Planning of Construction Projects: A Managerial Approach

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Thank you!

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AON	Activity-on-node
ARGE KWTB	Arbeitsgemeinschaft Kreislaufwirtschaftsträger Bau
ATV	Allgemeine technische Vertragsbedingungen
B2B	Business-to-business
BOOT	Build-own-operate-transfer
BOT	Build-operate-transfer
BRB	Bundesvereinigung Recycling Baustoffe
BTO	Build-transfer-operate
C&D waste	Construction and demolition waste
CAD	Computer aided design
CM	Construction Manager
CPM	Critical path method
CPT	Construction planning technique
CSC	Construction supply chain
CSCD	Construction supply chain design
CSCM	Construction supply chain management
CVP	Construction virtual prototyping
CVRP	Capacitated vehicle routing problem
DB	Design-build
DBB	Design-bid-build
DBOF	Design-build-operate-finance
DCMF	Design-construct-manage-finance
DIN	Deutsches Institut für Normung e. V.
EMMRCPSP	Extended MMRCPSP
EOLPs	End-of-life products
EPR	Extended producer responsibility
ESV	Energy-savings value
EWC	European Waste Catalogue
GMP	Guaranteed Maximum Price
HOAI	Honorarordnung für Architekten und Ingenieure
HVACR	Heating, ventilation, air conditioning and refrigeration

IRP	Inventory routing problem
IT	Information technology
ISO	International Organization for Standardization
JIT	Just in time
Krw-/AbfG	Kreislaufwirtschafts- und Abfallgesetz
LCA	Life cycle assessment
LCE	Life cycle energy
LCEA	Life cycle energy analysis
LOB	Line of balance
LSM	Linear scheduling method
MCDM	Multi criteria decision making
MCVAPST	Multiple contractor vehicle assignment problem with setup times
MDVRPTW	Multi day vehicle routing problem with time windows
MIP	Mixed integer program
MMRCPSP	Multi-mode resource-constrained project scheduling problem
MPM	Metra potential method
MRP	Material requirements planning
MVMMAP	Multi vehicle multi material assignment problem
NGO	Non-governmental organization
NPV	Net present value
OEM	Original equipment manufacturer
PBC	Phosphate bonded ceramic
PERT	Programme evaluation and review technique
PRM	Product recovery management
PVRP	Period vehicle routing problem
RCCP	Rough cut capacity planning
RCMPSP	Resource-constrained multi project scheduling problem
RCMPSP−DCF	Resource-constrained multi-project scheduling problem with discounted cash flows
RCPSP	Resource-constrained project scheduling problem
RCPSP−DCF	Resource-constrained project scheduling problem with discounted cash flows
RFID	Radio frequency identification

RIP	Resource investment problem
RLP	Resource leveling problem
RPM	Repetitive project model
RRBau	Richtlinien für die Durchführung von Bauaufgaben des Bundes
RRVRP	Roll-on roll-off vehicle routing problem
RSCM	Repetitive scheduling method
SC	Supply chain
SCD	Supply chain design
SCE	Supply chain execution
SCM	Supply chain management
SCVAPST	Single contractor vehicle assignment problem with setup up
SMEs	Small and medium enterprises
TCPSP	Time-constrained project scheduling problem
TSP	Traveling salesman problem
TSSM	Time space scheduling method
VMI	Vendor managed inventory
VP	Virtual prototyping
VPM	Vertical production method
VRP	Vehicle routing problem
VRPTW	Vehicle routing problem with time windows
WEEE	Waste electrical and electronic equipment
WMC	Waste management company
ZDB	Zentralverband des deutschen Baugewerbes

1 Introduction

1.1 Problem definition

The construction industry can be considered as one of the oldest industries organized on a project basis. Well known examples are, for instance, the Egyptian pyramids (3^{rd} millennium B.C.) and the aqueducts carrying water to cities and industrial sites, such as gold mines, with the first one constructed in Rome in 312 B.C. Thereby, construction has early started to develop characteristics of taylorism and specialization for complex buildings with diversified construction activities and a heterogeneous mix of materials and components. The project based organizational structure has mainly remained the same for centuries in construction, apart from recent achievements of standardization of construction with modular or pre-engineered housing and prefabricated standardized components, concepts taken over from the manufacturing industries. However, although being an old industry, construction is still an unsustainable industry in terms of the triple-bottom of sustainability comprising economic, ecological as well as social aspects. Focusing on economic means, construction is characterized by time and cost intensive production processes which make it prone to project risks and failure, mainly in terms of time and cost. In practice, this means, that the performance of construction projects is usually low. In particular, construction projects are very often delayed and over budget. This is not just due to problems faced during project scheduling, but also during related processes such as material procurement and material management. Apart from the economic dimension, negative environmental impacts include approximately 30–40 % of global energy consumption as well as 20–30 % of greenhouse gas emissions which can be traced back to the construction industry (UNEP 2007), complemented by a huge amount of construction and demolition (C&D) waste accumulating during deconstruction projects, which has to be dealt with. Concluding, these problems call for the construction industry to become the centre of efforts in achieving sustainability.

Moreover, the construction industry can be considered as a unique industry as the projects are customer driven, of a one-off nature and accompanied by locally concentrated production and high investments due to the complexity of its products. Following, supply chains of the construction industry are specific and, compared with those of the manufacturing industries, it can be observed that they are more complex due to the unique nature of the projects, the highly uncertain planning environment and the numerous stakeholders of a construction project. Hence, if the focus is drawn to individual construction, for instance, designer buildings as well as streets and tunnels, standardized construction processes to achieve competitive advantages cannot be applied. Concluding, sophisticated methods for project planning and control for these so called design-to-order planning environments would be required. However, researchers are still reluctant to tackle the complexity of individual construction due to the difficulties of generalization of approaches to be developed. Instead, supply chains of the traditional manufacturing industries have been well researched and have been tackled with qualitative as well as quantitative methods. These perform well for standardized production processes. Thereby, usually concepts for make-to-stock, assemble-to-order or make-to-order production were developed and have been established so far.

One important aspect in construction supply chain planning remains the proper project time planning. For many decades, methods such as the critical path method (CPM), the programme evaluation and review technique (PERT), the metra potential method (MPM), and Gantt charts have been applied in construction and have maintained their role for construction project planning. These simple techniques do not pay sufficient respect to the complex planning environment in construction and are solely suitable for the determination of time windows for project activities. In contrast, in construction, more difficult planning problems are faced. These range from pure project characteristics, like multiple projects that access the same resource pool, to external constraints opposed to construction projects, such as different stakeholder interests, and environmental concerns, like waste accumulation and disposal. With this respect, special emphasis has to be put on the aspect of sustainability, gaining increasing importance during the last years. Thus, according to the triple-bottom line of sustainability addressing the ecological, economic as well as social responsibility of actors, not just the efficient economic execution of construction projects has to be a core focus in construction management. Instead, the focus has to be shifted additionally to ecological and social issues as well. Especially focusing on ecological aspects, key issues comprise materials management in closed-loop supply chains due to the high amount of construction and demolition waste accumulating with respect to logistic activities as well as energy-related planning tasks in terms of processes and materials.

In addition to the traditional planning methods (e. g. CPM, MPM, and PERT) focusing on the economic aspects of the triple bottom line, existing guidelines and regulations assist in making the construction industry more sustainable in terms of environmental aspects. Admittedly, solely applying these approaches it is not possible to satisfactory tackle the occurring problems addressed. Instead, opportunities that might present an appropriate alternative are substitutionally or complementary applying quantitative approaches. The development of quantitative approaches or methods for construction project planning problems has just started. However, these solution approaches are not yet sufficiently methodologically sound enough to present a valuable and realizable contribution to the problem solution. Concluding, up to now, approaches to tackle these planning problems are not available. Hence, more sophisticated approaches are required to take the construction project environment into consideration during construction project planning.

1.2 Objectives and research design

The main objectives of this research are to develop new solution approaches for construction project planning problems by adopting concepts for production planning known from the manufacturing industries to construction projects, and to set out new perspectives on the reorganization of common project planning processes in construction. While a lot of other research on these issues presents approaches developed for construction without looking at other industry sectors, this research explicitly takes approaches developed for and successfully applied in other sectors into consideration and seeks for possible adoption and transformation of them to the particularities of the construction industry. Although aspects covered have already been investigated in Anglo-American speaking countries to some extend, knowledge about planning approaches from other industrial sectors has rarely expanded into the German construction industry. An application of methods from other industry sectors has only been marginally considered in theory as well as in practice in the construction industry in Germany.

For the achievement of the research objective, several research questions need to be addressed. These questions include: What is the performance of construction projects, hence, of construction project planning and which methods exist or have to be developed to appropriately tackle existing deficiencies? Furthermore, what is the role of sustainability in the construction industry, especially regarding the occurrence of construction and demolition waste? With this respect, what lacks of knowledge can be identified and which approaches for the ecologically end-of-life management of construction outputs exist or have to be developed?

The first part of the thesis focuses on the economic dimension of sustainability. In particular this comprises the development of approaches for successful construction project planning and materials management to ensure that projects are within time and budget. In contrast, the second part of the thesis shifts the focus to ecological aspects of construction projects and the decrease of its negative ecological impacts with respect to the high amount of waste accumulation. In more detail, this means, that approaches for the processing of arising material during deconstruction projects focusing on materials as well as energetic aspects during deconstruction projects are developed.

In section 2, problem awareness is established and the construction industry is distinguished from the manufacturing industries. This comprises the identification of the characteristics of the construction industry and its products, the discussion of the economic relevancy of the construction industry as well as the analysis of the structure of the construction supply chain and the role of stakeholders of construction projects.

Project planning in construction as currently practiced is addressed in section 3. Characteristics of construction projects are highlighted and project delivery systems are briefly introduced. Afterwards, performance problems are revealed and related to potential lacks of current methods for project planning. Thereby, the potential of resource oriented planning for construction projects is discussed. With this respect, procurement strategies for project resources are elaborated based on a classification scheme for project resources, which is developed in this section.

As outlined in sections 2 and 3, the project planning problems in construction are of complex nature, especially with respect to the consideration of limited resource availability. This aggravates the development of new planning approaches to tackle the performance problems. Hence, a decomposition of the problems is necessary to be able to deal with them. In section 4 a hierarchical planning approach for resource based construction project planning is developed and the role of quantitative resource-constrained project scheduling, an approach well researched in operations management within the context of construction projects, is investigated.

The underlying assumption is that project performance not only depends on an efficient resource allocation during the scheduling of the project but also on a proper materials management, which could be improved by applying concepts of supply chain management. Thus, in section 5 a proposition for the design and operation of construction supply chains is made by revealing potential benefits and risks for construction.

Afterwards, the focus is shifted towards the ecological dimension of sustainability in the construction industry in section 6. Thereby, the need for the consideration of ecological aspects in construction is highlighted and current accomplishments in Germany with respect to C&D waste treatment are highlighted. In response to the large amount of C&D waste accumulating, the relevancy of the establishment of closed-loop material flows in construction is stressed and aspects of reverse logistics in the context of product recovery as relevant for the operation of construction projects are discussed.

Section 7 concentrates on the organization of the material flow and reverse logistic tasks for the collection of construction and demolition waste. Therefore, quantitative planning models for reverse logistic operations in (de-)construction projects are introduced. These models are either especially developed for a particular planning context or are based on existing models which are extended. Finally, an approach for integrated project scheduling and reverse logistic planning is introduced to pay respect to the fact that the timely organization of reverse logistic activities depends on the project schedule.

Section 8 resumes the discussion on sustainability of section 6 and concentrates on project planning with respect to energy efficiency of materials. In particular, an integrated deconstruction-recovery planning approach for deconstruction projects is developed to include ecological as well as economic benefits throughout the life cycle of a building by extending a model for resource-constrained project planning discussed in section 4. Therefore, a measure called energy-savings value, which is based on life cycle energy analysis, is derived for the evaluation of the environmental impact of product recovery.

In section 9, a summary and outlook on future research efforts are given. A German executive summary of the thesis is presented in section 10.

2 Characteristics of the construction industry

The construction industry significantly differs from traditional manufacturing industries[1], such as the automobile, consumer food, and textile industry. In the following, a common understanding of the peculiarities of the construction industry, its products, production processes and stakeholders is created and the relevancy of the construction industry for the national and international economy is discussed.

2.1 Peculiarities of the construction, its products, and its production processes

The construction industry is that part of the economy which deals with the design, construction, maintenance, and utilization as well as with the modulation, modification and demolition or deconstruction of constructs (Rußig et al. 1996). It is a major sector in most national economies and a major contributor to environmental changes, both in terms of designing the built environment as well as in terms of anthropogenic effects on the environment. Thereby, it impacts economic, social, and ecological issues throughout the whole life cycle of a constructed product. For instance, the construction industry accounts to approximately 10 % to a countries gross domestic product (GDP)[2] and contributes approximately 30–40 % to global energy consumption as well as 20–30 % to greenhouse gas emissions (UNEP 2007). Thus, sustainability is of growing importance in the construction sector.

The construction industry can be divided into two broad categories: general building construction and engineered construction, as depicted in Figure 1 (Bennett 2003). The general building construction sector can further be divided into four types. The residential construction comprises buildings for human habitation, for example single-family dwellings, flats, multifamily townhouses or high-rise apartments. Retail and wholesale stores, shopping malls, office buildings or small manufacturing facilities belong to commercial construction. The institutional construction includes constructed assets such as hospitals, schools, government buildings or athletic stadiums. Especially institutional construction projects are often very complex and require more planning effort than general building construction projects. The fourth category of the general building construction is industrial construction in which large-scale projects are developed and executed. Unusually, these projects are also characterized by a high technical complexity. Examples for large-scale projects are

[1] The manufacturing industries comprise establishments engaged in the mechanical, physical, or chemical transformation of materials, substances, or components into new products. This includes all foods, chemicals, textiles, machines, and equipment as well as all refined metals and minerals derived from extracted ores and all lumber, wood, and pulp products (U.S.Census Bureau 2002a; U.S.Census Bureau 2002b).

[2] A detailed discussion on the role of the construction industry within Germany and the European Union is given in section 2.2.

manufacturing facilities, such as electric power-generating plants, petroleum refineries or other heavy manufacturing factories for the manufacturing of, for example, vehicles or rolling equipment.

In contrast to the general building construction, projects of the engineered construction industry sector usually emphasize functionality rather than aesthetics. Thus, designs are prepared by engineers and not by architects. Projects in engineered construction are usually related to the public infrastructure, owned by entities of the public and funded with bonds, rates or taxes. Furthermore, two common subcategories can be differentiated. While highway construction projects typically include excavation, embankment constructions, installation of bridges or special lightning and signage, heavy construction projects refer to, for example, dams, tunnels, pipelines, rapid transit systems, airports or different utility works like electrical transmission systems or water lines (Bennett 2003, 1–2).

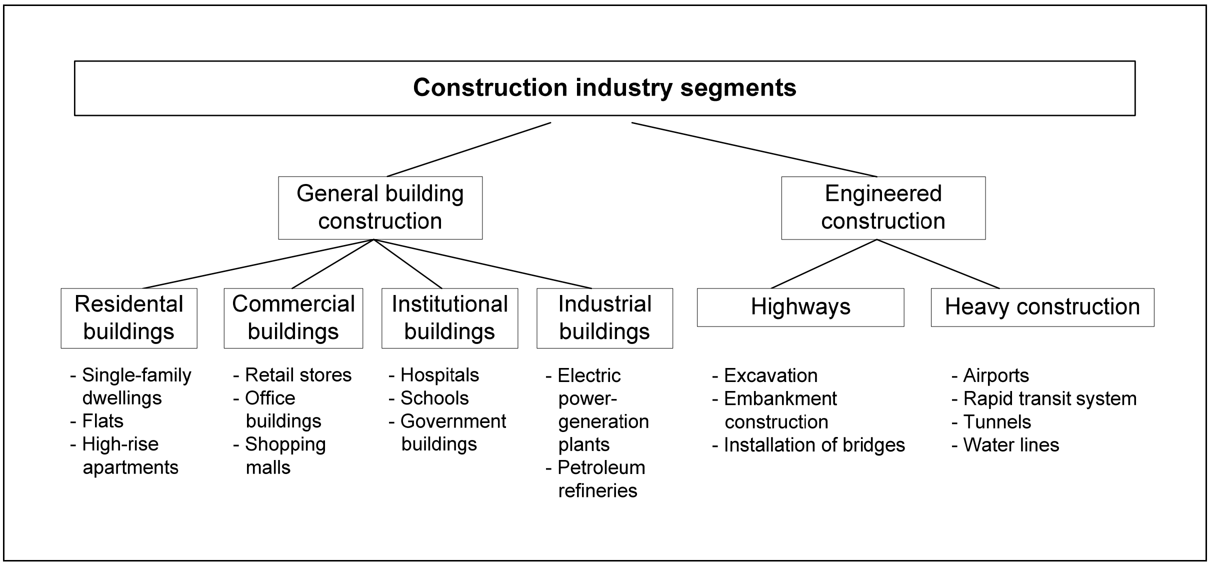

Figure 1: Segments of the construction industry

The mentioned products of the construction industry show five major characteristics (Nam and Tatum 1988): immobility, complexity, durability, costliness and high degree of social responsibility. The production of a building or infrastructure, in particular the final assembly of materials and components, usually takes place at the point of consumption, i. e. on the construction site. Due to the size of the finished product transportation from a manufacturing plant to the final destination is not possible. Hence, except for modular or mobile housing, construction products are generally *immobile*. In contrast, products from the manufacturing industries are produced in manufacturing facilities of permanent location and afterwards products are transported to the point of consumption, for instance cars or refrigerators to the retailer or customer.

The *complexity* of constructs stems from the high amount and heterogeneous mix of construction materials and components which need to be assembled. This is caused by composition requirements implied by design specifications as well as by the taste of owners and designers. In manufacturing, products are usually smaller and less complex, also caused by the higher degree of standardization which can be applied. In addition to the immobility and complexity of constructed products, the *durability* is a further distinguishing characteristic in contrast to products from the manufacturing industries. As a requirement, products of construction have to be in function over a long life span, ranging from 10 to 100 years depending on its purpose. The life span can be extended through maintenance, repair, modification and renovation. Thereby, goods like cars have a far shorter life span, amounting up to 10 – 15 years for regular cars depending on the maintenance effort or computer equipment being outdated after 4 years, while single components might be recovered at the end-of-life. Caused by the complexity and durability of construction products is its *costliness*. Due to the high amount of various materials and special requirements regarding their durability, expenditures on construction products generally far more exceed the ones made for the manufacturing industries, like computer equipment of coffee machines. These costs could be only decreased by advanced employment of standardization and innovating construction processes. However, innovation in construction seems to be hampered by the difficult research and development environment. For example, new buildings cannot be built and tested on seismic behavior to evaluate its suitability for earthquake prone regions. Hence, a tendency occurs to use well proven construction materials and processes. Finally, the social responsibility of constructed products addresses the public safety, health as well as the need to service the increasing awareness for environmental concerns due to its dominating part in the built environment and, hence, strong impact on its surroundings. In contrast, products from manufacturing are usually within private use of its consumers, are smaller, mobile and, hence, exert less impact on the general public.

The typical life cycle of a product of the construction industry comprises the design, production, construction, use and occupation as well as the end-of-life phase of a construction, as depicted in Figure 2[3]. Construction projects, as understood in the following, refer to the phase of the construction of the building; i. e. assembling construction materials and components on site for the final building. Deconstruction projects take place at the end-of-life of the building and initiate further activities such as recovery or waste management.

[3] In the manufacturing industries, the life cycle of a product comprises the production, use, and disposal or end-of-life. Thereby, the construction phase is not applied and the design for standardized products takes place in the development phase of the product, not for the single product itself.

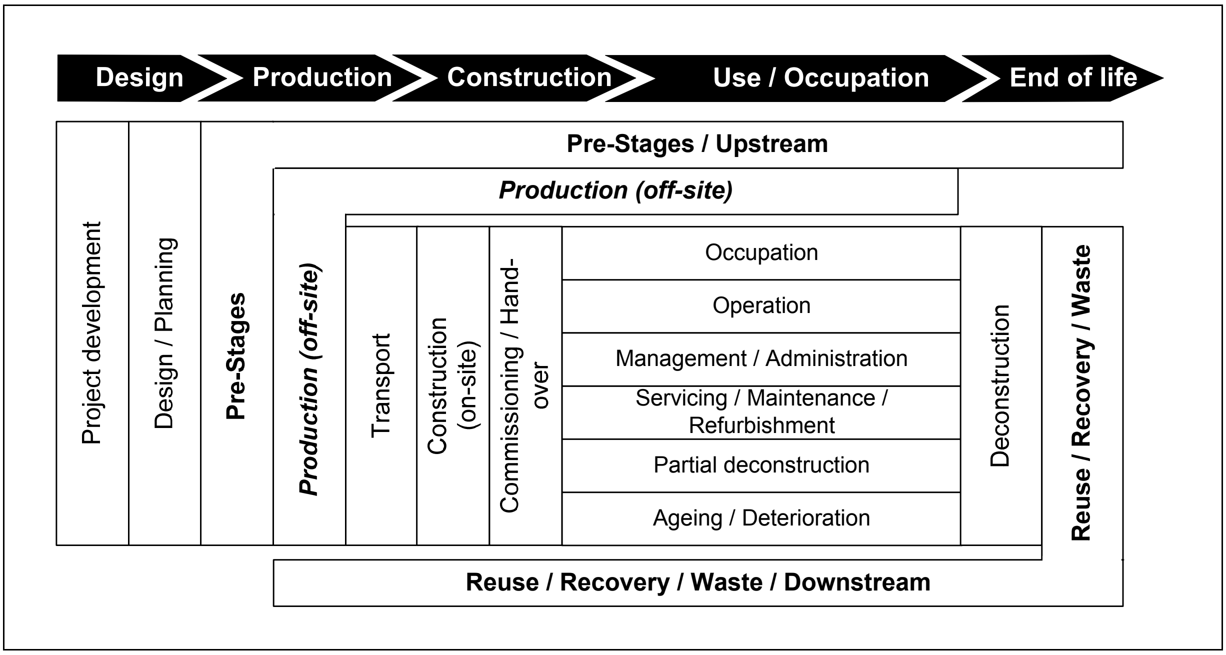

Figure 2: Typical building life cycle

(Lützkendorf and Lorenz 2006, 350)

In contrast to manufacturing with mainly standardized production processes and a high number of products, the construction industry is characterized by a project environment with a one-off nature which, in turn, means that economies of scale—as common in mass production—cannot be achieved and the potential for joint-production is low. Instead, construction is a combination of local production for intermediate products as well as on-site construction for final assembly and suffers from unstable demand cycles. Project based production as can be found in construction is usually customer driven and, contrary to manufacturing with decreasing product life cycles and short product development phases, includes a long design phase. In addition, the construction industry is based on local production, high investments, and high transaction costs due to the complexity and one-off nature of products. Furthermore, the production process is highly fragmented as a result of the proliferation in subcontracting[4]. Subcontracting also causes highly adversarial behavior of its actors and often leads to low margins. As construction projects are mostly temporary organizations, the coalition of participants is only short-term, hence, it is difficult to make sustainable improvements in construction processes through learning, trust or partnering (Cox and Ireland 2006, 404–6; Dainty et al. 2001, 163). Furthermore, the low homogeneity and standardization of construction materials as well as the significantly high number of materials and components complicate supply chain and materials management. This is aggravated by uncertain and less controllable project parameters, such as design changes in a late stage of the project (Ibn-Homaid 2002, 264). In addition, inefficient communication and

[4] Possible options for subcontracting are discussed in section 3.1 in conjunction with project delivery systems.

information practices between the project partners as a result of the fragmentation lead to a high risk proneness of construction projects as well (Cheng et al. 2001, 68).

