provider in his effort to optimize the construction process was also expected to identify the risks and opportunities of the project as early as possible, in order to consider them in the planning phase. Disabilities between the subcontractors on site should be minimized to allow independent work and synergies and to utilize the use of infrastructure. The complex construction project should be supported logistically, in order to make sure that despite the many parallel activities, a maximum of productivity could be achieved.

For the construction companies on site, the production conditions and processes affect significantly the efficiency of each construction activity and company. The efficiency of each company is dependent on the timely delivery of materials on site, the processes on site, the cost of disposal and recovery. Hence, the material handling should be smooth and secured, and the working area should be kept free of waste and residual materials.

The building owner also needed to make sure that the society would not face any issues during the building construction. Therefore, effects of dust and noise emissions from construction activities should be minimized in, e.g., both for the nearby residents and the kindergarten close to the site. Moreover, the unhindered flow of traffic on one of the main arterial roads of the city should be ensured, as this road passed the site entrance and exit. Finally, pedestrians, cyclists and visitors to the nearby opera house should continue unhindered walking along the site. The logistics plan should consider all these challenges.

5.2.2 Designing a waste management plan

The building owner instructed the main contractor on site to work out and implement together with a logistics service provider a logistic plan for the construction site that would optimize and coordinate all logistical processes. The main idea was that the logistics service provider would concentrate and work on the core logistic processes directly on site in order to achieve a better interaction of the different bodies and actions between project partners like the owner, architects, main contractor and subcontractor concerning delivery and disposal of material. In order to fulfill the requirements of the different project partners and the public as well as to enable construction work on site as productive, cost-efficient and ecological as possible, a waste management plan (WMP) was developed and implemented by the owner together with the main contractor and the logistics service provider.

5.2.3 Implementing a waste management plan

The WMP had to satisfy the regulatory measures and to sketch the roles of the main contractor and the subcontractors. In this way, the responsibilities of the staff responsible for the procurement of materials and the staff responsible for the logistics of disposal on site would be clear. The main contractor together with the subcontractors estimated the percentage and the quantity of the materials procured that would end up as waste even from the planning phase of the project. Data were needed to distinguish the responsibilities of the different actors in the WMP. Appropriate waste containers were procured to promote waste segregation already on site and on floor. Moreover, during construction, the real waste quantities and qualities were recorded and reported within the WMP and, thus, the quantities assumed in the planning for each waste fraction were now updated. A single system for the recording of the quantities was implemented and all relevant actors had access to it. Finally, the WMP described and determined the way of recovery and disposal for each waste fraction collected and separated on site. If the waste could not be used as a by-product in other construction activities, then it was reused or, at least, recycled. As long as no hazardous waste (e.g., asbestos) was generated on site, it was permitted to dispose waste fractions to landfill. A waste management enterprise was commissioned with the disposal and control of the contractors involved in the project. The contractors were contractually obliged to comply with the construction waste management plan. That also included an agreement that the proper removal and/or disposal of hazardous wastes produced by contractors was under the corresponding contractors' own responsibility. An area for recycling and separation activities was provided in accordance with the site equipment plan. The additional containers for separating the waste fractions were directly positioned at the relevant construction locations. Each company was equipped with several moveable lockable containers right from the beginning of construction in order to be able to throw their waste, separated into predefined waste categories anytime already at the working place on floor in the building on site. The logistics service provider was responsible for the clean separation of the waste that was regulated by the WMP and to collect and transport throughout the day the full waste containers from the floor to the collecting station on site.

The project manager was the one to introduce the concept of waste management to the construction supervisor and the subcontractors' supervisors. A technical engineer working for the waste management enterprise was on site every day and instructed the workers. He was also monitoring whether the activities were in compliance with the construction waste management plan, and he was the contact for all parties involved. The responsible construction managers as well as the responsible site managers of the contractors were trained in the WMP. Subsequently employed contractors were trained in individual sessions. The related documents were handed over and posted at designated locations.