As a result of the unique nature of the construction industry, planning is extremely difficult. On the one hand approaches applied in practice do not really ensure proper project performance, and on the other hand planning approaches developed for standardized production processes known from the manufacturing industries are not applicable without alterations. In particular, this means that approaches in practice have to be reconsidered and complemented, as done in section 3.

2.2 Economic relevancy of the construction industry in Europe and Germany

In 2006 the estimated construction investment of the EU 27[5] member states accounted for 1.196 billion €. The share of the GDP was 10.4 % and 2.7 million enterprises were operating in the construction sector. Thereby, 95 % of the enterprises had fewer than 20 and 93 % of the construction enterprises fewer than 10 operatives. While it is estimated that approximately 26 million workers depend, either directly or indirectly, on the construction industry the total number of direct employees amounts up to 15.2 million. Therewith, the construction industry accounts for 7.2 % of the total employment in Europe and even up to 30.4 % of industrial employment (FIEC 2007).

In Germany, the share in the national gross value added of the construction industry decreased from 7 % in 1994 to 3.9 % in 2006. However, the negative development of the construction sector seems to be stopped as the increase gross value added of 4 % is higher than the average increase in gross value added of all sectors with 2.6 % in 2006 (Statistisches Bundesamt 2007). Furthermore, in 2007 2.199 million out of 39.737 million people were employed in the construction sector. This accounts for approximately 5.5 % of total employment (Statistisches Bundesamt 2008a).

Hence, although the construction sector does not seem to play a major role in terms of contribution to the national economy with maximum shares of approximately 10 % of GDP within Europe, it plays an important role in economic growth and stimulates the demand for products in other industrial or service sectors. Examples are the demand for intermediate products and capital goods, such as construction materials and construction equipment. Further links exist to the service or tertiary sector—depending on the classification of the

[5] The EU 27 comprises the following 27 member countries of the European Union: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxemburg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom.

construction industry—such as design and engineering services, wholesale of construction materials and equipment as well as financial services, insurances and property management (Amil and Dolvet 2006).

2.3 Structure of the construction supply chain

As the peculiarities of the construction industry suggest (see section 2.1) the construction supply chain is of complex nature and significant differences can be identified between supply chains of the manufacturing industries and those in construction. Thereby, in literature, various definitions for the term *supply chain* (SC) exist. Chopra and Meindl (2006, 3) state, that a supply chain "…consists of all parties involved, directly or indirectly, in fulfilling a customer request." (Moore 1998, 172 cited by Cheng et al. 2001, 69) describe a supply chain as "…the links between a firm and its suppliers, through to its distribution organisation and on to its customers", whereas Stadtler and Kilger (2004, 7) illustrate a supply chain as "…network of organisations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer."

These definitions highlight that a SC consists of:

1. Various parties
2. involved in the fulfillment of customer requests whereas the
3. parties involved are linked throughout the whole manufacturing process.

In manufacturing industries, supply chains have been studied intensively during the last years. Typically, such supply chains consist of various stages depicted in Figure 3 illustrating a generic supply chain in manufacturing. This supply chain is characterized by different actors, for instance, suppliers, assemblers, and customers who take part in different processes, such as parts manufacture, sales, and finally consumption. Thereby, the supply chain is characterized by an information flow from the customer upwards the supply chain to the suppliers of the material indicating type and amount of the product requested by the customer and the derived information for preceding actors and a material flow in the opposite direction representing the chronological fabrication of the product.

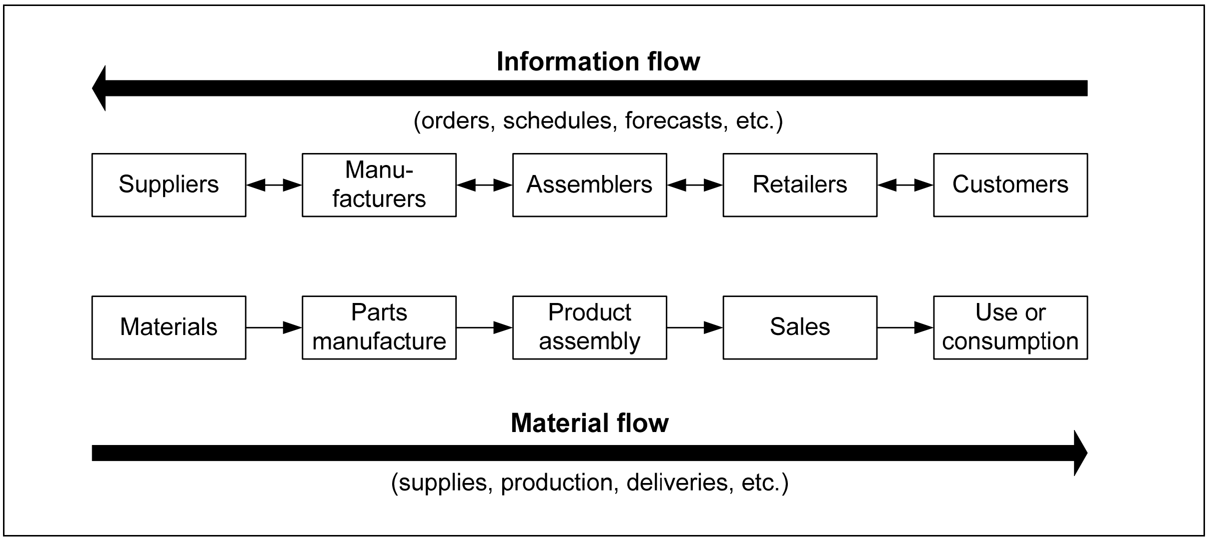

Figure 3: Generic configuration of a supply chain in manufacturing

(Vrijhoef and Koskela 2000)

However, construction supply chains are more complex than supply chains in manufacturing industries. Figure 4 illustrates a typical construction supply chain (CSC). The CSC, which is realistically rather called construction supply network, is a customer driven multi-tier supply network on a temporary basis and consists of two major parts: the organizations responsible for on-site production, assembly and installation of systems and numerous suppliers, e. g. architects, engineering consultants, and users. Thereby, the CSC is a converging supply chain as input materials are delivered to the construction site where the building is assembled. In contrast to the manufacturing industries, where multiple products are produced in one factory and are delivered to customers, the products of construction are of one-off nature manufactured at the place of its destination, as discussed in section 2.1 (Vrijhoef and Koskela 2000, 171).

A typical CSC has the main contractor located at the centre with external links to the client, main supply agencies in terms of sub-contractors and suppliers of materials and components and design and specialized services provided by architects and consultants (Dainty et al. 2001, 164). Generally, the contractor is in charge of the assembly of a number of different materials and components as well as of the integration of various systems and suppliers. Assembling the various systems and components on the construction site, the contractor can be referred to as a system assembler. Therefore, a wide scope of services is provided by architects, engineering consultants and cost consultants who exert strong influence on the product and its construction process (Nicolini et al. 2001, 38).

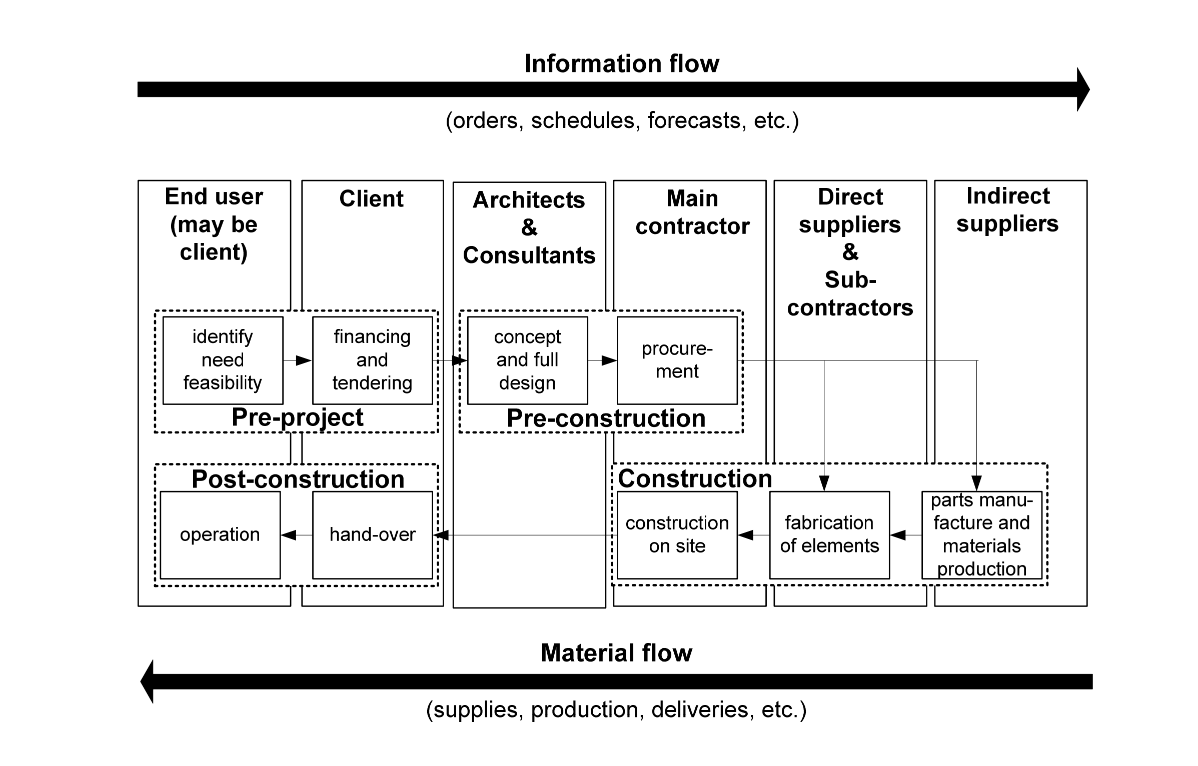

Figure 4: Typical configuration of a construction supply chain

(Cox and Ireland 2006, 407)

As construction projects are temporary activities in which multidisciplinary teams collaborate for the common purpose of delivering the project within defined start and finish dates, the CSC is also a temporary supply chain; i. e. the CSC is unique for each construction project each characterized by a new and reconfigured organization structure. At the end of the project, these collaborative relationships are disbanded and may be reconstituted on the next project. This means, that the constitution of the CSC for a project might be changing from project to project, and, hence, planning based on forecasts, the realization of learning affects or the application of standardized planning approaches is aggravated. Besides its temporary nature, the CSC shows instability, fragmentation and is characterized by a separation between design and construction (Tha 2005; Vrijhoef and Koskela 2000, 171). Thereby, the end-customer, whose role can be found at the start and end of the CSC, is the initial force of the construction process. These aspects do not only cause that standardized planning approaches and the development of a master schedule like in other industries cannot be applied but also that production cannot take place prior to a tender and bidding process. Hence, in section 4 a project planning approach is developed, considering both, the need for early information on the timing of project activities for the tendering process and the necessity of a more detailed planning based on available information of the project environment in conjunction with project progress.

Abstracting from the construction project phases, depicted in Figure 4, monetary flows as well as the directions of information, and material flows between the actors in the CSC could be considered, as depicted in the SC relationship model in Figure 5. The figure shows the various actors of a construction project who cooperate directly or indirectly with the general contractor and the other participants of the projects and the directions of flows of material and funds as well as of materials between them.

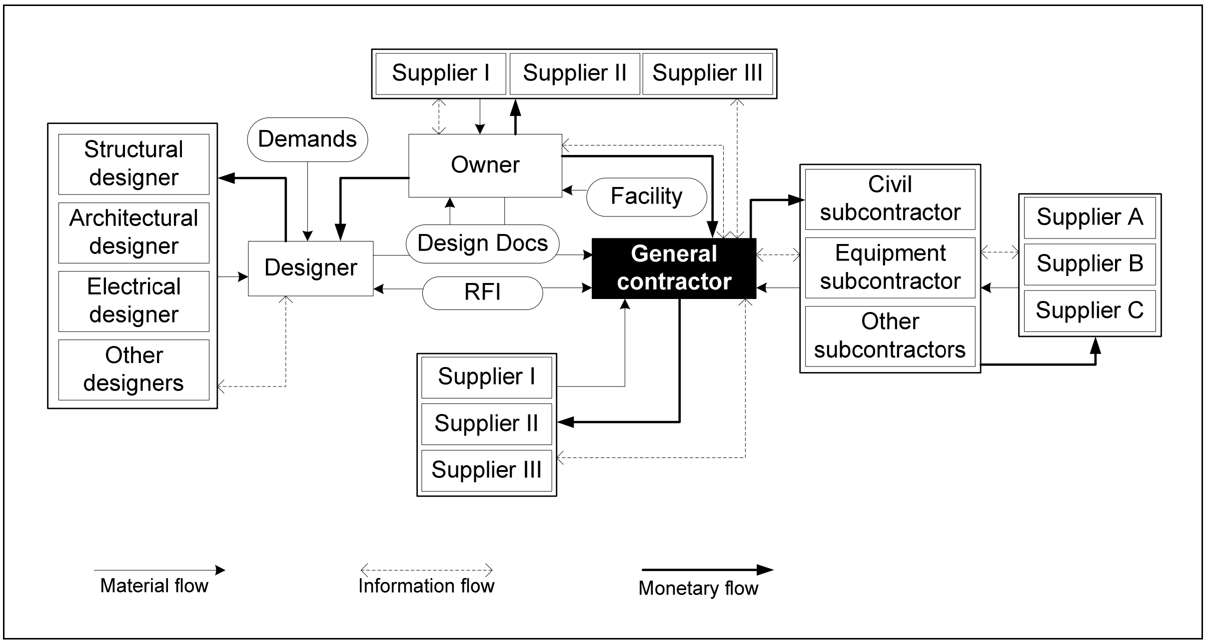

Figure 5: CSC relationship model

(Xue et al. 2007, 151)

Furthermore, the CSC comprises several sub-supply chains as depicted in Figure 6: the materials SC, the labor SC and the equipment SC which adds complexity to the application of SCM to the construction industry (Cox and Ireland 2006).

2.4 Stakeholders and their objectives

Projects in construction, as well as in any other industries, are subject to a variety of external and internal influences. These influences result, among others, from the interests of individuals or groups which claim to have a stake on the project and its outcome (Olander and Landin 2005, 321). The groups and individuals having an interest in the project are referred to as stakeholders. According to Freeman "…a stakeholder in an organization is (by definition) any group or individual who can affect or is affected by the achievement of the organisation's objectives…" (Freeman 1984, 46).[6] Stakeholders comprise, for instance, the owner or client, employees, suppliers, customers, the government, competitors, the media as well as environmentalists.

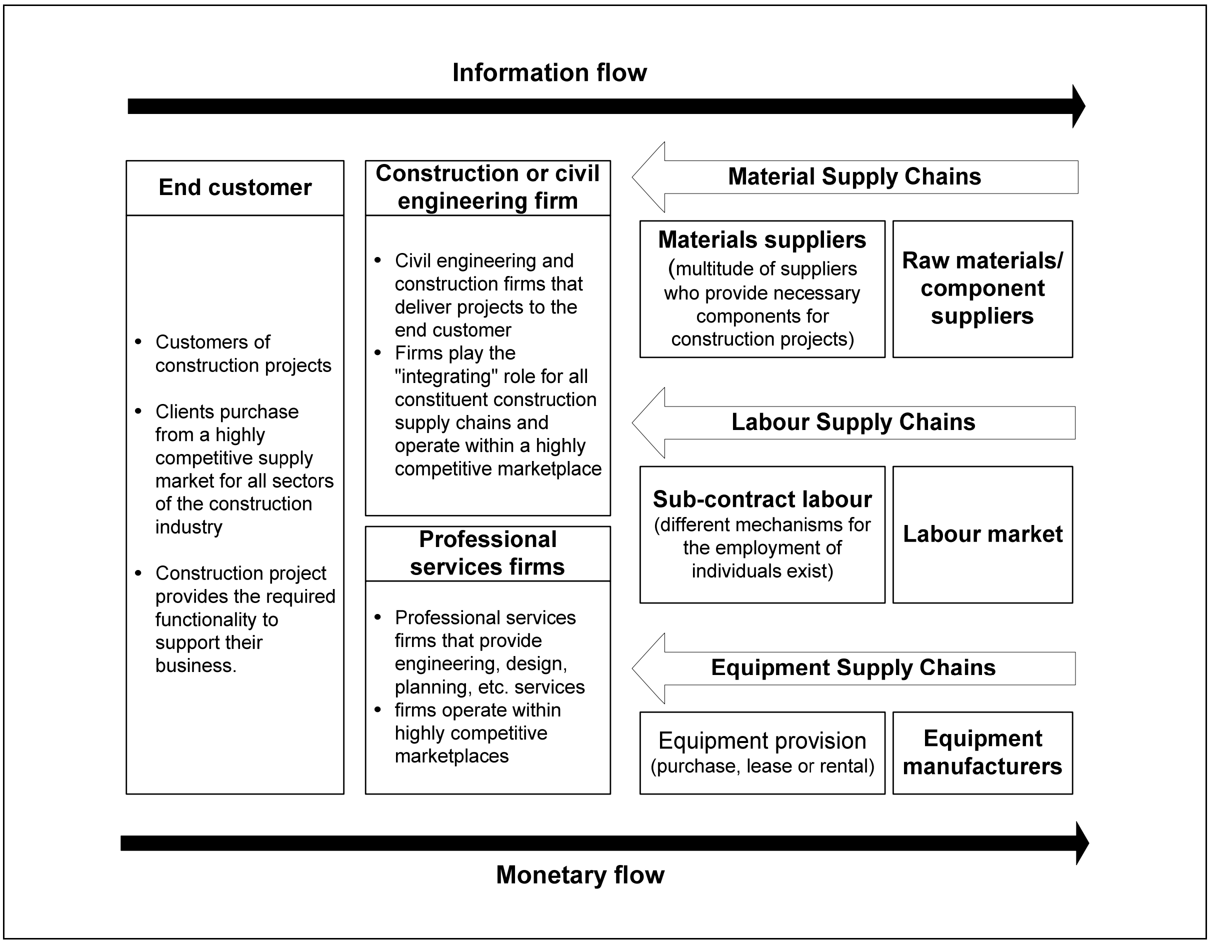

Figure 6: The myriad of construction supply chains

(Adapted from Cox and Ireland 2002, 411)

The specific structure and group of stakeholders varies from company to company as well as from industry to industry. The interests of stakeholders are diversified and sometimes also discrepant. Hence, they often lead to lively arguments and conflicts about the implementation of a project (Olander and Landin 2005, 321). Concluding, stakeholders significantly influence the success of a company or project. Hence, project failures, such as:

- Poor scope and work definition,
- inadequate quality and quantity of resources assigned to the project,

[6] An overview about definition approaches for 'stakeholder' in the literature as well as an extended discussion of these approaches is given in (Mitchell et al. 1997).

- unforeseen regulatory changes, and
- negative community reaction

could in principle be tackled by project planners and managers by actively integrating stakeholders and their interests into the planning process of a project (Jergeas et al. 2002, 18).

Groups of potential stakeholders can be further distinguished into internal stakeholders and external stakeholders. Internal stakeholders are in legal contract with the client and are further separated into internal demand side and supply side actors. In the construction industry, internal stakeholders comprise the construction company or project owners, usually with a financial stake in the project, as well as organizations, teams and individuals who have a contractual relationship with the project owner, for instance, construction material suppliers and employees. In contrast, external construction stakeholders are broken down into private and public actors as Table 1 reflects for the client of a construction project. They might inert a positive or negative influence through political lobbying, regulation or direct action and include governmental organizations on the local, national and international level, different interest groups like non-governmental organizations (NGOs), environmentalists, trade unions or residents in the vicinity (Donaldson and Preston 1995; Ward and Chapman 2008; Winch and Kelsey 2005, 67).

Table 1: Selected construction project stakeholders

Internal Stakeholders		**External Stakeholders**	
Demand side	**Supply side**	**Private**	**Public**
Client/Owner Financiers Client's employees Client's tenants Client's suppliers	Architects Engineers Consultants General contractor and related parties Trade contractors and related parties Materials suppliers	Local residents Local landowners Environmentalists Conservationists Archaeologists	Regulatory agencies Local government National government

(Winch and Kelsey 2005, 67)

Each of these groups of construction stakeholders follows particular objectives. Hence, the success of a construction project may have to be evaluated by different types of performance measures. These measures depend on the type of the project which is undertaken and on the particular objective of each of the stakeholders involved.

Generally, the objectives of construction project stakeholders can be classified into four broad categories (Schultmann and Sunke 2006):

- Economic objectives, for instance, the minimization of the project duration, and the maximization of project profit,
- technical objectives, for instance the adherence to safety requirements, the application of appropriate construction techniques, and the warranty of quality,
- social objectives, for instance, the pareto-optimal consideration of stakeholder interests, and the generation of value adding to social welfare, as well as
- sustainable objectives, for instance to create a sustainable built environment, the employment of environmental-friendly construction techniques, and the minimization of resource depletion and reduction of emissions.

For example, the client's major interests, besides the successful execution of its project, lies in technical objectives related to safety and in sustainable objectives. Technical objectives comprise the compliance to health and safety requirements during project execution as well as safety requirements regarding the product, in terms of use of safe materials and construction practice. Sustainable objectives refer to, for instance, the carbon footprint, pollution, waste generation and habitat destruction. In contrast, financiers of a construction project are mainly interested in economic objectives and related organizational requirements, i. e. good governance, transparency and leadership integrity of the project to ensure success of the project. Other objectives, such as technical, social or sustainable objectives are less important to them. Community groups, such as local residents, landowners or environmentalists are strongly focused on sustainable objectives, such as the use of sustainable materials (Moodley et al. 2008).

Some of these categories are in a conflicting relation. An example is the implementation of sustainable deconstruction techniques to reduce energy consumption as well as to facilitate the avoidance of waste by ensuring high material recovery. Usually, this process is time intensive and requires the use of expensive technology. The results are longer project spans and higher costs for labor and, even might result in delay penalties. Hence, these particular interests and conflicts have to be considered for project success. In accordance to the raising attention for environmental issues from governments, NGOs, global agencies and the general public, the construction sector can no longer afford neglecting objectives of certain interest groups, holding a stake in a sustainable environment (Ofori 1992, 369–70). Current project planning approaches like CPM, MPM or PERT do not offer options for the consideration of various stakeholder interests. Hence, in section 4.2.5 suggestions are made for the simultaneous integration of stakeholder interests into the project planning process.

3 Planning in construction

As discussed in sections 2.1 and 2.3 the construction industry suffers from unstable demand cycles and a proliferation in subcontracting which reinforces the fragmentation of the production process (Dainty et al. 2001). In addition to the peculiarities of the construction industry, the management of major projects is complex involving a high degree of coordination and dynamic decision making to maintain adequate control over the project (Tha 2005). Therefore, in the following, project planning in construction as currently practiced is addressed, performance problems are revealed and the potential of capacity oriented project planning for construction projects is discussed. As the efficient organization of the procurement of project resources is vital for their availability on site when needed, procurement strategies for project resources are elaborated. These procurement strategies refer to a classification scheme for project resources. This classification scheme is based on a well-known classification scheme for products from manufacturing industries which will be adopted to project resources.

3.1 Characteristics of construction projects and project delivery systems

The literature about project management holds quite a large number of definitions for the term project. According to Klein (1999, 3) and Slack et al. (1998) a project is characterized by the following elements—for detailed information see also, for instance, (Shtub et al. 1994; Spinner 1997):

- *Objective*: Every project has a defined output which is typically referred to costs, quality and timing of the project or its activities.
- *Uniqueness*: A project usually has a one-time character; i. e. it is unique as it possesses features which avoid completely reducing its execution to a standardized and always repeatable process. Even similar projects like the construction of a fab with equal specifications may differ in terms of resource consumption and environmental conditions. Therefore, a construction specific organization is established.
- *Complexity*: The relationships between the various sub-activities performed to achieve the goal of the project tend to be very complex. For example, both minimal and/or maximal time-lags may have to be specified between the start times of activities. Additionally, more than one project might be carried out simultaneously which causes a high interaction between single projects.
- *Temporary*: Projects have a defined start and end date. This requires a concentrated use of resources to carry out the project. Additionally, the duration of the project is restricted by the achievement of the project objective and is terminated as soon as the purpose of the project is fulfilled.

- *Resources*: Resources to realize the project are usually restricted. This refers to the budget, the availability of human resources, and to the equipment.
- *Uncertainty*: Generally, a project involves a considerable degree of uncertainty. Although projects are planned in advance they carry an element of risk which is not to be neglected. Potential causes of uncertainty include variations in the performance of resources, inadequate or inaccurate data, and the inability to forecast satisfactorily due to the lack of prior experience.
- *Life cycle*: Each project passes through a life cycle which often comprises of five phases: conceptual project design, project definition, project planning, project execution, and project termination.

Construction industry projects involve complex packages of work, for which design and contracting organizations are responsible; the product is generally large, discrete and prototypical (Abeyasinghe et al. 2001). In particular, the high number of internal and external stakeholders changing from project to project, the high consumption of a heterogeneous mix of different materials, equipment and labor, as well as the production environment which changes from project to project due to the on-site character of construction leads to constantly changing project planning problems. Not just that the contractor highly depends on outside project parties and, hence, it has to be coped with a combination of multiple objectives (see section 0). Further externally given constraints such as construction specific legislation, in particular environmental legislation and, for instance, seasonal dependency due to the high amount of outside work also add to the complexity of construction projects.

The main particularities of construction industry projects are:

- Shifting production sites,
- spatial constraints,
- seasonal dependency,
- construction specific legislation, in particular environmental legislation,
- time/resource trade-offs,
- concurrency of multiple projects,
- highly uncertain planning environment, and
- combination of multiple objectives: time, cost, quality, resource leveling.

For the organization of construction projects, different project delivery systems exist. In contrast to the stakeholders of the construction industry as addressed in section 0, the main three parties directly involved in a construction project are the owner or client, the designer and the construction organization. For the successful execution of a construction project, these parties have to define their contractual relationship and decide upon the span and duration of the responsibilities of each party. Therefore, the owner or client has to choose between different delivery systems for construction projects (Bennett 2003, 12). In Germany, applied construction project delivery systems are “Totalübernehmer”, “Totalunternehmer”, “Generalübernehmer”, and “Generalunternehmer”. They differ in the scope of services (engineering and/or construction services) as well as on the amount of services delivered on own account. While the “Totalübernehmer” authorizes the majority of engineering as well as construction services to other parties, the “Totalunternehmer” is involved into sub-contracting with construction firms. In contrast, the “Generalüber-” as well as the “Generalunternehmer” are responsible for the construction and related sub-contracting activities. In contrast to the “Generalübernehmer”, the “Generalunternehmer” processes major activities on its own account. In the Anglo-American speaking regions, more diversified project delivery systems have emerged. The most well-known and only briefly introduced project delivery systems are[7]:

1. The traditional design-bid-build,
2. design-build,
3. construction manager (CM),
4. project manager,
5. document and construct, and
6. separate prime contracts.

The design-bid-build (DBB) delivery system, closely related to the German “Generalunternehmer”, has been most commonly used in the past. In this system the client contracts with a design organization (an architect or an engineer), which is responsible for the preliminary planning, the carrying out of the design work and for the preparation of the contract documents. After the completion of this project phase, a construction contractor is selected according to the client’s criteria and the construction on-site is started. The main characteristic of the DBB system is the separation of the design and the construction phase and, hence, also the separation of the contracts the client has to agree upon with a design and a construction organization. Usually, the design organization as well as the construction contractor subcontracts works to several sub consultants and subcontractors who also subcontract work packages to subcontractors. Exemplarily, Figure 7 shows a possible scheme for the organization of a DBB system in simplified form. Not shown in the figure are, for instance, further sub consultants and subcontractors as well as material suppliers.

[7] Similiar explanations can be found in other books and standard work on construction project management. An extensive literature review for basic principles on project delivery systems does not add knowledge to the subject. Thus, reference is made to (Bennett 2003) only.

Due to the separation of design and contractor work, the project's design work must be completed before tenders are solicited and construction work can first begin after a successful tender has been selected. Therefore, this procedure is very often time consuming and lacks the integration and cooperation between the project partners (Bennett 2003, 12). Nevertheless, advantages of this delivery system are that a certainty or price and clarity of roles exist and a risk of coordination between the two parties does not exist for the owner. Instead it is easy for the owner to accomplish changes during the design stage. However, due to the three step procedure an overlapping of the phases is omitted and a fixed price is firstly established late in the process. Thereby, the client administers the design as well as the construction contracts while the contractor itself has no influence on the design process (Bennett 2003, 28).

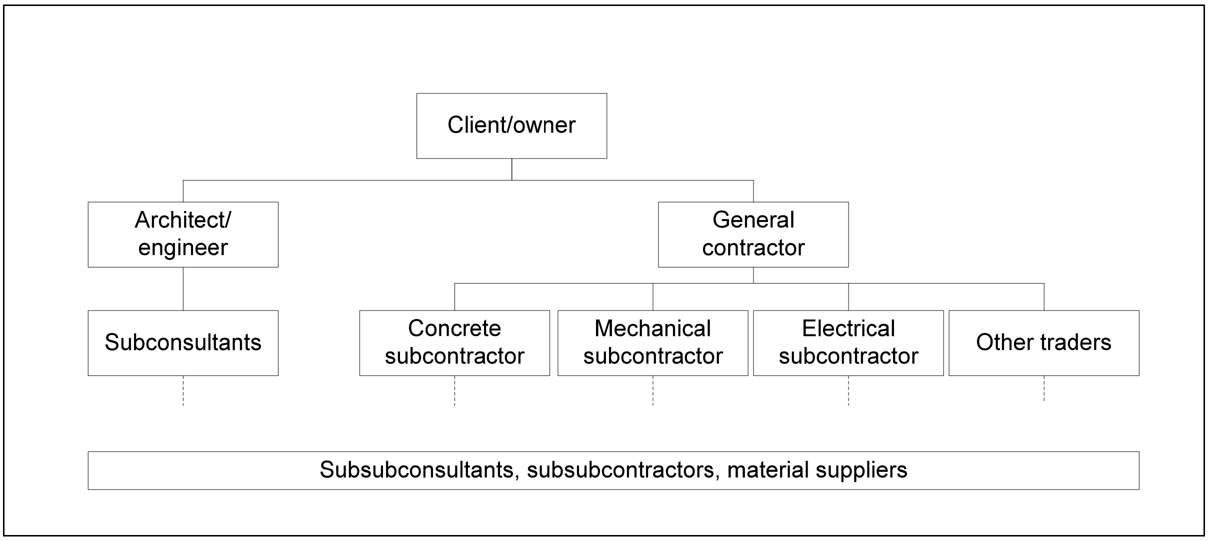

Figure 7: Traditional design-bid-build delivery system

(Bennett 2003, 13)

In the design-build (DB) system the owner contracts to only one enterprise which is responsible both for the design as well as for the construction phase of the project. Hence, the owner only communicates to one organization and the responsibilities as well as liabilities are clearly defined. Cost and time savings can be realized as the occupied enterprises work as teams together in a project where the construction phase can partly overlap with the design phase. However, difficulties arise in fixing the price as long as the design phase is not yet completed and the tender periods are short. Furthermore, it is in the owner's responsibility to control the construction activities to ensure high quality.

Another construction project delivery system is the engagement of a construction manager (CM) who provides professional construction management services. These services include advice on all construction matters, such as construction costs, schedule, safety and the construction process throughout the project life cycle or for specific issues. For the engagement of a construction manager, two management arrangements exist: ‘agency’ CM and ‘at-risk’ CM. In the ‘agency’ type the owner only employs the CM as an adviser for a fee and additionally holds contractual relationships with separate contractors and design organizations, similar to the DBB delivery system (Figure 8).

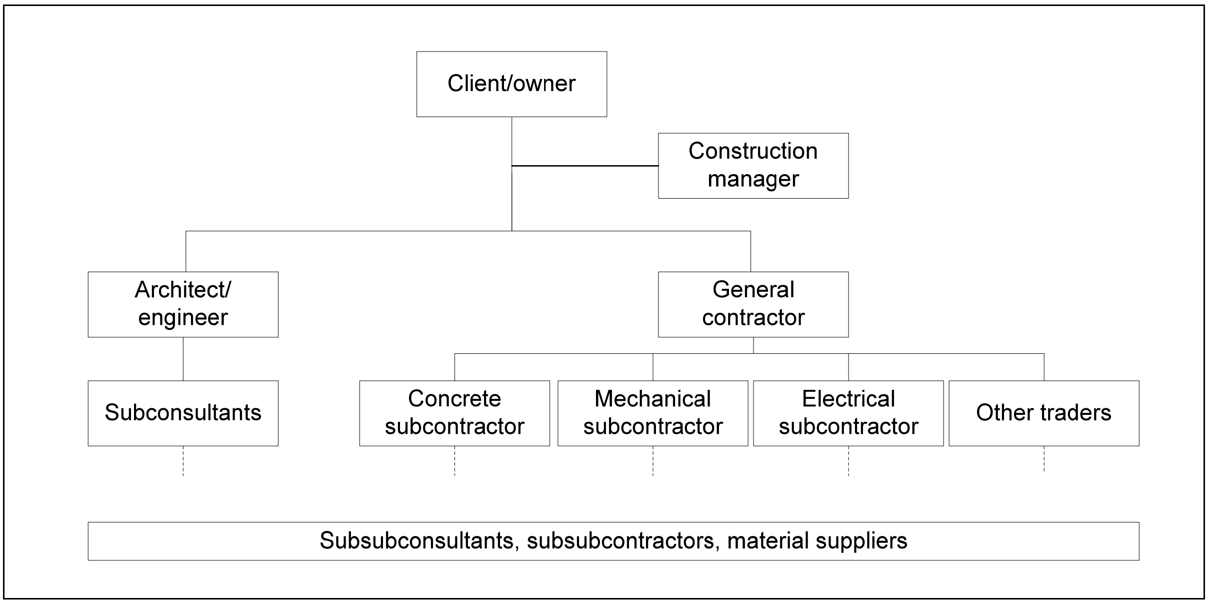

Figure 8: Agency construction manager delivery system

(Bennett 2003, 16)

In contrast, in the ‘at-risk’ construction management arrangement the owner contracts with a CM organization, which in turn contracts to various subcontractors and trades. The ‘at-risk’ CM gives professional advice on all issues related to construction, very often also before work on-site starts.

In this delivery system the ‘at-risk’ CM replaces the general contractor of the DBB delivery system. However, in contrast to the DBB system where the general contractor delivers part of the construction work itself, most or all of the construction work is executed by subcontractors under the ‘at-risk’ CM. Thereby, the contracts with the subcontractors are often in the name of the client and, hence, subcontractors might draw on the owner for payment however, although the ‘at-risk’ CM directly contracts with subcontractors (Bennett 2003, 16–7). Thereby, similarities can be drawn to the German “Generalübernehmer”, whereas here the “Generalübernehmer” is responsible for resulting duties from contracts.

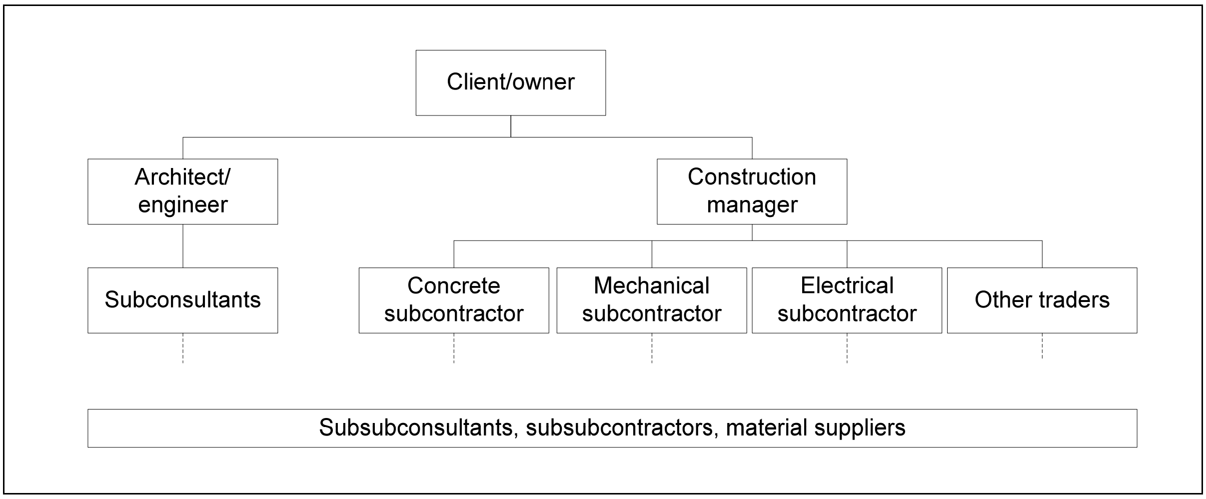

Figure 9: At-risk construction manager delivery system

(Bennett 2003, 17)

In the project manager delivery system, the owner hires an independent project manager and hands the entire project over to the project manager who manages the project on the owner's behalf (Figure 10). The underlying assumption is the 'outsourcing' of the responsibility for the entire project to a separate firm on behalf of the owner, similar to the German "Totalübernehmer". This might be the case if in-house experience is not sufficient to undertake a construction project and temporary professionals are needed to arrange and control the planning, the design and the construction process. The project manager itself has the choice between the various delivery systems already mentioned, i. e. he could decide to use a DBB or CM 'at-risk' approach for project execution (Bennett 2003, 18).

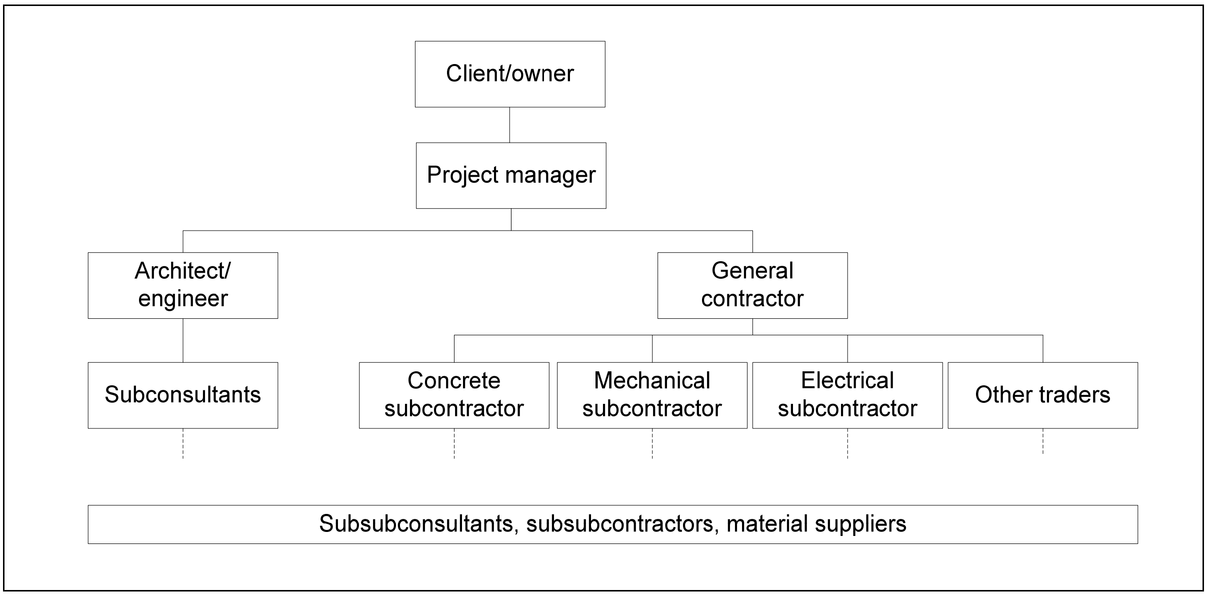

Figure 10: Project manager delivery system

(Bennett 2003, 18)

The document and construct delivery system is a variation of the DB arrangement. In this system, the client contracts to a design team which is responsible for the development of a project concept, the overall schematic layouts, the performance specifications and further design details essential for the selection of a general contractor or construction manager through a tender process. After the selection of the contractor, the contract between the client and the design organization is transferred to the contractor. This process is called *novation*. With the novation, the contractor becomes the only responsible person to the contractor for the remaining design as well as for the construction, similar to the DB delivery system, as shown in Figure 11.

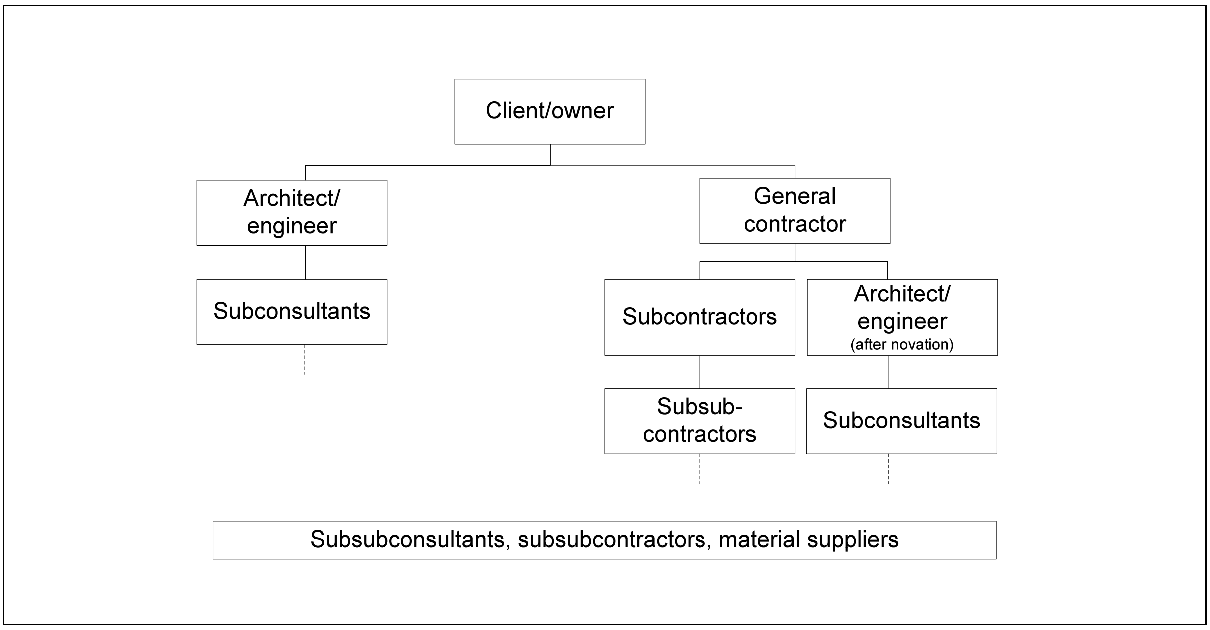

Figure 11: Document and construct relationship chart

(Bennett 2003, 19)

Apart from the advantages of the DB system, the owner exerts greater control on the planning and specification of the project. However, in addition to the disadvantages of the DB arrangement, the design organization lacks knowledge und suffers uncertainty about the party to which it will be contracted to in future project phases (Bennett 2003, 19).