5.2.4 Logistic site plan and handbook

Furthermore, logistic practices that were successful in the past were implemented on site and supported the WMP. Specifically, starting in the designing phase the planning of logistics at an early stage identified potentials and restrictions for the site tailored to the particular needs of the construction project. A logistics site plan and a handbook were used as a guideline for all contractors. The logistics handbook was considered as a binding regulation without exception for all contractors and their employees on site. In order to optimize all transports, all deliveries to site had to be registered either manually or via an online registration form. The space, time and lift capacities required for unloading as well as the precise use of forklifts supporting the unloading and horizontal transports were also coordinated.

5.2.5 *Interim conclusion*

It can be stated that the implementation of the recently introduced waste management concept was the basis for the entire disposal system on site. In the waste management plan, the disposal option of each material was defined. The listed recycling companies were certified companies (most of them were based locally) and were audited by an environmental officer. Already within the demolition and construction activities, the recyclable materials were separated on their place of origin and were brought out of the building to a site-specific recycling storage.

5.3 Quantitative results

5.3.1 *Ecological assessment*

First, we analyze the reuse and recycling rate using the material flow on site for the waste generated by demolition and construction activities.

As shown in Table 2 a total quantity of 33,467 t of CDW was produced during the whole construction period. Thereof, 997 t (3.0 %) can be reused as material for other construction sites, whereas 25,523 t (76.3 %) can be recycled. Furthermore, 448 t (1.3 %) waste was incinerated and 6,389 t (19.1 %) waste was collected on site for mining-regulated recycling. Finally, during demolition and gutting phase, 111 t (0.3 %) insulation materials containing asbestos had to be separated and delivered to landfill. In total, the reuse and recycling rate is 79.3 % by weight.

In order to assess the ecological concerns of the waste management directly on site, the amount of mixed CDW from the reuse and recycling rate is left out from the above calculation (Fig. 2), and it is counted to energy recovery (Fig. 3), as this waste fraction is not separated already on site into its different fractions. Here, the total reuse and recycling rate on site is 68.7 % by weight.

In order to measure and discuss efficiency of the implemented WMP below, we used a sample set of data for the period from April 2009 to March 2010 provided by the logistics service provider for a more in-depth ecological analysis (see Fig. 4). In these 12 months, during the construction phase, 3,236 t waste was disposed on site. Thereof, 2,289 t (70.7 %) could be recycled. Furthermore, 724 t (22.4 %) waste was collected on site for mining-regulated recycling, whereas 223 t (6.9 %) were disposed as mixed construction waste to a sorting plant for further treatment and disposal.

The waste was collected and mostly separated directly at its place of origin and transported to the collection station on site. Material for reuse, namely marble, false floor and inventory, was subsequently transported from construction site to intermediate warehouses and then transported to different sites in Germany and Europe. The waste fractions sorted on site for material recycling were delivered to recycling companies which collected the waste and transported it to manufacturers from different industries where the material was finally used as raw material for production. Mixed construction and demolition waste generated on site was transported to a sorting plant close to the refurbishment project where most of the fractions were sorted out for material recycling, whereas a low percentage went to energy recycling. The gypsum material was transported to mining, whereas a low percentage of insulation materials containing asbestos was disposed on landfill.

5.3.2 *Economic assessment*

Despite a detailed data collection through screening secondary data and interviewing responsibilities for the waste management from the case study, a complete picture of the total costs for implementing a waste management could not be drawn as data for measuring the costs for the whole project period was not provided. Nevertheless, we present an economic assessment of the logistics of disposal for the phase of construction during refurbishment from April 2009 to March 2010 as this data was completely provided by the logistics service provider. Therefore, we analyzed the sample set of data. The results are following (see Fig. 5a, b). In total, the costs for logistics of disposal are 556,892 € and 172 €/t compared with the total amount of waste generated in this period through construction activity. All costs for collecting, separating and handling waste on site during finishing activities were included as well as the disposal fees for disposing each waste fraction from site. The total costs are splited: 285,856 € (51.3 %) for operating costs of the waste disposal service on site and 271,036 € (48.7 %) for the disposal fees.

6 Discussion

6.1 Efficiency

In this paper, we wondered whether using a logistics service provider can decrease environmental and economic impacts while increase efficiency of logistics processes of disposal on site at the same time. Therefore, we need to compare the results that arose in Sect. 5 on the ecological and economic impacts of our case study with the case what

Table 2 Overview to the total amount of waste and the disposal option of the different waste fractions

Waste fraction	No. (European waste catalogue)	Total (t)	Reuse (t)	Material recycling (t)	Energy recycling (t)	Mining-regulated recycling (t)	Landfill (t)	Reuse and recycling rate (%)
Paper and cardboard packaging	150101	70	0	70	0	0	0	100
Plastic packaging	150102	60	0	46	15	0	0	75
Mixture of concrete, bricks, tiles and ceramics	170107	15,060	178	13,645	0	1,236	0	92
Wood	170201	1,885	0	1,885	0	0	0	100
Glass	170202	1,427	0	1,317	0	111	0	92
Plastic	170203	92	0	92	0	0	0	100
Bituminous mixtures	170302	256	0	256	0	0	0	100
Aluminum	170402	532	0	532	0	0	0	100
Iron and steel	170405	119	0	119	0	0	0	100
Mixed metals	170407	2,966	0	2,966	0	0	0	100
Cables other than those mentioned in 170410	170411	94	0	94	0	0	0	100
Insulation materials containing asbestos	170601*	111	0	0	0	0	111	–
Insulation materials consisting of or containing dangerous substances	170603*	804	0	804	0	0	0	100
Gypsum-based construction materials	170802	5,996	699	111	144	5,042	0	14
Mixed construction and demolition wastes	170904	3,827	0	3,539	288	0	0	92
Inventory/bulky waste	200307	120	120	0	0	0	0	100
Other: EPDM	–	47	0	47	0	0	0	100
Total (t)		33,467	997	25,523	448	6,389	111	79

* Hazardous waste

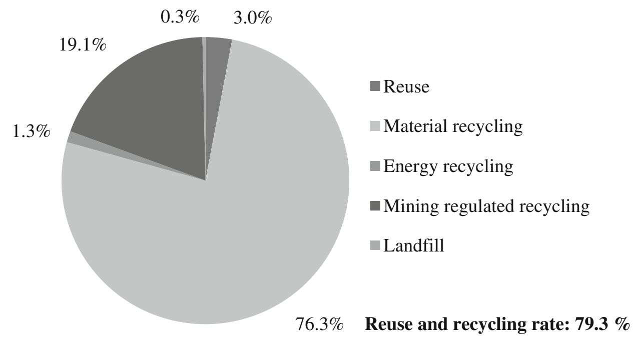

Fig. 2 Percentage of waste according to its disposal option/mixed CDW mostly counted to material recycling

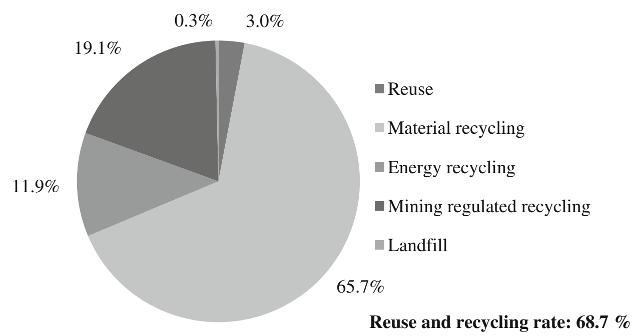

Fig. 3 Percentage of waste according to its disposal option/mixed CDW counted to energy recycling

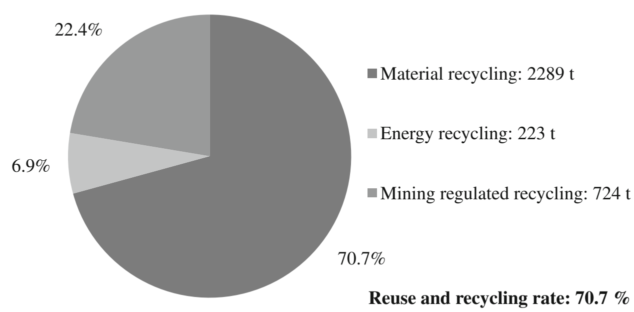

Fig. 4 Percentage of waste according to its disposal option in the period from April 2009 to March 2010

would have happened if no WMP was implemented and if there was no logistics service on site. Hence, we analyze an alternative scenario (baseline scenario) where no waste management approach and no logistics service on site are implemented. Thus, most of the CDW is not collected separately already on site, but largely produced as mixed CDW. This has the consequence that the recovery rate decreases to 37.7 %, while the costs decrease to 324,109.07 € or 100 €/t, naturally due to the lower effort for the logistics of disposal on site (see Figs. 5a, b, 6). The much lower cost cannot compensate the lower recycling rate. Hence, the efficiency within the baseline scenarios is 0.0037 t/€ and, thus, by 9.4 % lower compared to the efficiency of our case study with 0.0041 t/€ (see Fig. 7).