The last system, the separate prime contracts, is different to the others as the owner directly contracts with individual specialty contractors also referred to as prime contractors due to the absence of one general contractor. Very often, an agency construction manager is engaged to advice the owner on all questions related to construction and coordination etc. (Figure 12).

However, as the CM is only bound to the owner, while the owner or client organization is responsible for the coordination of the prime contractors. Due to the absence of the general contractor, separate prime contracts must to cover every kind of work necessary to complete the project as the owner usually does not have own construction forces (Bennett 2003, 20).

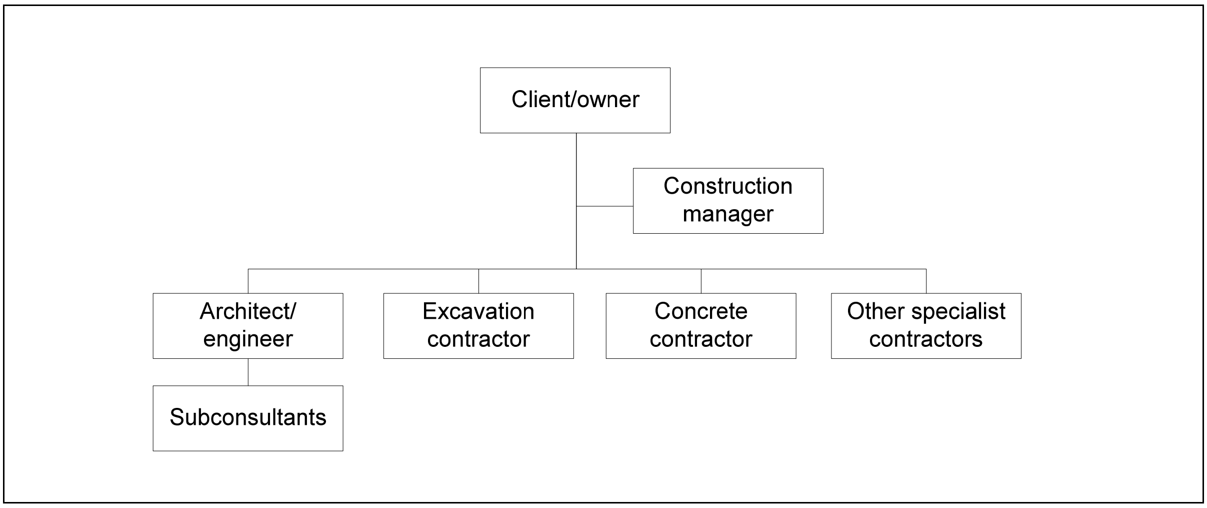

Figure 12: Separate prime contracts relationship chart

(Bennett 2003, 20)

Summarizing, the general structure, advantages and limitations of the above discussed delivery systems are summarized in Table 2.

Further arrangements for project delivery exist (Bennett 2003). These comprise, for example, the turnkey contract, the build-own-operate-transfer (BOOT) system as well as the force account approach. The turnkey system is similar to the design-build delivery system; i. e. the owner contracts solely with a turnkey contractor but additionally includes services such as project financing, land procurement etc. After completion of the project the owner inspects the work arranges payment if the requirements are fulfilled, ‘turns the key’, occupies and operates the facility. It is characterized by an overlapped sequence of design and construction phases while the procurement begins during the design stage. The BOOT system is often used for public infrastructures. In BOOT projects a private company finances, designs, builds, operates and manages the facility. After a predefined concession time, the facility is transferred to the public sector free of charge. Examples are parking lots, tunnels or roads, where costs are covered from the parking fees, tunnel or road charges. Thereby, BOOT is part of the public-private-partnership (PPP) scheme.

Table 2: Delivery systems in construction - a comparison

Delivery system	**Features**	**Advantages**	**Limitations**
Design-bid-build	Separation of design and construction responsibilities Completion of design prior to contractor selection	• Certainty of price • Clarity of roles • No coordination risk to owner • Easy to accomplish changes during design	• No phased construction possible • Fixed price established late in process • Owner administers all design and construction contracts • No contractor input to design
Design-build	Single organization responsible for design and construction	• Single point responsibility • Constructability input during design • Fixed price early in process • Phased construction possible	• Difficult formulating price prior to design • Lack of oversight by designer • Costly tendering process • Less control by owner
Construction manager	Professional manager to advice owner and designer on construction aspects Two types: Agency (advisory role only) At-risk (responsible for on-site performance)	• Construction expertise available in design phase • Construction manager provides advice to owner during construction • Allocation of certain risk to construction manager under at-risk system	• Increased overhead costs • Increased risk of owner under agency system • Owner relinquishes some control
Project manager	Professional manager to advice owner and designer on all aspects of project	• Owner relies on project manager for coordination of most aspects of project • Potential for rapid project start-up and prosecution	• Owner relinquishes considerable control • Increased overhead costs
Document and construct	Early design performed under contract to owner Later design performed (possibly by the same designer) under contract to contractor	• Fixed-price contract and complete documentation before construction starts • Centralized responsibility • Constructability considered during design	• Designer may not control for whom it ultimately works for • New and unfamiliar method • Limitations similar to design-build
Separate prime contracts	Owner contracts with individual specialty contractors	• High degree of control by owner • Cost savings in engaging general contractor • Potential for effective phased construction	• Requires owner construction expertise • General contractor risks assumed by owner • Less clear relationship between designer and on-site activities

(Bennett 2003, 28–9)

The role of PPPs has increased significantly during the last years, triggered by inefficacies of government funded infrastructure projects and budget deficits at the same time facing an ageing infrastructure and growing demand in public services. Thus, PPPs have become the preferred way for the provision of public services in many countries. “A public-private partnership is an arrangement between public sector and private sector investors and businesses (the Private Sector) whereby the private sector on a non-recourse or limited recourse financial basis provides a service under a concession for a defined period that would otherwise be provided by the public sector.” (Leiringer 2006) Its aim is the risk transfer to the private sector, which is expected to manage project risks better and more efficiently due to its higher managerial and technical skills. In turn, this means that infrastructure services may be provided at cheaper costs and of higher quality (Ahadzi and Bowles 2004; Jin and Doloi 2008 and cited literature). In addition to the BOOT system, PPPs comprise most common contractual arrangements between the private and the public sector, such as build-operate-transfer (BOT), build-transfer-operate (BTO), design-build-operate-finance (DBOF) as well as design-construct-manage-finance (DCMF) (Leiringer 2006). Last but not least, the force account approach can be used for relatively small, uncomplicated projects that have to be built for the owner’s use. With this approach the owner carries out the work with its own forces, provides field supervision, materials, equipment and labor (Bennett 2003, 20-3).

3.2 Current practice in construction planning

Construction and engineering firms, as stated before, are usually operating on a project level and, hence, are generally organized as matrix or project based organizations. Planning situations in matrix and project based organization are typically unique and differ from project to project (see section 2.1 and 2.3). Additionally, more than 90 % of these firms face a situation where they have to cope with more than one project at a time (Payne 1995, 163) competing for limited resources. The performance of a project from a contractors point of view, here understood as the adherence to delivery dates, budget, quality—regarding the triangle time, cost, and quality—as well as stakeholder satisfaction, is significantly influenced by the quality of the project management. In the following sections, construction project planning is briefly introduced with the related tasks and methods which are currently applied in practice. Based on this discussion, the performance of construction projects, as a result of the quality of the construction project planning process is analyzed with reference to existing surveys on international construction projects.

3.2.1 Project schedule and construction project planning approaches

Project management comprises the conception, definition and planning of a project as well as its execution and termination, as depicted in Figure 13. Project planning consists of project structuring with the tasks of project scheduling and resource allocation. Whereas the aim of project scheduling is to determine start and finishing dates of project activities, the objective of resource allocation is to ensure the sufficient and timely supply of resources for project execution (Klein 1999). Normally, resources are not available in unlimited amount. After all, at least the most important project resources are scarce. In construction projects, these resources comprise money, labor, equipment and construction materials. The timely allocation of scarce labor and equipment to construction projects is objective of construction project planning. Thereby, the selection of the appropriate project planning method for allocation of the scarce resources labor and equipment is prerequisite for efficient project planning. Efficient is thereby described as 'as accurately as possible, but as loose as necessary'.

The result of project planning is a project schedule, i. e. a definition of a set of starting and finishing times of project activities. A project schedule is not just a valuable instrument in communication and coordination of processes with external partners in the company's inbound or outbound supply chain. It also serves both the planning of project activities and a related resource assignment to each activity considering some measure of performance as well as the planning of external activities. Hence, a schedule can be understood as source of information for advanced booking of key staff or equipment which especially refers to a multi project environment. Furthermore, on the basis of a reliable schedule external activities are planned, such as delivering data for material procurement, preventive maintenance or the delivery of orders to internal or external customers. In the company's environment cooperation between the actors in the supply chain includes the settlement of agreements on time windows for the work by subcontractors and especially the agreement on the delivery of material, the planning of supporting activities (setups, supporting personnel), the settlement for due dates for the delivery of project results and cash flow projections based on a schedule for budgeting (Herroelen and Leus 2005a, 107).

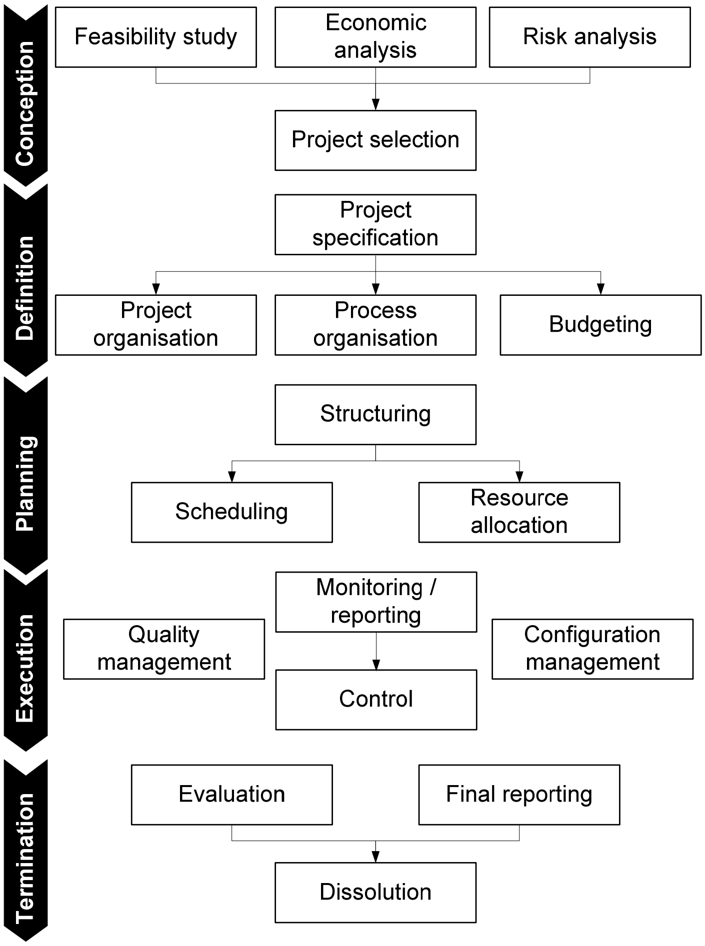

Figure 13: Project management life cycle

(Klein 1999)

Since the late 1950s, CPM, MPM, and PERT[8] have been focus of intensive research effort and acknowledged a wide spread use by practitioners in management and control of large-scale construction projects (Galloway 2006; Winch 2006, 257–67). However, the construction industry differs significantly from other industries as discussed in sections 2.1 and 2.3. Main particularities are changing production sites, multiple simultaneous projects and, hence, allocation of resources from site to site. Bearing the complexity of the construction project planning problem in mind, these project planning techniques cannot satisfy the specific needs of project planners in the construction industry. In 2005, a study showed that the available project management software could not fully satisfy requirements of project planners and did not always guarantee a user friendly and easy to comprehend application (Herroelen and Leus 2005a, 104).

[8] For further reading on the critical path method (CPM), the metra potential method (MPM), and the programme evaluation and review technique (PERT) see (Pinedo 2005, 54–61; Winch 2006, 257–67).

Nevertheless, project scheduling in practice, especially in the construction industry, is still often conducted with rather simple techniques, such as common project planning approaches like the mentioned CPM, MPM, as well as PERT or Gantt charts focusing on time oriented objectives and network diagrams when activity durations and precedence relations are known and deterministic (e. g. Allam 1988 and related literature). Their main advantages are the explicit representation of activity relations and their easy application. Paradoxically, however, even though a lot of scheduling procedures have been developed and tested for construction purposes, the scarceness of resources is often either neglected in scheduling approaches or seen as of minor importance in initial schedule generation in practice (e. g. Herroelen and Leus 2005a).

Nevertheless, over the last two decades IT applications have played significant roles in construction project planning both with respect to technology development and project level applications. Among them are the development of a variety of tools for project planning and scheduling as well as 4D modeling and virtual prototyping. Tools for project planning comprise, for instance, Oracle's Primavera P6 Professional Project Management for large-scale projects and Microsoft Office Project 2007. Initiated by the lack of spatial representations in two-dimensional diagrams, such as bar charts or critical path network charts, further techniques have emerged. These techniques comprise three-dimensional (3D) and four-dimensional (4D) modeling as well as virtual prototyping. 4D modeling is based on three-dimensional (3D) computer-aided design (CAD) methods by integrating and allowing the interaction of additional data for schedule information in the 3D model (Chau et al. 2005). For instance, Chau et al. 2005 developed a 4D site management model aiming at linking scheduling data to a three-dimensional computer graphics building model in order to provide planners with a graphic simulation tool of the construction process at any particular date. Thereby, their prototype model extends the 4D technology, used for the planning of building construction, with aspects of resource management and site space utilization. Further research undertaken on 4D project planning can be found in Chau et al. (2005); all authors given emphasize the applicability and use of computer graphics as scheduling tool. However, current 4D models do not cover all the information required to evaluate the schedule. Nevertheless, although building components and construction equipment usually modeled in the 3D images are linked with the schedule in the 4D planning, the 4D systems do not comprise issues such as scaffolding or other temporary works, which are originally part of the 3D model. In particular, the space needed for the execution of an activity and the potential congestion of the site caused by temporary work is not reflected. With this respect, virtual prototyping has been introduced. Virtual prototyping (VP) is a computer-aided design process during which digital product models, so called ‘virtual prototypes’ are generated to allow realistic graphical simulations. Thereby, aspects such as the physical layout, the operational concept, the functional specifications, and dynamics analysis under various operating environments are addressed. Its purpose is to enhance the effective communication of designs and ideas without the manufacturing of physical samples (e. g. Xiang et al. 2004; Shen et al. 2005; Huang et al. 2007). VP has already been implemented successfully in the manufacturing industries, such as the automobile industry. In contrast, construction process simulation with VP has been limited, mainly because the uniqueness of construction projects and the therefore specific project conditions and constraints. Research efforts which have been undertaken to apply VP to construction project planning are given in Huang et al. (2007). With this respect, Huang et al. (2007) have shown the benefits of VP in construction. They introduce a construction virtual prototyping (CVP) system which allows project teams to evaluate constructability and safety of a construction project as well as to visualize 3D models of a facility prior to construction works. This includes the site layout, the temporary work design, as well as resource planning (Huang et al. 2007).

However, especially for the numerous SME in the construction industry, the high investments necessary for the procurement, implementation (including installation and training of workers), and the maintenance as well as necessary knowledge transfer present an obstacles for the implementation of these IT applications. Additionally, they provide a toolbox covering a much wider scope of functionality than necessary for the purpose of SME of the construction industry. Hence, these parties are reluctant to make use of these applications as the end not entirely justifies the means.

Concluding, 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. This is also reflected analyzing the performance of construction projects.

3.2.2 Performance of construction projects

The construction industry, more than any other industry, still suffers a poor image and is known for the often poor quality of its products and projects which are over budget and beyond time (Fenn 2006, 249). Additionally, the construction industry is prone to contractual disputes, also known as *adversarial attitudes* of the project participants, whose occurrence has risen significantly recently and negatively affects the industry. Disputes in construction have a long history and several mainly empirical studies have been conducted and published on the causes of disputes between the parties of a construction projects. A comprehensive overview is given in (Fenn 2006). While some authors claim, that the main reasons for disputes cover aspects such as risk allocation, design changes and handling during project execution (e. g. Lewis et al. 1992; Revay 1992) others mention fairness and clarity of contractual arrangements, payment as well as construction delays as main causes for disputes in construction (Al-Momani 2000; Assaf and Al-Hejji 2006; Kumaraswamy 1997). Both, the late delivery as well as cost overruns in projects jeopardize project success leaving the client of the construction project unsatisfied and the contractor with expensive and time consuming dispute resolution and extensive claim management efforts. Hence, despite the careful organization of contractual agreements and establishment of reliable partnerships, delays could be avoided considering success factors for construction projects. For an extended overview it is referred to (Fenn 2006).

Delays in construction projects have negative effects both for owners and contractors. While owners suffer of loss of revenue through, for instance, a lack of production facility, dependence on present facilities or a loss of income from rentable space, the contractor faces higher overhead costs due to, for example, longer work periods, higher material costs caused by inflation as well as increases in labor costs (Assaf and Al-Hejji 2006, 349), not to mention the damage of the company image and decreased chances in future bids. Analyzing project delays, they can be classified according to their origin, i. e. related to the owner, the contractor, or caused by a third party. However, still it is the contractor who has to provide evidence for the cause of the delay by one party (Lee 2003, PS.14.1). Thereby, owners might cause delays throughout all phases of the project life cycle whereas the contractors responsibility can be found only in the phases in which they perform work.

Several studies on causes of delays of construction projects have been conducted[9] and it has been shown that approximately one-third of all construction projects are beyond time and budget although these are key competitive factors (Yeo and Ning 2002). According to surveys among construction practitioners the causes are, among others, constant changes in project requirements, the development of multiple projects at the same time delaying less important projects, deficient communication between project partners, a lack of available resources—e. g. a shortage of site workers and technical personal, late delivery of construction materials, insufficient number of equipment—and equipment allocation problems as well as a vague definition of the scope of project budget and schedules (Ogunlana et al. 1996; Yates and Eskander 2002; Yeo and Ning 2002). With this respect, causes of delays could be related to different groups, for instance, to (Assaf and Al-Hejji 2006, 325–6; Sambasivan and Soon 2007, 520): the client, the contractor, the consultant, the contract itself, the design, materials, labor and equipment, as well as external factors, such as weather changes, regulatory changes and unforeseen events. Among the ten most important

[9] For reasons of simplification an extended literature review on studies investigating causes of project delays is not conducted. Literature reviews summarizing the results of proceeding studies can be found in papers, e. g. by (Al-Momani 2000; Assaf and Al-Hejji 2006; Chan et al. 2004; Fenn 2006; Sambasivan and Soon 2007). As a detailed investigation of existing studies does not further support the argumentation of the thesis, it is therefore obsolete.

causes of project delays mentioned by owners in a survey in Saudi Arabia among owners, contractors and consultants are ineffective planning and scheduling of the project by the contractor as well as conflicts encountered with subcontractors' schedule, besides, for instance, a shortage and low productivity of labor and inadequate contractor's experience. Contractors mention the delay in progress payments by the owner, design specifications as well as late procurement of material as causes, while consultants refer to, among others, the type of project bidding and award, a shortage of labor as well as ineffective planning and scheduling of the project by the contractor (also mentioned by the owners) and a delay in material delivery (Assaf and Al-Hejji 2006, 354). A similar result is gained in a survey among 150 construction practitioners in Malaysia. Among the ten most important causes of delays in construction projects, improper planning was considered to be most important followed by a, among others, a shortage in material (rank 6) (Sambasivan and Soon 2007, 522). Hence, from several studies two major causes for delays which refer to the planning of the project as well as to materials management can be identified; i. e. delays are caused by insufficient scheduling and the non-availability of material and resources on-site.

Further discussing *insufficient scheduling* of construction projects four characteristics of project schedules exist, which are in correlation with the performance of a project (Griffith 2005, PS.05.2): Integration of all project phases into a single schedule, application of CPM, resource-loading of project schedule, detailed review of the schedule by the core project team. Referring to project planning, i. e. scheduling and resource allocation, especially the application of CPM as a simple network and resource-loading could help to reduce construction project delays. Network techniques force project participants to break down the project into smaller pieces of work and define precedence relations between the discrete activities. The resulting schedule could be used for project controlling during execution. However, a schedule simply defining start and finishing times neglecting the availability of resources does not always present a feasible solution for project execution. The definition of the type and amount of resource consumption of each activity and assignment to the activities according to their availability results in an adjusted schedule. Based on the schedule considering limited resources, critical resources can be identified and resources can be leveled as well as managed, especially if there is more than one project to run. An analysis among 494 capital projects in the heavy industrial sector revealed that at the time of project authorization around 50 % of the schedules were based on CPM techniques and only further 24 % of the schedules were resource loaded (Griffith 2005, PS.05.4).