Based on the previous study and results, we can postulate for our case study that through the implementation of a WMP and the introduction of a logistics service, the reuse and recycling rate can be increased for a large-scaled, inner-city construction project. Even if this is associated with higher costs for separation and collection of CDW on site, it can also increase the efficiency of logistics of disposal. Whether and to what extent this statement can be generalized has to be reviewed in the future. For this, further case study research on this topic is necessary.

6.2 Observations

Based on our analysis, the following three observations according to the propositions formulated in Sect. 4.1 can be made:

Observation 1 concerning the proposition, why the different actors in the case study decided to use a logistics service provider responsible for the successful implementation of the waste management on site: For our case study, we showed that due to the complexity of the site of such a large and inner-city refurbishment project and the variety of requirements and challenges that the actors faced, a smooth material and waste flow to site, on site and from site has to be secured. At the same time, the building owner wanted to certify the construction project according to the international sustainability systems that provide high standards for the reuse and recycling rate of CDW, and hence, documentation of these results was necessary. This was successfully achieved with the help of a logistics service provider and a waste management approach.

Observation 2 concerning the proposition, how the actors implemented this strategy by different alternatives within the operation phase and which was the impact of each alternative: Main idea for an efficient waste management on site was to implement a logistic system for the site as well as a WMP for all contractors and actors on site within the whole construction time. The WMP determined the way of disposal for each waste fraction collected and separated on site. Furthermore, a logistics site plan and handbook were used as a guideline for all contractors to fulfill their work always in consideration of the logistical processes. The logistics handbook was considered as a binding regulation without exception for all contractors and their employees on site. This led to a coordination of all logistical processes on site and to a better interaction of the actions between the project partners concerning delivery and disposal of material.

Observation 3 concerning the proposition, what quantitative results could be achieved from ecological and economic perspective: In total, a quantity of 33,467 t of

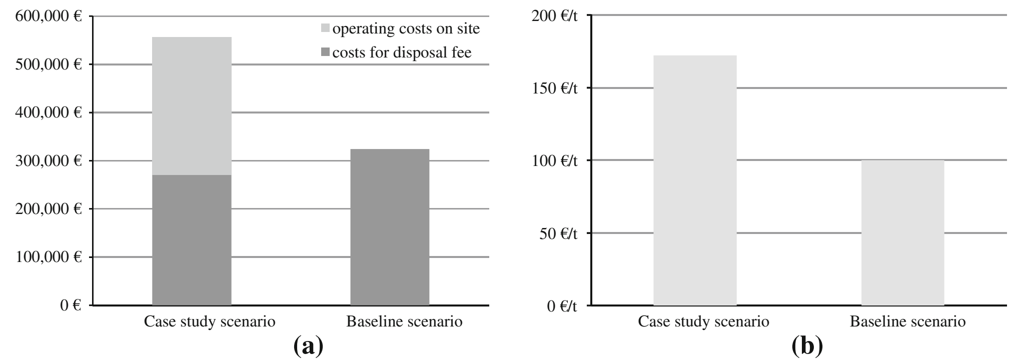

Fig. 5 **a** Absolute costs for logistics of disposal in the period from April 2009 to March 2010, case study and baseline scenario. **b** Relative costs for logistics of disposal in the period from April 2009 to March 2010, case study and baseline scenario