Regarding material management the *non-availability of material* on site has been identified as one major and most common frequent cause for delays in construction projects (Ibn-Homaid 2002 and related literature) although costs for construction material make up a considerable percentage of overall construction costs. Hence, without adequate planning of material procurement and delivery, disturbances in project cost, schedule, and quality are likely expected to occur (Tserng et al. 2006). Therefore it is to note, that material orders are set based on the initial schedule. Hence, the more appropriate the initial schedule and the better the materials procurement and management process is organized the higher the probability of availability of material on site when needed.

Accordingly, causes which are related to the planning of projects, hence, to scheduling and materials management are well known problems in many projects and significantly influence project success (Assaf and Al-Hejji 2006; Chan and Kumaraswamy 1997; Faridi and El-Sayegh 2006, 1169). Concluding, a key factor to ensure project success in addition to the selection of appropriate project partners, the experience of the project planner, the project organization, and appropriate information flow between project partners is an:

1. Efficient resource allocation during the scheduling of the project and a
2. proper materials management.

Both causes will be addressed in detail in sections 4 and 5.

3.3 Resource oriented project planning in construction

In section 3.2.2 it was shown, that the construction industry suffers poor project performance which can be traced back to insufficient project planning practices. Usually conducted with CPM, MPM and PERT the project schedule has to be adjusted to limited resource availabilities afterwards. Simulation or planning approaches from Operations Research, such as resource-constrained project scheduling with the well-known resource-constrained project scheduling problem (RCPSP) integrating the scheduling as well as resource allocation process, represent an appropriate alternative to planning methods, such as CPM, MPM and PERT.

The choice of a solution method to solve a particular resource allocation problem strongly depends on the combination of the specifications, i. e. on the type of construction project referring to:

- Its objective,
- the number of projects to be planned,
- the resource types and availabilities as well as
- the time horizon and project participants.

Hence, different project types can be identified for which planning strategies can be derived. Generally, two groups of projects can be differentiated:

1. Repetitive projects, and
2. general project structures.

For both types of projects, different planning methods can be applied. At first, the specific type of repetitive construction projects is discussed and scheduling approaches especially developed for this particular type of projects and partly implemented in practice are introduced. Then, the focus is drawn to projects with a generalized activity structure and the role of resource-constrained project planning models suggested for this particular type of construction projects in literature is shown. Finally, a comparison of common project planning approaches, such as CPM, MPM, and PERT, as well as resource-constrained project planning approaches, like the RCPSP and its extensions, is given. Thereby, the need for resource-constrained project planning approaches is highlighted and further explicated in section 4.

3.3.1 Project planning approaches for repetitive projects

Particular project types in construction are repetitive projects. Hereby it is differentiated between horizontal and vertical repetitive projects. Horizontal repetitive projects, like highway, pipeline or tunnel construction, are also considered as continuous repetitive or linear projects. In linear projects project progress is measured in terms of horizontal length due to the linear nature of the geometrical layout and work accomplishment, i. e. a number of activities following each other linearly. In comparison, vertical repetitive projects describe the type of projects in which units of work packages are repeated throughout the project in discrete steps, for instance in high-rise building construction or housing communities. Therefore, this type of project is also referred to as discrete repetitive project. These project types have already attracted intensive research. In contrast to traditional concepts like CPM or PERT, various scheduling methods considering work continuity constraints to reduce resource idleness in repetitive projects have been proposed, as outlined in (Harris and Ioannou 1998, 269; Vanhoucke 2006, 14).

Usually, the line of balance (LOB) method is applied to repetitive project planning problems. It consists of various graphical and/or analytical linear scheduling techniques. These techniques include, for instance, the linear scheduling method (LSM), the time space scheduling method (TSSM), the vertical production method (VPM), velocity diagrams as well the repetitive project model (RPM) and line of balance scheduling (Lutz and Hijazi 1993, 100). An overview on literature differentiating between solution methodologies for horizontal as well as vertical repetitive projects is given in (Harris and Ioannou 1998). For vertical repetitive projects methods like the LOB, the construction planning technique (CPT), VPM, as well as the TSSM exist. For linear projects velocity diagrams and the LSM can be applied. Other techniques developed comprise the repetitive scheduling method (RSCM) (Yang and Ioannou 2004), techniques for stochastic resource-constrained scheduling for repetitive construction projects with uncertain supply of resources and funding (Yang and Chang 2005) or resource-driven scheduling of repetitive activities (El-Rayes and Moselhi 1998). A recent selection of literature in scheduling of repetitive projects is given in (Tokdemir et al. 2006).

The proposed methods have been exceptionally designed for repetitive projects and are customized to its particularities. However, if one wants to consider more general project types, these methods cannot be applied. However, to reveal the scope of project planning approaches for particular project types repetitive projects were briefly discussed. In the following, the focus is shifted to project planning approaches for generalized projects.

3.3.2 Project planning approaches for generalized projects

For more general types of projects, optimization models, such as the RCPSP, have been introduced. RCPSP models seem to be suitable for more general types of project planning situations and offer freedom for the integration of construction specific particularities into the generation of a construction project schedule. Thereby, various objectives can be considered in the planning and resource allocation process. Common objectives in construction project management and scheduling are, for instance, the minimization of project durations under multiple resource constraints (Moselhi and Lorterapong 1993), the minimization of the total project delay (Tsai and Chiu 1996) as well as the minimization of costs of total resource consumption, including time and a leveled resource distribution (Karshenas and Haber 1990). Furthermore, objectives like maximizing the total project net present value by considering project delay penalties and early completion boni (Chiu and Tsai 2002) as well as finding the optimal resource selection optimizing time and cost objectives of a construction project (Burns et al. 1996) are pursued. Additionally, considering the case of repetitive activities, objectives might address the minimization of crew idle time (El-Rayes and Moselhi 1998). Finally, project management can address the generation of a schedule-dependent site layout planning (Elbeltagi et al. 2001). In section 4.2, the concept and the application of the RCPSP and its extensions is discussed in detail for selected construction specific particularities of projects.

3.3.3 Common versus resource-constrained project planning

A synopsis of traditional as well as resource-based project scheduling approaches for the criteria *scope*, *basic principle*, *capacity planning*, *number of projects*, *objective*, *constraints*, and *uncertainty* is given in Table 3.

Table 3: Brief comparison of CPM, MPM, and PERT with RCPSP

Scope	**Common planning approaches (CPM, MPM, PERT)**	**Resource-constrained project planning (RCPSP and extensions, see section 4.2)**
Basic principle	- Time based	- Resource based
Capacity planning	- Sequential (succeeding resource leveling)	- Integrated
Number of projects	- Single	- Single: RCPSP - Multiple: Resource-constrained multi project scheduling problem (RCMPSP)
Objective		
Type	*One type:* - Time: Min project duration	*Various types:* - Time: e. g. MIN project duration, MIN project delay, MIN mean activity delays - Money: e. g. MAX cash flow, MIN additional resource costs - Resources: e. g. MAX resource leveling - Environment: e. g. MAX energy savings
Relation	- Single	- Single - Multiple
Constraints		
Precedence constraints	*One type:* - Finish-to-start	*Various type, e. g.:* - Finish-to-start - Start-to-start - Min-max time lags
Processing modes	- Single	- Single: RCPSP - Multiple: Multi-mode resource-constrained project scheduling problem (MMRCPSP) with time-resource, resource-resource and time-cost trade-offs
Resource types	- No consideration of resources during initial schedule generation	- Non-renewable (e. g. budget) - Renewable (e. g. equipment, labor)[10]
Uncertainty Activity durations Resource availability	- Probabilities: PERT	- Applies to activities and resources - Probabilities: Stochastic resource-constrained scheduling - Possibilities: Fuzzy Scheduling

[10] Renewable and non-renewable resources are discussed in detail in section 3.4.1.

The strength of the RCPSP refers to the integrated time and capacity planning and the consideration of various resource types, as discussed in detail in section 4.2.1. This is especially important, as construction projects are characterized by a high consumption of a heterogeneous mix of different equipment and labor. Furthermore, it is applicable in construction for a wide variety of objectives, which accommodates the various direct and indirect stakeholders of a construction project, as highlighted in section 3.3.2. The possibility to extend the constraints allow for the consideration of externally given constraints, such as regulations on waste management and the explicit representation of stochastic values for the duration and resource consumption of activities compensates the lack of knowledge on the exact distribution of this occurrences.

In contrast, CPM, MPM and PERT leads to a rather rough plan without direct consideration of capacity constraints. Nevertheless, in addition to the fact that CPM, MPM and PERT are already proven in practice, they can compete with its easy to comprehend character, the less amount of information needed (activity durations, probabilities, resource consumption and availabilities for succeeding resource leveling), and, hence, its easy computing, and implementation in current project management software.

However, although the RCPSP apparently seems to be superior, the other side of the coin of a more realistic description of the planning problem due to more information has to be regarded as well. On the one hand models become more complex due to the risen number of constraints and variables. Hence, although efficient heuristics to solve the problem have been developed high computing times still occur due to this complexity. On the other hand, the more information required, the more information have to be gathered which is either time consuming or not possible due to a lack of information and the unique nature of the projects.

Concluding, both traditional as well as resource-constrained (i. e. RCPSP and extensions), project planning approaches coexist legitimately because of their appropriateness for various planning contexts. Thereby, the achievement of the project’s objectives significantly depends on the availability, the amount and the costs of resources to be allocated to projects and their corresponding activities over the project time horizon, hence, the quality of the project schedule. For construction projects, these resources can be distinguished according to different criteria.

3.4 Development of procurement strategies for project resources

Resources in construction projects usually comprise money, labor, equipment, and material as well as more intangible resources like know-how and information. While the allocation of labor and equipment is the objective of project planning, money is subject to project financing and investment strategies. The planning and allocation of materials is subject to procurement strategies and supply chain management.

Considering the planning effort for scheduling and resource allocation, appropriate planning should be dedicated to the different type of resources according to the maxim ‘as accurately as possible, but as loose as necessary’. Therefore, labor and equipment are differentiated and classified by various criteria, such as renewability, supply variance, mobility, consumption pattern etc. Based on this classification a differentiation between critical, non-critical and risk prone resources can be conducted and planning strategies determining the planning effort and suggestions for appropriate project planning approaches can be derived. Based on this differentiation, suggestions can be made for the organization of project structures or sourcing of labor and equipment to achieve a low criticality of resource pool.

3.4.1 Characterization of resources for project execution

For an efficient project planning a differentiation of resources according to the risk they are exposed to is necessary. This risk refers to different criteria, as summarized in Table 4, and can be used to define how critical a resource in the project planning is. A first differentiation can be made according to the criterion *renewability*. Renewable resources are resources which are only available in a limited amount per period, for instance machines or workers whereas the amount of available renewable resources might vary from period to period. If resources are non-renewable they are constrained over the whole planning horizon or project duration, e. g. budgetary constraints. Thus, non-renewable resources represent cumulative resources which are consumed over time without being replenished. Finally, doubly-constraint resources are defined to be limited both per period and over the whole planning horizon, for example the budget which is ‘renewed’ at the beginning of every month but is limited in its total amount for the project (Slowinski 1979, 455–6; Weglarz 1979, 522). Hence, doubly-constrained resources can be described as a combination of renewable and non-renewable resources and therefore do not need to be considered as separate resource type in further reflections (Talbot 1982, 1198–9). Usually, labor and equipment are renewable resources.

However, to reduce the complexity of the project planning problem and to provide a basis for a selection of particular resources for detailed resource planning, further classification criteria, besides the renewability, have to be applied. Concluding, project resources can further be distinguished and evaluated according to the criteria: Technology/know-how, value, mobility, type of supply, supply variance, demand variance and procurement pattern.

Table 4: Criteria for resource categorization

Criteria	Specification	
Renewability	Renewable	Non-renewable
Technology/Know-how	Common technique / low skilled	Highly specialized / high skilled
Value	Low value / cost insensitive	High value/cost intensive
Mobility	Immobile	Mobile
Type of supply	In-house	Third parties (lease, rent, buy)
Supply variance	Steady	Variable
Demand variance	Steady	Variable
Procurement pattern	Time independent	Time dependent

Technology of resources mainly addresses construction equipment which can either be common technique (e. g. excavator in construction) or special technology, usually manufactured and configured for a particular project (e. g. formwork) or only rarely used in most projects (e. g. drilling units for installation of geothermal heat units). *Know-How* refers to the knowledge and skills of labor, i. e. to workers. In construction projects labor includes, for instance, project managers, site managers, construction workers, and craftsmen. While construction workers are likely to be replaced due to the standard type of skills required, site or project managers are more likely to be selected carefully, not just because of their knowledge but also because of the costs or wage for their work.

The *value* of a resource addresses the price—for equipment—or wage—for labor—and their sensitivity to market changes, for instance, change in interest rate. Low value equipment, such as hammer, wheelbarrows or shovels in construction is more likely to be procured without difficulty if broken or not available in sufficiently high amount. In contrast, high value or cost intensive equipment, e. g. digger, crane, freight elevators or scaffolding underlie stronger restrictions in planning subject to overall project profitability. Reasons are on the one hand more costly procurement and on the other hand the dependency on the availability of financial resources.

Especially in a multi-project environment resources have to be shifted between different places, e. g. construction sites. Thus, in such environments the *mobility* of resources needs special attention. Whereas mobile resources belong to a pool of resources available to all projects, e. g. pool of workers or construction equipment, immobile resources belong to a particular project and cannot be consumed by other projects. Examples for immobile resources are the project budget and purpose made equipment.

The *type of supply* of a resource is differentiated into *in-house supply* and *third party supply*. The latter consists of the options, for instance, lease, rent or buy. In-house supply suggests that the resource availability is more likely to be controlled easily within the enterprise, whereas third party supply also depends on suppliers outside the scope of the enterprise. This may apply to the leasing of cranes or lifts. However, the existence of either one of the two options, in-house or third-party supply also presents a potential risk. This becomes obvious if in-house supply is not possible due to, for instance, resource consumes in other projects and an opportunity for third-party supply does not exist.

The *supply variance* addresses the variance of the amount with which a supply with the corresponding resources is possible. While a steady supply would most likely be possible for resources in a sufficiently high amount (e. g. shovels, etc.), variable supply variance occurs, if equipment or labor cannot be freed over the planning horizon at any point in time.

In contrast to *supply variance*, the *demand variance* describes the amount or pattern of resource demand, i. e. the stability of resource utilization. It is also differentiated into variable and steady. Variable demand occurs, for instance, for equipment which strongly depends on the project phase. Steady demand exists for equipment, but also for facilities (e. g. sanitary facilities, generators, or water supply), which are required over the whole project time span.

Closely related to the supply and demand variance is the *procurement pattern*. The procurement pattern relates to the time dependency of the supply or procurement possibility of a product. Time independent procurement occurs for instance for standard construction equipment available in retail markets. Time dependent procurement refers to either quality dependencies on, for instance, seasonal demand peaks on the market for material, labor or equipment.

To give a comprehensive example, a patented technique with the enterprise holding a unique selling proposition can be considered as cost-intensive and highly specialized equipment. This equipment is characterized by a steady supply and the absence of the opportunity of third party supply, i. e. renewable resource. However, attention shall also be paid to technology and know-how requirements or the availability of qualified personnel required for project execution which cannot be supplied in-house. Hereby it is to note, that usually purpose made equipment combines high specification of the enterprise with a high resource value and in-house supply.

3.4.2 Classification scheme for project resources

Sophisticated resource allocation does not necessarily mean to precisely allocate all resources of a project. In order to reduce complexity of the planning procedure, it is be advisable to rank resources or their impact on the stability of the project schedule according to certain criteria. A well established procedure for the ranking and classification of objects is the ABC/XYZ analysis known from material requirements planning (MRP) and inventory classification (Zipkin 2000; Grochla 1978).

The *ABC analysis* is a traditional well known and practical approach for the efficient control of huge amounts of inventories of distinct goods. It classifies the inventory into different groups based on a single measure such as annual revenue or annual consumption (Ng 2007, 344). Based on the classification appropriate inventory control policies or warehousing and dispatching strategies as well as approaches for the determination of material requirements can be derived to reduce stock and, hence, storage costs. For instance, Group A inventory items amount up to 70 % of the company's revenue but only 10 % of the inventory which usually requires a deterministic MRP as they are critical and might jeopardize the business success of the company. Group B inventory items represent about 20 % of company's revenue while taking about 20 % of inventory. Group C items only contribute around 10 % to company revenue but account to 70 % of inventory and stochastic methods for MRP are seen to be appropriate due to their low value and success contribution as well as minor criticality (Grochla 1978; Ng 2007, 344; Zipkin 2000).

The *XYZ analysis* evaluates the flow of requirements of goods. It aims at determining inventory categories based on their demand and the predictability of their demand. Inventory classified as X is characterized by a constant demand, a high predictability of demand, usually high amounts procured but easy access to the goods. The just in time principle is here regarded as appropriate method for material supply. Thereby, the procurement and delivery of goods takes place at the time of consumption to avoid inventory costs.[11] Z materials or goods are identified by their highly unsteady demand and, hence, low predictability of their demand. However, procurement costs are usually low though these goods or materials are not always available and easy access is restricted. Concluding, the application of procurement in discrete orders most likely contributes to low inventory costs although longer replenishment lead time or delays in delivery might have to be accepted. Materials of category Y are situated between X and Z materials and show a seasonal increasing or decreasing demand (Grochla 1978).

[11] The just in time principle is a concept for the operation of supply chains and is further discussed in section 5.2.2. As mean to ensure material availability on site in order to ensure an efficient project execution its application to the construction supply chain is elaborated in section 5.3.4.

The combination of ABC and XYZ analysis results in the two dimensional product classification as depicted in Figure 14.

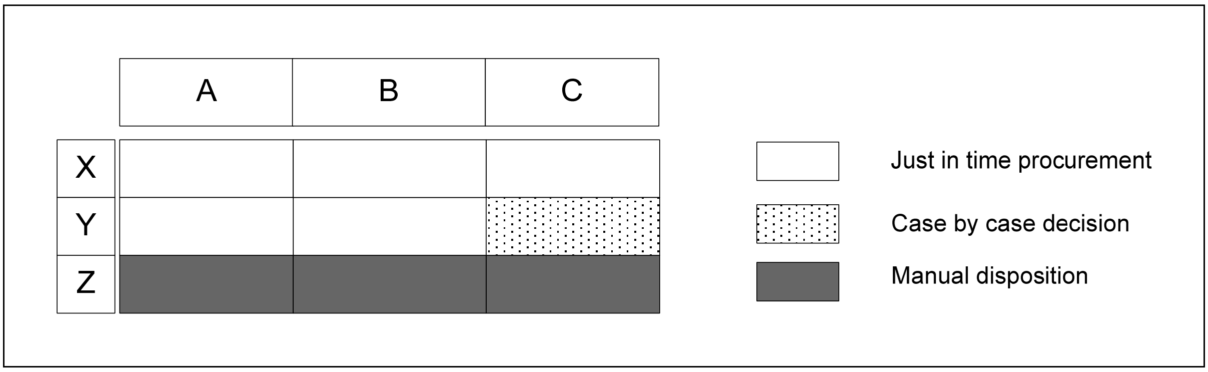

Figure 14: Two-dimensional classification

(Grochla 1978)

While just in time procurement is recommended for the combinations XA, XB, XC as well as YA and YB, manual disposition is advised for goods and materials of categories ZA, ZB, ZC, i. e. for goods with highly uncertain demand independent on their value.

Some investigators claim, that a one or two dimensional analysis of inventory is not sufficient for inventory control due to a number of other influencing factors such as inventory cost, lead time, substitutability, number of requests per year, scarcity, order size requirement, demand distribution and stock-out penalty (e. g. Ng 2007). However, a two-dimensional representation is regarded as appropriate for resource classification in projects as more restrictions and influencing factors would unnecessarily complicate project planning in a per se unstable planning environment. Thus, for resource classification an extended two dimensional classification scheme is developed. Thereby, the ABC/XYZ classification of materials as introduced is the basis for the determination of critical and non-critical resources for projects. While the availability of critical resources—usually uncertain and scarce—is assumed to be of major importance for the success of a project, the supply of non-critical resources—usually low value, standardized products—is assured in general. In dependency on the degree of criticality it must be decided on the justifiable planning effort in the resource allocation process. Hence, planning effort could be considerably decreased if each resource was planned according to its criticality.

For resource allocation purposes the transformation of the ABC analysis criteria of materials requirement planning according to the resource criteria *technology/know-how* and *value* corresponding to *value* of ABC analysis is suggested. Hence, in the ABC analysis for resource classification it is no longer simply referred to, for instance, the revenue but additionally to their qualitative equivalent reflected in technology/know-how. In XYZ analysis the criteria of *supply and demand variance* as well as *procurement pattern* represent the *demand and the predictability of their demand*. In line with this categorization, resources can be classified into critical, non-critical and risk-prone resources with the ABC/XYZ analysis of resources allocation, as depicted in Figure 15. Thereby, it is assumed that the resource classification is applied to renewable resources only. Non-renewable resources are required to execute the project and have to be available already at the beginning of the project planning in sufficient amount.

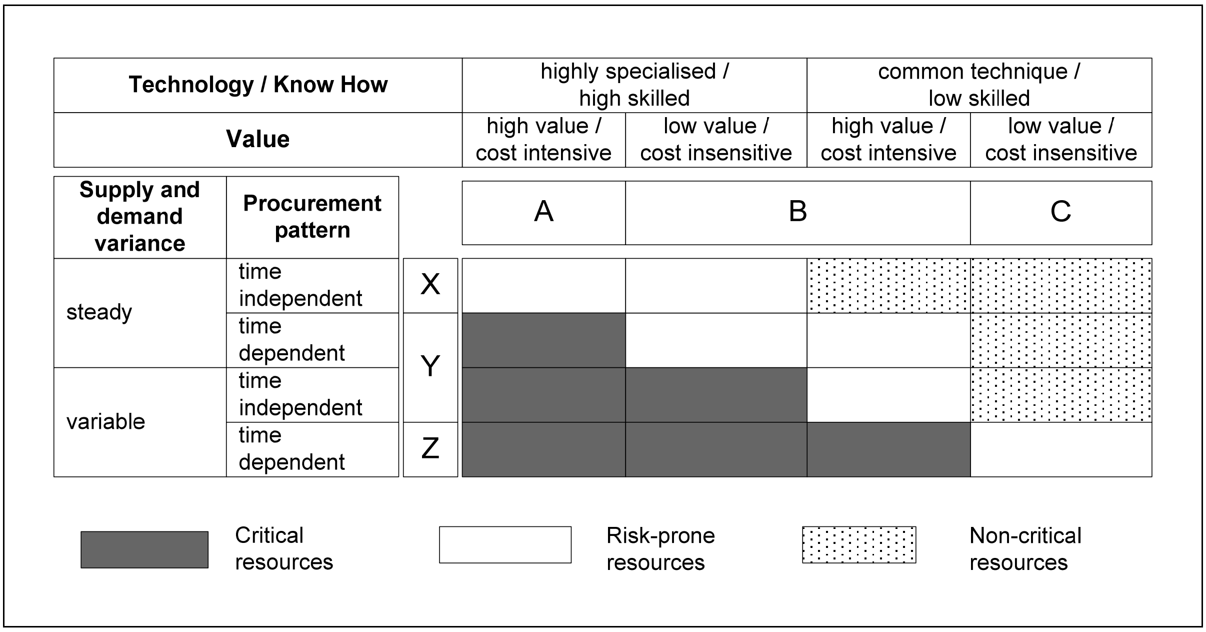

Figure 15: Resource classification

It has to be noted that for the introduced resource classification analysis the criteria of mobility, and supply type (see section 3.4.1) are not considered. Primarily, *mobility* is not considered to be as critical for project success as the chosen criteria, i. e. high value or purpose-made equipment requires high planning effort, no matter if the resource belongs to one particular project or to different ones. The same holds true for the type of supply, i. e. third-party supply and in-house supply both cause high costs if cost intensive equipment or high skilled personnel is to be scheduled. On the other hand, procurement of low value equipment does not claim for very detailed planning and allocation in advance independent on the type of supply.

3.4.3 Strategies for providing resources

Critical resources (classified as AY, AZ, BY, BZ resources according to Figure 15) are resources which can interfere with project progress and—in a worst-case scenario—also force project activities to stop and delay project finish as well as budget beyond schedule. They are characterized, among others, by a high value and limited accessibility. The high value results either from transaction or procurement costs or from costs for renting or leasing. Longer time periods for necessary equipment, e. g. a mobile crane in construction projects, and resulting longer available on-site periods, result in higher costs. Additionally, critical resources are resources which are often not easily accessible or which are not available at any particular point in time. Hence, longer lead times have to be accepted and incorporated into the project planning process.

In contrast, low value equipment can be classified as CX resource (according to Figure 15). Its supply is a necessary condition to execute the project, but due to the low criticality of the resource it is not subject of a detailed resource allocation. Hence, it cannot be considered as scarce in a sense that access and procurement is difficult and consume is unpredictable. An exception exists, if these resources can only be supplied within a defined timeframe (as CZ or risk-prone resources).

Due to the high impact of critical resources on project success, project planning should especially focus on critical resources to ensure their availability on time in order to proceed with the project. For reasons of efficiency, less effort shall be put into non-critical resources.

So far, all required resources are taken into consideration regardless of their potential to be critical. That often results either in complex planning environments or, if the availability of resources is neglected, in non-reliable schedules. Thus, in the following section, strategies for the mitigation of resource criticality are developed.

3.4.4 Strategies for the mitigation of resource criticality

Although project planning concentrating on critical resources should enable project planners to reduce risk and error-proneness in case of unforeseen events, unexpected interferences might nevertheless jeopardize schedule adherence and project success. Hence, proactive measures to avoid the occurrence of high criticality of resources have to intervene already in the characteristics of the resources.

Interferences in projects can be differentiated into:

1. The timely distortion of resource demand due to delayed preceding activities or
2. the breakdown of resources during project progress, and
3. the non-delivery of resources by suppliers.

For risk reduction in all three cases two approaches can be applied: buffering and multiple sourcing strategies. Buffering is the introduction of a safety measure to protect construction schedule while sourcing strategies are correlated with the *type of supply* of a resource. While the *type of supply* is differentiated into in-house and third-party supply, it can be further differentiated between single and multiple sourcing. While in-house supply refers to single sourcing of resources, third party supply can either be organized with single or multiple sourcing strategies. For an overview and discussion of sourcing strategies see, for instance, (Burke et al. 2007; Zeng 2000). In-house supply suggests that resource availability is likely to be controlled easily within the enterprise whilst third-party supply is expected to come along with more dependencies on external suppliers and, hence, risk. This risk especially occurs if in-house supply is not possible due to, for instance, resource consumption in other projects or non-availability of the resource. The dependency on third-parties outside the enterprise can be decreased by applying a multiple sourcing strategy instead of single sourcing. In the case of the loss of a sourcing partner resources could be bought, leased or rent at another partner's enterprise.

Buffering as well as multiple sourcing strategies could be used in project planning according to the inherent probability of occurrence of the interference. If a project delay, e. g. due to changing weather conditions, varying on-site conditions or variations in other basic parameters, is likely to be expected, an additional activity buffer could be added to the project activity. This buffer would enforce the availability of equipment or labor for a longer period than the actual activity duration. Hence, resource availability is also ensured beyond scheduled activity time and the project is not interrupted in the case of early delay. However, in contrast to project planning supported by sophisticated optimization and buffering techniques (e. g. Park and Pena-Mora 2004), it is usually in the eye of the project planner to decide upon the length of the buffer based on experience and anticipated delays. If a delay of preceding activities is not expected backup solutions, such as a multiple sourcing strategy, could on the one hand avoid additional resource costs for 'just-in-case' availability and on the other hand enable project planners to quickly find a substitute from another supplier.

In case of a resource breakdown (breakdown of equipment or a labor slack) the allocation of additional resources against additional fees is a reasonable solution. This is suggested only in case of a high probability of breakdown of machinery as a trade-off exists between resource costs and risk reduction, because additional resource costs might outweigh the risk reduction of project progress. With an underlying low probability of equipment shortage, multiple sourcing strategies, as already addressed, can be applied.

Especially in construction, long term relationships, as a necessary basis for multiple sourcing, are not yet widely established due to the project character of the production process in construction. Project cooperation's and contracts are made based on a particular project and tend to dissolve after project finish. Partnering concepts, approaches of supply chain management (SCM) (just in time, continuous replenishment, vendor managed inventory etc.) in manufacturing (e. g. Cigolini et al. 2004) as further developed in section 5.3, and multiple sourcing strategies could also be applied for construction (e. g. Cox and Ireland 2002; Dainty et al. 2001; Love et al. 2004; Tserng et al. 2006; Vrijhoef and Koskela 2000). Enterprises could then benefit from extended resource accessibility and flexible arrangements in case of unforeseen events.

3.5 Discussion of results

The investigations on current practice in construction project planning showed that the construction industry still lacks efficient project planning procedures. Main causes for project failures are thereby insufficient scheduling with respect to resource allocation to project activities and the non-availability of material on-site at the time required. It was shown, that the resources to be allocated differ in their nature and therefore require different amount of planning effort and planning detail. Thus, detailed planning, generally related with high planning effort, should be devoted to critical resources. For the identification of critical resources a resource classification scheme was introduced. The scheme allows the differentiation between the three types of resources *critical resources*, *non-critical resources*, and *risk-prone resources* based on selected criteria. Based on the characterization of critical resources, procurement strategies were developed to reduce the negative impact on project success. These procurement strategies one the one hand address suggestions on how critical resources could be provided more reliably as well as recommendation for the mitigation of resource criticality.

The resource classification can be applied to any construction project in practice. It does not only serve as a framework for resource allocation in construction project planning, but it can also easily be adapted to other project types and resources. However, the resource classification scheme according the ABC/XYZ analysis of materials requirement planning and inventory classification is subject to user-specific and project-specific particularities. For instance, concepts of SCM applied can help to reduce uncertainty and risk in resource supply and, hence, shift planning effort from the contractor to the supplier of the resources, as further discussed in section 5. Out of these circumstances, the need for more detailed investigation of related strategies in dependency on the resource class arises.

Future research should also address the enlargement of the view on the availability of construction materials. In project planning and resource allocation the availability of materials is usually not incorporated into the project planning process, as material orders are placed after initial schedule generating. However, construction materials can also be categorized according to ABC/XYZ analysis from MRP and inventory control to derive procurement and dispatching strategies based on the generated project schedule to reduce storage costs or guarantee reliable and non interference-prone material availability. In this context, the role of concepts of SCM and their adaptation from processing industries to the construction industry should be elaborated to ensure material availability on site. Hence, this is done in detail in section 5.

4 A concept for capacity oriented construction project planning

Applying the RCPSP to construction projects, optimization problems of high complexity arise. This is due to the large number of variables and the structure of the planning problem itself[12]. This not only hampers the acceptance of sophisticated planning approaches by practitioners, but also the applicability in real world construction projects. In response, a decomposition of the planning problem and use of a hierarchical planning approach could improve the quality of construction project schedules and raise their acceptance among project planners.

The objective of this section is the presentation of a hierarchical planning approach for resource based construction project planning. Within this approach, the role of quantitative resource-constrained project scheduling in the context of construction projects is investigated.

4.1 Development of an approach for hierarchical project planning

4.1.1 Hierarchical production planning and related decision levels in enterprises

An option to overcome the obstacles of complexity which is related to resource-based project planning approaches is the decomposition of the planning problem. The decomposition favors the dynamic and uncertain project environment in which project management is forced to forecast a number of prospective situations during initial planning and subsequent refinement of the project plan. Therefore, a number of decisions over a defined time horizon in increasing level of detail are required.

Decision processes of an enterprise can be related to three different planning levels. Taken from production management, these are (Hax 2001):

1. Strategic decisions, for instance, policy formulation, capital investment decisions,
2. tactical decisions comprising aggregate production planning, and
3. operational decisions concerning detailed production scheduling.

These planning levels are characterized by different types of objectives and related decisions, by the managerial level on which the decisions take place, by varying time horizons and planning frequencies, as well as by different modeling assumptions and levels of detail of data (Hand et al. 2005).

[12] It is shown by Garey et al. (1976) and Blasewicz et al. (1983) that the RCPSP is a so-called NP-hard problem.

While strategic decisions are made on an enterprise wide basis, tactical as well as operational decisions refer to the actual production line or product. Similar to production planning, project management includes planning activities which range from the strategic level to the operational level. As strategic decisions are not supposed to trigger capacity related problems they are not considered further.

At the tactical level aggregate decisions are made early in the planning process. These decisions have longer time horizons and usually cover the whole project make span. Tactical decisions comprise setting due dates and the procurement of material (Dempster et al. 1981).

In contrast, detailed decisions are made in operational planning and are usually based on more accurate information. For instance, the timely allocation of resources to project activities can be postponed just before the actual operation of a sub-project to benefit from reduced uncertainties in project progress, due to for instance, changing weather conditions or machine break downs causing project interruptions. Thereby, the scheduling of specific activities must be carried out in light of an appropriate trade-off between time, cost and resource usage (Speranza and Vercellis 1993). The time horizon of detailed decisions is necessarily shorter, usually contains the duration of one sub-project or work-package, for instance, the sub-project of deconstructing the roof within a deconstruction project. Figure 16 illustrates the decomposition of a project into sub-projects, related activities and resource assignments, whereas different activities might well consume the same resource either at the same time or in disjunctive time intervals.

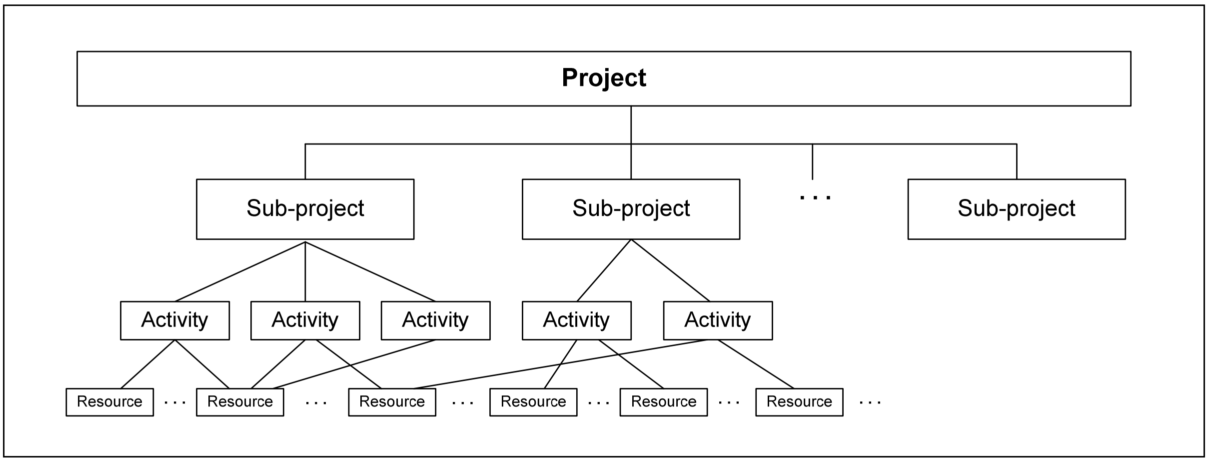

Figure 16: Decomposition of a project

For the integration of both, tactical as well as operational planning decisions, into the decision process hierarchical planning approaches are proposed as known from production planning. Hierarchical systems are supported by mathematical programming models for decision making at each level. Elements of hierarchical production planning are the decomposition, the definition of hierarchies, the aggregation, as well as the coordination (Kistner and Steven 1991). Generally, solution of a higher level model imposes constraints on the lower level, while interaction and feedback loops are allowed and ensure the integration of both levels. Reasons for the application of hierarchical planning models can be found in the reduction of complexity by decomposing the planning problem into sub-problems and the possibility to cope with uncertainties. For example, if detailed and aggregated decisions were made at the same time, much information for detailed decisions is not yet available and the decisions would have to be based on uncertain information and unreliable forecasts on future developments (Dempster et al. 1981). For further details on hierarchical production planning it is referred to (Bitran et al. 1981; Bitran et al. 1982; Bitran and Tirupati 1993; Schneeweiß 1995) and related literature.

Research on hierarchical project planning has already been undertaken. For example, Hans et al. (2005) develop a generic hierarchical project planning-and-control framework for multi-project planning under uncertainty. Thereby, they differentiate between the tactical planning where they introduce a rough cut capacity planning (RCCP) problem and the operational RCPSP. Furthermore, they give reference to prior work undertaken on hierarchical project planning, for instance, Leachman and Boysen (1985) as well as Hackman and Leachman (1989) who develop a two-phase hierarchical approach for a multi-project environment. In the first phase, due dates are selected for new projects and resources are allocated among projects. Thereby, a project consists of aggregated activities, while detailed activities with similar mixes of resource requirements are transferred into aggregate activities. In a second phase, the selected due dates and the computed resource allocations are solved as single-project scheduling problem. They propose to iteratively solve the linear programs and to update the former due dates until an acceptable resource loading plan is calculated. Furthermore, Speranza and Vercellis (1993) distinguish between a tactical and an operational level with different planning objectives. On the tactical level due dates are set and resources are allocated. On the operational level activity modes are set and the timing of the activities is determined. Their approach is based on the assumption that a set of aggregated activities forms a macro-activity on the tactical level. If precedence relations exist between these macro-activities, it is called a program. For further work on hierarchical project planning, for instance by Neumann et al. (2003), and Neumann and Schwindt (1998) it is referred to Hans et al. (2005).

Generally, large scale construction projects consist of work packages undertaken by different trades. Usually, these different trades aim at different objectives and might have different options for the organization of their work package. For instance, they have access to additional resources, they can apply various modes to activities, or they pursue different objectives like the minimization of the project finishing time or the minimization of project costs as well as the maximization of cash flows. Thereby, they could exploit the trade-off between earlier project cash-flows or boni for early completion and costs for additional resource consumption. If the project manager or contractor takes part in bidding activities, only rough estimates about the duration and cost of work packages can be given. Only after subcontracting, it is possible for the contractor to consider the particular objective of the trade; i. e. negotiating durations and costs with the trade. Thereby, the models given, usually only consider the same objectives in each planning level which is an assumption that not necessarily depicts real world situations in construction projects. Especially in reactive scheduling, objectives of projects and enterprises might change depending on the urgency of the project or the remaining budget. Additionally, in existing approaches for hierarchical project planning the resource allocation already starts on the tactical level; i. e. a rough capacity planning is processed to assign resources to particular sub-projects. On the operational level these resources are allocated in detail among subprojects and related activities. However, at the beginning of the bidding process or the construction project, the information on resource availabilities of its potential subcontractors is not available to the contractor. Concluding, a hierarchical project planning approach for construction projects should consider these particularities, for instance, allow for the integration of different objectives, constraints and the possibility of the separate planning of subprojects, as usually found in practice when work packages are executed by trades.

4.1.2 A hierarchical project planning approach

4.1.2.1 Methodology

Regarding the different decision levels when projects are addressed, project performance could be improved by explicitly considering both, tactical as well as operational decisions. This could be realized by a hierarchical planning approach, similar to hierarchical planning approaches for production planning, making use of both currently used project planning methods as well as resource-constrained project planning.

In the following, a hierarchical two-stage decomposition approach for project planning and scheduling is proposed, depicted in Figure 17. The methodology consists of decomposing the project planning process into two stages, corresponding to the tactical and operational levels. The tactical planning level, i. e. the *project level*, refers to the whole project and contains a long term planning conducted with traditional project planning methods without the explicit consideration of limited resources. The operational level, considered as *sub-project level*, concentrates on the scheduling of smaller work packages of the project, so called sub-projects, considering scarce resources.

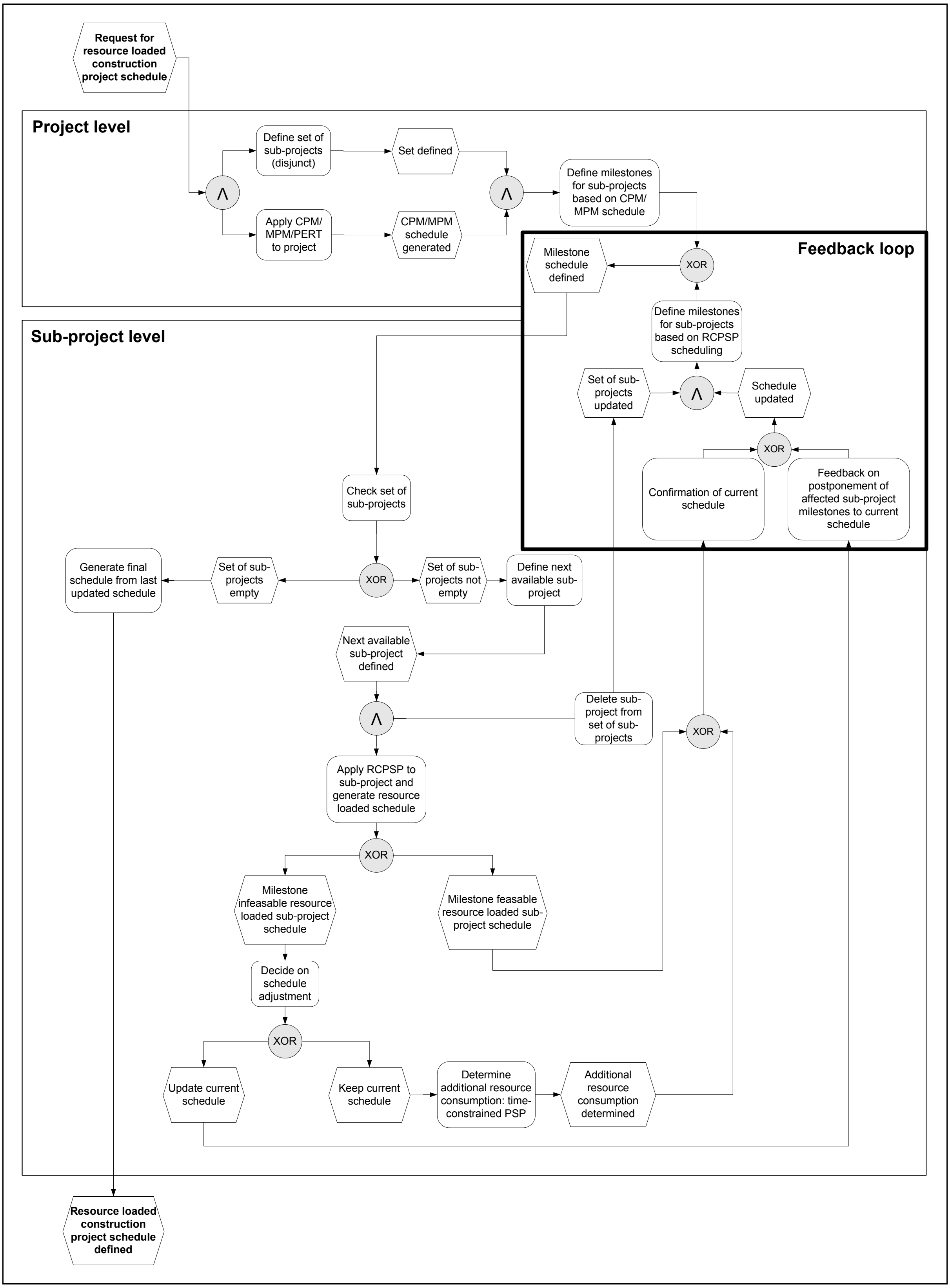

Figure 17: Hierarchical project planning approach

Both decision levels interact by means of feedback loops. In particular, higher level decisions impose constraints on lower level decisions while lower level decisions provide feedback on updated schedule times to the higher level to ensure that the project schedule is in accordance to the resources availabilities.