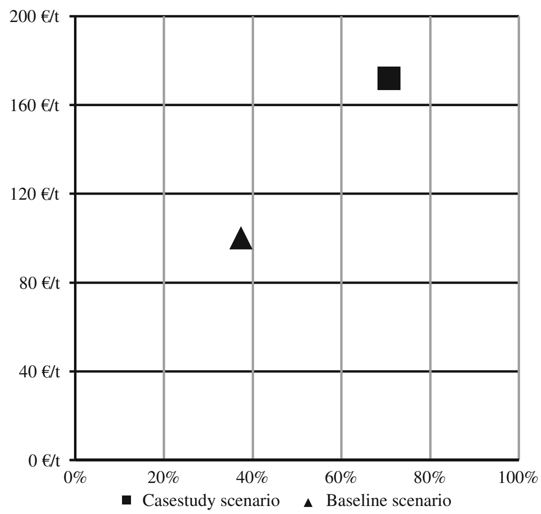

Fig. 6 Costs and reuse and recycling rate for the case study and baseline scenario

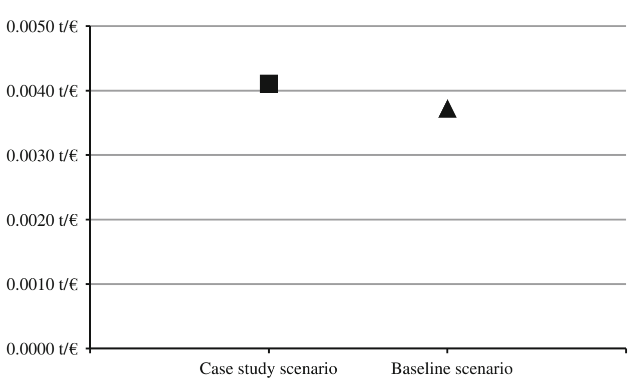

Fig. 7 Efficiency for the case study and baseline scenario

CDW was produced during the whole construction period. Thereof, 3.0 % was reused as material for other construction sites, 76.3 % was recycled, 1.3 % waste was incinerated, 19.1 % waste was collected on site for mining-regulated recycling and 0.3 % insulation materials containing asbestos had to be separated and delivered to landfill. The reuse and recycling rate in our analyzed case study is 79.3 % by weight. If we want to assess the ecological concerns of the waste management directly on site, the amount of mixed CDW from the reuse and recycling rate is left out and it is counted to energy recovery. Then, the total reuse and recycling rate on site is 68.7 % by weight. Although a detailed data collection according to the economic impacts of the waste management could not be drawn, we were able to analyze a sample set of data from April 2009 to March 2010. Here, the total costs for logistics of disposal are 556,892 € and 172 €/t in relation to the total amount of waste generated in this period through construction activity. The efficiency of logistics of disposal is approximately 9 % higher for a construction site when a WMP is set up and a logistics service is used, compared to a site without a WMP and a logistics services and when there is a collection of mostly mixed CDW on site.

7 Conclusion

For our research, we formulated the research question in Sect. 4.1 which the ecological and economic impact of implementing a plan for the logistics of disposal on waste management on site is and if we can decrease environmental and economic impacts while increase efficiency at the same time.

We found that the implementation of a waste management plan can reduce environmental impacts concerning the reuse and recycling rate. By involving a logistics service company, despite the challenges of an inner-city and large-scaled construction project, the waste streams can be sorted on site and returned to the material cycle directly from site. However, this is associated with higher costs incurred by the collection and separation of waste on site as well as by the associated monitoring and coordination of the logistical processes. Compared to the collection of mixed CDW on site, these higher costs cannot compensate the increase in costs due to the disposal fees. Nevertheless, we could show that the efficiency of logistics of disposal coupled through the implementation of a waste management plan using of a logistics service company increased by approximately 9 % compared to an acquisition of mixed CDW without a logistics service provider on site.

A major limitation of our research is that we use only one case study. It remains for future research to verify, if the results of this case study can be generalized. For this, further case studies of real-world examples are necessary. At the same time, it would be interesting to know what environmental impact in terms of emissions, such as noise, dust and CO_2, has the implementation of a logistics service company on large-scaled construction projects to ensure a smooth handling and management of CDW on site. Additionally, it would be also interesting to know whether, and if so, how a logistics service company within the logistics of delivery influences the smooth flow of materials to site—measured also here on the increase or decrease in costs in relation to environmental issues.

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