In particular, at first, the project objective and project structure in terms of sub-projects, activities and related estimated durations and precedence relations have to be defined on a project level. Then, methods like CPM, MPM or PERT are used to generate a project schedule with the objective of minimizing the project make span. With the resulting schedule, milestones can be assigned to each sub-project. The milestones are either based on the schedule or consider a given project due date by the client. If milestones are based on the schedule minimizing the project make span, they take buffers and critical activities into consideration. Thereby, the possibility exists that the project schedule can be resource loaded with common, yet not optimal techniques before the assignment of milestones. If milestones for sub-projects are based on a given project due date by the client, sub-projects might be allowed to have a larger buffer and milestones can be adjusted accordingly.

At the tactical level, resource availabilities in terms of integrated time and capacity planning have been fairly neglected so far. Hence, the initial schedule has to be succeedingly updated by planning the particular sub-projects in detail with an integrated time and capacity planning in the short term. Thereby, the detailed planning can be postponed just before the actual execution of the sub-projects as more accurate information become available during project progress. This reactive planning philosophy ensures that sub-projects are scheduled based on latest and more accurate information regarding, for instance, resource availabilities, interruptions of preceding sub-projects or changes in project requirements.

The necessary input data for the integrated time and capacity planning of sub-projects derives from the outcome of the planning on the tactical level with set due dates or updated information on delays in project progress and activity specifications for the sub-projects, i. e. precedence relations, detailed estimates of activity durations and resource consumption, as well as resource availability over the planning horizon. Following, the sub-projects are chosen in chronological order and scheduled considering resource limitations. Based upon the results feedback is provided to the tactical level. In particular, if the resulting sub-project schedule is feasible in terms of the project milestone schedule a positive feedback is given to the project schedule and the milestones are confirmed. If the sub-project schedule is milestone infeasible two options exist: Either the project schedule is adjusted and the succeeding sub-projects are postponed while updating the project milestone schedule or the sub-project is scheduled again by taking into account that additional resource could be supplied at a certain cost to keep the milestone schedule, for instance with the time-constrained project scheduling problem (see section 4.2.4.2), before confirmation of the project schedule. Additionally, the scheduled sub-project is deleted from the set of sub-projects and the next available sub-project is chosen for integrated time and capacity planning if operation of the sub-project is to start in the short-term. If multiple sub-projects are to be processed in parallel, approaches of multi project planning can be applied, as discussed in section 4.2.3.

Hence, the result of this planning procedure is a resource loaded project schedule on rolling time horizons benefiting from the easy application of CPM, MPM and PERT and the larger scope of the RCPSP to consider resource limitations.

4.1.2.2 Fields of application

The application of the proposed hierarchical planning approach offers two major benefits regarding project and resource planning:

1. Support of tendering and procurement or planning of critical resources, and
2. support of procurement or planning of non-critical resources.

CPM, MPM and PERT based schedules can be applied in the first stages of project planning when little information is known about project progress. These schedules support tendering activities by allowing rough estimates on project duration. Furthermore, critical resources with long lead times or high costs, comprising both renewable resources (e. g. machines and manpower) and non-renewable resources (e. g. construction material) can be allocated or ordered in advance to ensure availability on time (Schultmann and Sunke 2007c).

In contrast, resource-based schedules on the tactical level ease procurement of less-critical resources with short lead times, high availability and low costs (Schultmann and Sunke 2007c). These resources do not need to be stored on site well in advance and can be delivered just before execution of the sub-project. This also ensures that, especially in construction, site space is not congested if preceding sub-projects are delayed. For resource based project scheduling, the RCPSP, as already mentioned can be applied. The RCPSP not only integrates capacity planning but can be adapted to specific project particularities, for instance, multiple execution modes for activities and multiple objectives of different project stakeholders. Hence, especially in the short term, customized planning can increase customer satisfaction and schedule reliability.

4.2 Possible applications of resource-constrained project scheduling in construction

Having introduced a hierarchical project planning approach, the next step is to analyze the appropriateness of the RCPSP for the planning of construction projects. Being aware of the huge amount of work existing on resource-constrained scheduling in the field of Operations Research, references are exemplarily given for the most well-known extensions of the RCPSP. Literature for further reading is recommended in each section. Comprehensive review papers on the RCPSP are, for instance, (Brucker et al. 1999; Hartmann and Kolisch 2000; Herroelen et al. 1998; Herroelen et al. 2001; Kolisch and Hartmann 2006; Kolisch and Padmann 2001; Özdamar and Ulusoy 1995). Hence, instead adding another review on literature about the theoretical foundations of the RCPSP, the further sections are intended to give a comprehensive overview on solution approaches for possible planning problems in dependency on the objectives and constraints of construction projects for which the RCPSP could be applied.

4.2.1 A generalized resource-constrained project scheduling model

The RCPSP in its basic formulation describes a single project which consists of $j = 1,...,J$ activities, also known as jobs, operations or tasks, with a known constant duration of d_j periods. It is characterized by a deterministic finish-to-start precedence relation in an activity-on-node (AON) network, which means, that an activity cannot be started before all its predecessors have been finished. Figure 18 shows the AON network for the deconstruction of a house with two floors and a basement. The nodes represent the construction or deconstruction activities j (also known as jobs) of the project; 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. five hours) as well as a resource consumption (e. g. two workers, two pneumatic hammers) is assigned, whereas the duration and the resource consumption of the source and sink activity are zero.

Furthermore, pre-emption of the jobs is not allowed, i. e. whenever a job has been started at the beginning of period t it must be performed without interruption in the time periods $t,...,t + d_j - 1$, while the time points t and t+1 define the start and end of period $t+1$ as depicted in Figure 19.

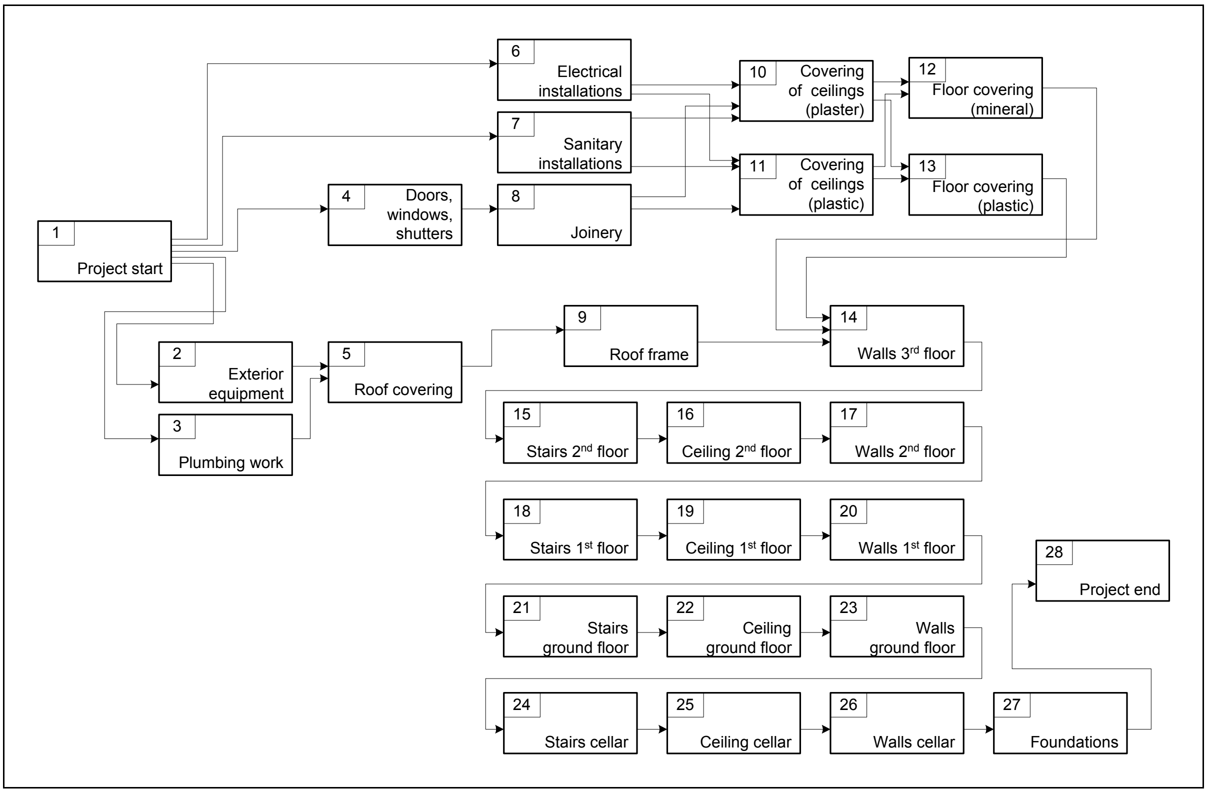

Figure 18: Activity-on-node network for the dismantling of a residential building

(Schultmann and Rentz 2002, 396)

With respect to the time in mathematical model formulation, it has to be paid attention to the *granularity of the model*. In formal models with the time t as a parameter, the planning horizon is usually divided into planning periods with $t = 1,...,T$. Each planning period is characterized by a duration. This duration might differ in dependency on the planning context. For instance, construction projects are usually operated on a daily basis, i. e. an interval of 1 day. In contrast, scheduling of busses takes place on a minute basis. In dependency on the duration of the planning period the granularity of the model varies. In particular, the shorter the planning periods are the larger the granularity of the model becomes due to the increased number of time periods to be considered. Hence, although a better representation of real world problems could be achieved by using very short time intervals the complexity of the model increases (Asbach 2008). Hence, in dependency on the planning context, an appropriate length of the planning period should be chosen in order not to unnecessarily increase the model complexity.

In addition to the prohibition of pre-emption, resource constraints have to be observed in the RCPSP during the procession of the jobs. These resource constraints are differentiated according to the renewability of the resources. Thereby, it is distinguished between renewable, non-renewable and doubly-constrained resources, which are discussed in detail in section 3.4.1.

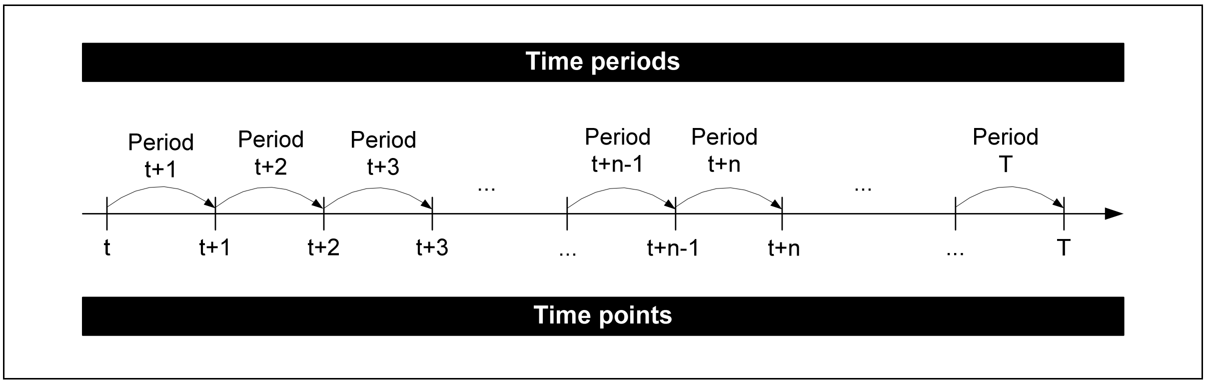

Figure 19: Time points and periods

(Klein 1999, 79)

In the RCPSP job j requires constant q_{jr} units of the renewable resource type $r \in R$ during every period of its duration. The resource type r is known and available in a constant amount Q_r over the whole planning horizon. Thus, jobs might not necessarily be scheduled at their earliest possible (precedence feasible) start time. The objective of the RCPSP is to find a non-pre-emptive schedule (i. e. a feasible schedule) by assigning starting times to the jobs such that the precedence and resource constraints are satisfied following one or more targets. An early mathematical programming formulation was given in (Pritsker et al. 1969). Objectives of the RCPSP might be (Klein 1999, 77; Kolisch 1996, 320; Kolisch and Padmann 2001, 250; Tsubakitani and Deckro 1990, 83):

- Minimization of the project make span, resp. finishing time of the project,
- minimization of the project delay,
- maximization of the net present value, and
- minimization of activity- and/or resource-costs.

The most commonly considered objective of the RCPSP is the minimization of the project finishing time. This is mainly due to the following reasons (Kolisch 1996, 180):

1. The majority of income payments of projects (e. g. in the construction industry) occur at the end of a project or at the end of predefined project phases. Finishing the project early reduces the amount of tied-up capital.
2. The quality of forecasts tends to deteriorate with the distance into the future of the period for which they are made. Minimizing the project duration reduces the planning horizon and, therefore, the uncertainty of data.
3. Finishing products as early as possible lowers the probability of time-overruns of the project.

4. By freeing resource capacity as early as possible the flexibility of the company can be raised in order to better cope with changes of the economic environment.
5. Additionally, high resource utilization at the beginning of the planning horizon leads to a larger amount of free resources at the end of the planning horizon and, thus, raises the ability to accept and process new projects.

With the assumptions made the RCPSP can be modeled as mixed integer program (MIP) as introduced in the following:

$$MIN \quad \theta(x) = \sum_{t=EF_J}^{LF_J} t \cdot x_{Jt} \tag{4.1}$$

subject to

$$\sum_{t=EF_j}^{LF_j} x_{jt} = 1 \qquad j = 1,...,J \tag{4.2}$$

$$\sum_{t=EF_h}^{LF_h} t \cdot x_{ht} \le \sum_{t=EF_j}^{LF_j} \left(t - d_j\right) \cdot x_{jt} \qquad j = 2,...,J;\ h \in P_j \tag{4.3}$$

$$\sum_{j=1}^{J} \sum_{\tau=t}^{t+d_j-1} q_{jr} \cdot x_{j\tau} \le Q_{rt} \qquad r \in R;\ t = 1,...,\overline{T} \tag{4.4}$$

$$x_{jt} \in \{0,1\} \qquad j = 1,...,J;\ t = 1,...,\overline{T} \tag{4.5}$$

With the following notation:

j : activity j, $j = 1,...,J$, with 1 = single source, J = single sink
d_j : duration of job j
EF_j : earliest finishing time of job j
LF_j : latest finishing time of job j
r : renewable resource type $r, r \in R$
q_{jr} : per period resource consumption of renewable resource type r by job j
Q_{rt} : availability of resource type r in period t
P_j : set of immediate predecessors of job j
$\overline{T}$: end of planning horizon
x_{jt} : $\begin{cases} 1 & \text{if job } j \text{ finishes in period } t \\ 0 & \text{else} \end{cases}$

The objective function (4.1) minimizes the project finishing time with $\overline{T}$ being the end of the planning horizon. Constraints (4.2) ensure that every job is processed once. Constraints (4.3) 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 (4.4) limit the resource demand q_{jr} of the renewable resource $r \in R$ of jobs j which are currently processed in order not to exceed the constant resource availability per period Q_{rt}. Finally, constraints (4.5) define the decision variable $x_{jt} \in \{0,1\}$ as binary, with $x_{jt} = 1$ if job j ends in period t, 0 else.

The introduction of time windows, i. e. earliest and latest finishing times $\left[EF_j, LF_j\right]$ and earliest and latest starting times $\left[ES_j, LS_j\right]$, for the completion of the jobs in the model serves the reduction of variables in the integer programming formulation of the RCPSP. The calculation of the time windows for the jobs is done with the critical path analysis by applying forward and backward recursion. Thereby, the purpose of critical path analysis is to calculate the smallest feasible completion time of a project without violating the precedence constraints of the jobs. In the following, an algorithm for the critical path analysis applied to acyclic precedence networks with finish-to-start precedence relations is introduced. For reasons of simplification of the algorithm the jobs have to be numbered in topological order, i. e. $h < j$ with $h \in P_j$ and $j \in S_h$ with S_h the set of successors of h (Klein 1999, 44; Schultmann 1998, 118):

$$ES_1 = 0 \tag{4.6}$$

$$EF_1 = d_1 \tag{4.7}$$

$$ES_j = \max\left\{ES_h + d_h \,\middle|\, h \in P_j\right\} \qquad j = 2,...,J \tag{4.8}$$

$$EF_j = \max\left\{EF_h \,\middle|\, h \in P_j\right\} + d_j \qquad j = 2,...,J \tag{4.9}$$

$$LS_J = \overline{T} - d_J \tag{4.10}$$

$$LS_h = \min\left\{LS_j \,\middle|\, j \in S_h\right\} - d_h \qquad h = 1,...,J-1 \tag{4.11}$$

$$LF_J = \overline{T} \tag{4.12}$$

$$LF_h = \min\left\{LF_j - d_j \,\middle|\, j \in S_h\right\} \qquad h = 1,...,J-1 \tag{4.13}$$

Additionally, the following relations hold:

$$ES_j = \max\left\{EF_h \,\middle|\, h \in P_j\right\} \qquad j = 2,...,J \qquad (4.14)$$

$$EF_j = ES_j + d_j \qquad j = 1,...,J \qquad (4.15)$$

$$LF_h = \min\left\{LS_j \,\middle|\, j \in S_h\right\} \qquad h = 1,...,J-1 \qquad (4.16)$$

$$EF_h = ES_h + d_h \qquad j = 1,...,J \qquad (4.17)$$

If additionally release *rd* and due dates *dd* are given externally by, for instance the client of a general contractor, $ES_1 = 0$ is replaced with $ES_1 = rd$ and $LF_J = T$ is substituted by $LF_J = dd$.

The RCPSP in its generalized form can be applied to several cases in project planning. However, in construction projects several particularities as discussed in section 2.1 have to be considered if one aims at developing appropriate models for a good transformation of the real world project environment and planning conditions into the model. Selected criteria are depicted in the following.

4.2.2 Alternative processing modes of construction activities

Alternative processing modes of construction activities are common in practice and are evident in, for instance, deconstruction processes of buildings. As disposal costs for building waste or deconstructed material raises a separation of different types of material is a necessary condition to enable a reuse and recycling of building waste and material. However, the quality of the deconstructed material and its suitability for reuse and recycling can be influenced by the technical and organizational planning of the deconstruction process and, hence, the depth of the deconstruction process as well as the chosen processing option (Schultmann 2003). These distinct processing options are modeled as modes *m* in resource-constrained project scheduling problems. These modes are representations of either resource/resource trade-offs or time/resource trade-offs (in contrast to time/cost trade-offs as addressed). Time/resource trade-offs occur when the duration of a job is affected by the bundle of input resources and can therefore be decreased/increased at the expense of providing additional/less resources or by using different resources. “For example, an excavation may be dug by five construction workers within a week, whereas the same work may be performed by an excavator within a single day.” (Klein 1999) Resource/resource trade-offs are a special case of time/resource trade-offs and represent the substitution of the resources needed to execute a job without affecting the duration of the job (considering that resources are substituted with resources the term resource/resource trade-off is not quite correct, as there actually does not exist a trade-off between resources). For instance, the excavation may be dug by five construction workers within a week or alternatively by two construction workers and seven apprentices within the same time. Other examples might also include working overtime or replacing manpower with machines (Demeulemeester and Herroelen 2002).

While in the RCPSP each job is processed in a single mode, i. e. each job is assigned a deterministic resource consumption and a corresponding duration, e. g. (Christofides et al. 1987; Davis and Patterson 1975), the modeling of the RCPSP using modes results in the multi-mode resource-constrained project scheduling problem (MMRCPSP). In the MMRCPSP formulation each job j is assigned a mode m defining the relation between resource consumption q_{jmr} and job duration d_{jm} in one of several different modes $m = 1,...,M_j$. Additionally, "….the execution of a job might require renewable r, $r \in R$ as well as non-renewable n, $n \in N$ resource types…" (Klein 1999), while in the single-mode case (RCPSP) non-renewable resources, e. g. budget and material, are disregarded as either the amount of them is sufficient to process the project over the planning horizon or not. Examples for multi-mode RCPSP across industries are given in (Alcaraz et al. 2003; Buddhakulsomsiri and Kim 2007; Heilmann 2003; Jozefowska et al. 2001; Kolisch and Drexl 1997; Mori and Tseng 1997; Ranjbar et al. 2009; Sprecher and Drexl 1998).

The primary objective of the MMRCPSP is, according to the RCPSP, to minimize the project finishing time by selecting an execution mode for each activity and assigning feasible finishing times of the jobs according to the resource and precedence constraints. Hereby, it is assumed that a pre-emption of jobs as well as a change of the mode while a job is active is not allowed and that the dummy start activity as well as the dummy end activity can only be processed in a single mode with the duration and resource consumption equal to zero. For the general formulation of the MMRCPSP the decision variable is redefined as $x_{jmt} = 1$ if job j finishes in period t in mode m, 0 else.

The mathematical programming formulation of the MMRCPSP is (e. g. Pritsker et al. 1969; Talbot 1982):

$$MIN \quad \theta(x) = \sum_{m=1}^{M_J} \sum_{t=EF_J}^{LF_J} t \cdot x_{Jmt} \tag{4.18}$$

subject to

$$\sum_{m=1}^{M} \sum_{t=EF_j}^{LF_j} x_{jmt} = 1 \qquad j = 1,...,J \tag{4.19}$$

$$\sum_{m=1}^{M_h} \sum_{t=EF_h}^{LF_h} t \cdot x_{hmt} \le \sum_{m=1}^{M_j} \sum_{t=EF_j}^{LF_j} \left(t - d_{jm}\right) \cdot x_{jmt} \qquad j = 2,...,J;\ h \in P_j \tag{4.20}$$

$$\sum_{j=1}^{J} \sum_{m=1}^{M_j} q_{jmr} \sum_{\tau=t}^{t+d_{jm}-1} x_{jm\tau} \le Q_{rt} \qquad r \in R;\ t = 1,...,\overline{T} \tag{4.21}$$

$$\sum_{j=1}^{J} \sum_{m=1}^{M_j} q_{jmn} \sum_{t=EF_j}^{LF_j} x_{jmt} \le Q_n \qquad n \in N \tag{4.22}$$

$$x_{jmt} \in \{0,1\} \qquad j = 1,...,J;\ m = 1,...,M_j;\ t = 1,...,\overline{T} \tag{4.23}$$

With the additional notation:

m : mode in which activity j can be performed, $m = 1,...,M_j$

d_{jm} : duration of job j performed in mode m

n : non-renewable resource type $n, n \in N$

q_{jmr} : per period resource consumption of renewable resource type r by job j performed in mode m

q_{jmn} : per period resource consumption of non-renewable resource type n by job j performed in mode m

Q_n : availability of non-renewable resource type n

x_{jmt} : $\begin{cases} 1 & \text{, if job } j \text{ is performed in mode } m \text{ and finishes in period } t \\ 0 & \text{, else} \end{cases}$

The objective function (4.18) minimizes the project finishing time. Constraints (4.19) ensure that every job is processed once. Constraints (4.20) depict precedence constraints of jobs, where P_j is the set of immediate predecessors of job j. The duration of job j in mode m is represented by d_{jm}. Constraints (4.21) limit the resource demand, q_{jmr}, of the renewable resource $r \in \mathbb{R}$ of jobs j which are currently processed in mode m in order not to exceed the constant resource availability per period Q_r. Constraints (4.22) limit the amount of non-renewable resources, such as budget. Finally, constraints (4.23) define the decision variable $x_{jmt} \in \{0,1\}$ as binary, with $x_{jmt} = 1$ if job j ends in period t, 0 else.

4.2.3 Multiple simultaneous construction projects

If resources are shared among projects, difficult scheduling problems might arise if projects are to be scheduled in parallel. This situation is common for construction contractors, engineering firms, maintenance crews and similar organizations which must simultaneously manage a variety of projects subject to resource and due date constraints. This comprises the assignment of scarce resources to different projects or shifting them from construction site to construction site (e. g. cranes are scaffolding), generally, minimizing time or cost objectives. For research on multi-project scheduling see, for instance, (Artigues et al. 1999; Ghomi and Ashjari 2002; Gonçalves et al. 2008; Kim and Schniederjans 1989; Kim and Leachman 2003; Lawrence and Morton 1993; Woodworth and Willie 1975). However, the multi project environment in the construction industry does not just refer to single enterprises managing various site projects at a time but also to construction project partner networks where multi-project management presents a type of cooperation possibilities for subcontractors and small and medium enterprises (SMEs) to be integrated into large delivery project networks. Hence, with the occurrence of large construction projects involving multiple parties, such as designers, contractors, subcontractors, construction managers, and specialists the complexity of project management has risen.

The circumstance of planning multiple projects in parallel, multiple projects have to be introduced in the model. Extending the MMRCPSP, a multi project scheduling problem consists of a number of independent projects given by $i = 1,...,I$ which simultaneously compete for limited resources within their project specific precedence relations of finish-to-start type whereas resource transfer times between the projects are assumed to be negligible (Kurtulus and Narula 1985). As the multi-mode resource-constrained multi project scheduling problem (MMRCMPSP) is a generalization of the MMRCPSP, the properties and assumptions of the MMRCMPSP are equal to the ones of the MMRCPSP.

The MMRCMPSP can be formulated as follows:

$$MIN \quad \theta(x) = \sum_{i=1}^{I} \sum_{m=1}^{M_{iJ}} \sum_{t=EF_{iJ}}^{LF_{iJ}} \frac{t \cdot x_{Jmt} - dd_i}{I} \tag{4.24}$$

subject to

$$\sum_{m=1}^{M_{ij}} \sum_{t=EF_{ij}}^{LF_{ij}} x_{ijmt} = 1 \qquad i = 1,...,I;\ j = 1,...,J \tag{4.25}$$

$$\sum_{m=1}^{M_{ih}} \sum_{t=EF_{ih}}^{LF_{ih}} t \cdot x_{ihmt} \le \sum_{m=1}^{M_{ij}} \sum_{t=EF_{ij}}^{LF_{ij}} \left(t - d_{ijm}\right) \cdot x_{ijmt} \qquad i = 1,...,I;\ j = 2,...,J;\ h \in P_{ij} \tag{4.26}$$

$$\sum_{i=1}^{I} \sum_{j=1}^{J_i} \sum_{m=1}^{M_{ij}} q_{ijmr} \sum_{\tau=t}^{t+d_{ijm}-1} x_{ijm\tau} \le Q_{rt} \qquad r \in R;\ t = 1,...,\overline{T} \tag{4.27}$$

$$\sum_{i=1}^{I} \sum_{j=1}^{J_i} \sum_{m=1}^{M_{ij}} q_{ijmn} \sum_{t=EF_{ij}}^{LF_{ij}} x_{ijmt} \le Q_n \qquad n \in N \tag{4.28}$$

$$x_{ijmt} \in \{0,1\} \qquad j = 1,...,J;\ m = 1,...,M_j;\ t = 1,...,\overline{T} \tag{4.29}$$

With the additional notation:

i : project i, $i = 1,...,I$

d_{ijm} : duration of job j of project i performed in mode m

q_{jmr} : per period resource consumption of renewable resource type r by job j of project i performed in mode m

q_{ijmn} : per period resource consumption of non-renewable resource type n by job j of project i performed in mode m

x_{ijmt} : $\begin{cases} 1 & \text{, if job } j \text{ of project } i \text{ is performed in mode } m \text{ and finishes in period } t \\ 0 & \text{, else} \end{cases}$

In contrast to the objective of the RCPSP and MMRCPSP, which most commonly minimize the project finishing time as only one project is scheduled, a relative measure has to cope with multiple projects, i. e. a mean value of an objective. Considering that projects usually come in late the objective function (4.24) of the basic model for the multi-mode multi project scheduling problem under constrained resources with the multi-project approach is to minimize the mean project delay *MPD*, whereas the project delay is the difference between the resource-constrained project finish ($\sum_{t=EF_{iJ_i}}^{LF_{iJ_i}} t \cdot x_{iJ_imt}$) and the due date dd_i of project *i*. The structure of equations (4.25)–(4.29) of the multi-mode multi project case is equivalent to equations (4.19)–(4.23) of the MMRCPSP.

4.2.4 Measures for construction project performance

Construction project performance is usually understood as the adherence to time, cost and quality objectives. Thereby, construction projects are very often behind time and budget, as revealed in section 3.2.2. While the most commonly considered objective of the RCPSP is the minimization of the project finishing time, construction project management in general covers a much wider scope of objectives. Construction project management can either concentrate on one superior objective of a construction company or simultaneously follow the aim of satisfying multiple objectives. The aggravating factor in construction project planning, which is closely related to the complexity of the project, is the type and the number of participants involved in a project who claim the fulfillment of their various interests (Schultmann and Sunke 2006). Objectives might hereby be induced either by the project owner, its stakeholders, such as subcontractors or material suppliers, but also by a regulatory framework or other external conditions. These objectives can address different issues such as time, cost and resource allocation etc., as discussed further below. Thereby, recently, additional objectives, for instance, the environmental performance of construction are also acknowledged.

4.2.4.1 Construction project duration

The most common considered objective of the RCPSP is the minimization of the make span of a project like in the CPM, MPM or PERT methods. Usually, in construction projects several construction sub-contractors and trades are selected and have to be scheduled for a particular project by a particular instance, dependent on the project delivery system chosen, for instance, DBB, DB, or CM, as introduced in section 3.1. These parties involved in a project depend on each other but yet run their own business and have to rely on the preceding party to finish their work on time. In the RCPSP, this circumstance can be modeled by considering not just the project and its make span but each single activity and its delay within the schedule by minimizing the (weighted) delays of activities. Thereby it can also be differentiated whether a given due date (either externally given by the client or internally given by the construction contractor) exists and serve as basis for the calculation of limiting time windows in which each activity can be executed.

If, in case multiple projects are to be considered simultaneously as typical for construction contractors (see section 4.2.3), this project portfolio has to be scheduled minimizing the mean multi project delay over all projects, unlike a single project in CPM, MPM, and PERT.

Hence, time-based objectives in projects address the optimization of measures related to finishing times, make spans, tardiness of activities and projects. With the RCPSP, for instance, the following objectives could be considered (Kolisch and Padmann 2001, 250−1; Schultmann 1998, 123−30):

- Minimization of the make span of a project i,
- minimization of the (weighted) flow time of j,
- minimization of the (weighted) delays of activities for given activity due dates dd_j,
- minimization of the mean multi project delay for given project due dd_i under simultaneous consideration of more than a single project.

4.2.4.2 Construction project profit

In construction projects different contractual arrangements and contract types define the financial conditions of the project, e. g. Lump Sum, Fixed Price Contracts or a Guaranteed Maximum Price (GMP) (Bennett 2003, 26−33; Winch 2006). These contracts are complemented for instance by the specification of delay or contractual penalties as well as Bonus-Malus clauses. The payments of the client shall cover the costs of the construction contractor or sub-contractor for the execution of its work package. Thereby, costs can be considered as expenses triggered by initiating activities for instance for resource consumption, for additional resource costs c_r for renewable as well as c_n for non-renewable resources if a project deadline has to be met. A possible example is the construction contractor acquiring additional equipment or labor to avoid contractual penalty imposed by the client. Additionally, costs can occur for setting up activities but also for incurred project delay penalties p_i and other payments to be made during construction project progress if the project cannot be finished on time.

On the other hand cost or related cash flows[13] can be contractual or not-contractual agreed progress payments by the client for the completion of parts of the project or completion boni (Klein 1999). Hence, monetary oriented project objectives comprise resource-cost oriented

[13] A cash flow is he balance between cash inflows and cash outflows of an enterprise during a defined period of time. A cash flow might also be tied to a specific project (Needles et al. 2007). Typical outflows of a construction project comprise, for instance, interest, material, and labor costs. Cash inflows include various payments, for example, bonuses (Liu and Wang 2008).

objectives, activity-cost oriented objectives as well as objectives concerning the cash flow or net present value (NPV) of a project (Kolisch and Padmann 2001, 251).

In general, *resource-cost oriented objectives* are reflected in two extensions of the RCPSP: time-constrained project scheduling problem (TCPSP) and resource investment problem (RIP). The objective of the TCPSP is the minimization of additional resource costs for additional resource consumption if the project finish is set. The RIP aims at determining a non-delay schedule and the amount of each resource provided minimizing total costs (e. g. (Demeulemeester 1995; Möhring 1984).

Considering *activity-cost oriented objectives* so called time/cost trade-off problems occur. The underlying assumption is that the activity duration might be influenced by the amount of money spent for processing. Research discussing the time/cost trade-off problem can, for instance, be found in (Demeulemeester et al. 1996; Icmeli and Erenguc 1996; Vanhoucke 2005).

Additionally, boni and penalty costs for project finish, or both, negative as well as positive *cash flows* as reflected in the NPV of a project can be considered, as for instance agreed upon in a GMP contract with a Bonus-Malus clause in construction. Problems aiming at maximizing the NPV depending on the time at which cash flows occur are called resource-constrained project scheduling problem with discounted cash flows (RCPSP−DCF). Examples are given in (Chiu and Tsai 2002) or with various extensions, for instance, for multiple-projects, for multiple-processing modes or varying payment models in (Jozefowska et al. 2002; Kim and Leachman 2003; Lawrence and Morton 1993; Mika et al. 2005; Ulusoy et al. 2001). An additional overview on research on project scheduling and related cash flows is given in (Liu and Wang 2008).

Summarizing, relevant objectives of the RCPSP taking the profit orientation of construction parties into consideration are, for instance:

- Minimization of resource costs or costs for additional resource consumption with a defined project due date,
- minimization of delay costs or penalty costs,
- minimization of weighted tardy costs for multiple projects
- maximization of profits, and
- maximization of net present value (NPV).

4.2.4.3 Construction project resource utilization

Especially in construction projects, a huge amount of equipment is very cost-intensive, for instance, cranes, scaffolding, and on-site facilities. Hence, underutilization of equipment and facilities leads to the occurrence of unnecessary equipment holding costs. In particular, machine downtimes or underutilization is to be avoided, instead it should be aimed at leveled resource utilization. Regarding the RCPSP, this problem is considered as resource leveling problem (RLP), for instance, Bandelloni et al. 1994, Hegazy 1999, and Neumann and Zimmermann 2000. The RLP serves to achieve an even capacity utilization of, for instance, construction equipment by assigning start and finishing times to activities such that the available resources are evenly distributed among the activities and a leveled resource profile is generated. Thereby, the close relationship to the TCPSP becomes obvious. While costs are the essential part in the TCPSP, the focus of resource oriented objectives is not to allocate resources to activities minimizing costs or maximizing benefits but to allocate resources in a way such that deviations in resource consumption per period are minimized.

4.2.4.4 Construction project sustainability

Sustainability in construction becomes increasingly important due to issues like the high amount of waste accumulating in construction and deconstruction projects, the high energy consumption, the related pollutions to the environment and the increasing awareness of the public to foster environmental sound behavior due to resource depletion and climate change (see section 6.1). These issues have led to regulations imposed by governmental bodies in several countries during the last years. For instance, regulations imposed in construction comprise country specific laws about waste management (see section 6.2.3), energy consumption and emission control on site. Formalizing these regulations for the use in the RCPSP, new objective functions can address the maximization of material to be recovered in deconstruction projects (e. g. construction materials such as wood, bricks, steel, modules, sanitary installation etc.) or the minimization of emissions (noise, pollution, etc.) during construction projects.

In contrast to the construction industry, these issues have already been studied and implemented in the manufacturing industries, for instance, under aspects of the minimization of pollution risks or expected returns under environmental constraints, such as bounds on expected pollution levels (e. g. Rädulescu et al. 2009). In construction project planning, quantitative modeling of environmental constraints has not yet been addressed. With this respect, especially discussions on issues like embodied energy of construction materials could present potential fields of research. Due to the high energy consumption aspects of embodied energy have gained raising attention in the last years due to the high energy consumption of the construction industry (see section 8.3.1). Particularly in deconstruction projects, this might address the deconstruction of valuable materials and components and recovery of them under the aspect of retaining as much of embodied energy inherent in a material as possible. Thereby, an extension of the RCPSP considering the energy-efficient deconstruction and recovery planning and the choice of appropriate deconstruction techniques based on the MMRCPSP has been proposed. In this extension of the MMRCPSP an energy savings value is additionally assigned to each activity and each mode. This value integrates the energy saved by recovering the material deconstructed in comparison to using primary raw materials on a life cycle perspective (Schultmann and Sunke 2007a) and is developed and discussed in detail in section 8.

4.2.5 Interests of different project stakeholders

Particular project failures, such as negative community reaction and unforeseen regulatory changes (see section 0) could, in principle, be tackled by clients and contractors actively integrating stakeholders and their interests into the planning process of the project (Jergeas et al. 2002, 18). Thereby, in advance, possible trade-offs between the satisfaction of as many stakeholder interests as possible and the project objective need to be identified. To be prepared for resolving arising conflicts during project progress, possible consequences should be elaborated in case a satisfaction of particular stakeholder interests is not possible (Olander and Landin 2008). However, if the interests of various stakeholders are to be considered simultaneously, complex optimization problems might arise as their objectives usually differ significantly from each other. For instance, the implementation of sustainable deconstruction techniques to facilitate a high material recovery (see section 4.2.4.4) is time intensive, may cause longer project make spans (see section 4.2.4.1) and usually requires cost-intensive equipment. This, in turn, causes higher labor costs and might even lead to delay penalties (construction project profit). This means, that a single unique solution which is globally maximum or globally minimum with respect to all objectives does not exist, for example, environmental objectives usually counteract monetary objectives as environmentally friendly construction techniques are more cost intensive than traditional ones. This leads to multi-objective optimization problems which can be tackled by methods of multi criteria decision making (MCDM), for example, T'kindt and Billaut 2006.

4.2.6 Construction project planning with uncertainties

Most of the project scheduling literature concentrates on the generation of (near) optimal schedules assuming underlying complete information in a static as well as deterministic environment. In projects in practice however, and especially in construction projects, the supply conditions of resources as well as the duration of the project activities are subject to risks and uncertainties in a non-deterministic environment. Material may arrive late, due dates might have to be changed, or additional activities have to be incorporated or dropped due to changing environmental conditions during project progress. Such uncertainties result from the one-time character of projects (e. g. seasonal dependency of construction projects, working conditions on site, and conflicts in international project environments) and the relating lack of experience. Hence, durations of activities as well as costs might only be rough estimates and are most likely imprecise and change depending on the project environment and project progress. Neglecting these influencing factors in the decision making and scheduling process might cause severe project interruptions and project failures, such as missed deadlines, resource idleness, and cost increases (Herroelen and Leus 2005b).

The consideration of risk and uncertainties in non-deterministic project planning and scheduling has already been addressed in literature with various methods. The decision maker either has the opportunity to create a deterministic baseline schedule and revising or re-optimizing this schedule when an unexpected event occurs (reactive scheduling) or to create baseline schedules already incorporating uncertainty. Among these methods, an early representative of probabilistic methods is the PERT-method addressed by Malcom et al. (Malcolm et al. 1959). Additionally, stochastic programming approaches (e. g. Karni 1987; Yang and Chang 2005), simulation (Abou Rizk and Wales 1997; Ammar and Mohieldin 2002; e. g. Leu and Hung 2002; Zhang et al. 2002) as well as sensitivity analysis have been proposed in project scheduling dealing with uncertainty. For a detailed discussion of these approaches it is referred to (Herroelen and Leus 2005b).

However, the axiomatic of probabilistic approaches, such as PERT and stochastic programming, implying the existence of reliable probability distributions for occurring events does not hold for project-scheduling problems, as judgments in a usually unique project setting rely on expert knowledge and are therefore rather imprecise and vague (Herroelen and Leus 2005b). Hence, methods of possibility theory, such as fuzzy approaches to project planning and scheduling have gained attention in the research community initiated by papers, for instance, by Dubois and Prade (1978), Prade (1979), and Chanas and Kamburowski (1981). Since then extensive effort has been undertaken to develop sophisticated fuzzy scheduling approaches for project management, for instance, in (Fortemps 2003; Hapke and Slowinski 1996; Hapke and Slowinski 2000). A more extensive overview on fuzzy scheduling is given in (Dubois et al. 2003; Herroelen and Leus 2005b; Leu and Hung 2002).

The result of fuzzy scheduling is a fuzzy schedule indicating fuzzy starting or finishing times. However, this information cannot be interpreted as realistic starting and finishing times to certain extend. Instead, the schedule represents a certain degree of freedom in project planning and supports the decision maker whether to start an activity a little bit earlier or later.

Schultmann et al. (2006a) extended the MMRCPSP to a fuzzy project scheduling model. Applications for the manufacturing industries indicate that fuzzy scheduling can give valuable decision support to project planners in an environment with vague and imprecise data. The model can be adapted to the conditions of construction projects.

4.2.7 Further construction project particularities

Despite the introduced extensions of the RCPSP, it can also serve further construction project related particularities of which selected are briefly addressed in the following.

In construction, an activity might require that a succeeding activity starts at a specific time after its predecessor has been finished, for instance for varnishing and painting procedures. The basic model of the RCPSP and its already described extensions are representations of the simple finish-to-start type of precedence relations; i. e. a job j can only be started after all its predecessor jobs h have been completed. This type of precedence relation is very often not sufficient to cope with real-world situations properly. To include start-to-finish (time between start of job h and end of job j), finish-to-start, and finish-to-finish (time between finish of job h and finish of j) relations between jobs an extension could include the consideration of minimum and maximum time lags between activities as, for instance, considered in (Bartusch et al. 1988; Klein 1999, 99f; Neumann and Schwindt 1997).

Another characteristic of construction projects, especially in the multi-project environment, is that resources, such as construction equipment, once scheduled have to be adjusted or transported from construction site to construction site in order to perform the project. Adjustment refers to activities such as resetting, positioning, changing, cleaning or warm up of machines; for example, equipping an excavator with different scoops to perform various activities. Transport occurs for heavy construction equipment, such as cranes or excavators, when they are requested at different construction sites. The adjustment and transport of construction equipment not only leads to so called setup or transport times but also to setup or transport costs which would have to be considered in the construction project planning problem. Generally, an assumption of the RCPSP is that these setup times and setup costs of resources are negligible. However, setup times and setup costs of resources between projects can be considered for the multi project extension of the RCPSP, so that a resource might rather be idle for two periods in project A than being transferred from project A to project B and back to project A for 4 periods (Kurtulus and Narula 1985, 58). For further information regarding setup times and setup costs as well as transition and idle time, rewards for early completion and penalty for delayed completion it is referred to (Dodin and Elimam 2008; Mika et al. 2006).

Finally, in construction as well as in deconstruction projects a common problem is the limited capacity of storage space for materials or C&D waste accumulating on site before the final assembly on site or the collection and transport from the site to recovery facilities. If the storage space is congested, construction activities would have to wait until material has been processed and deconstruction activities would have to wait until the C&D waste has been picked up. The extension of the RCMPSP addresses this problem with state preserving jobs. State preserving jobs occur if a job has a variable duration that depends on the finishing and starting times of its predecessors and successors; i. e. "…it starts as soon as the execution of all its predecessors has been terminated and finishes immediately before the first of its successors is begun." (Klein 1999) A similar problem was analyzed for the manufacturing industries. For instance, goods in a flow shop system which have to wait for the next working station to be free and are transferred to storage with limited capacity in between, whereas the time the goods have to wait for machine two is not determined. Hereby, it has to be considered that there is only limited storage capacity which is a restriction for the duration of the state preserving job whose resource consumption depends on its duration (Klein 1999, 100f).

4.2.8 Solution procedures and applications in construction project planning

Solution procedures for the problem (4.1)–(4.5) and its multimode extension (4.18)–(4.23) as well as multi project extension (4.24)–(4.29) in the single mode case have attracted intensive research since the late 1950s. Solution procedures for the RCPSP and its extensions are divided into exact algorithms, and heuristic approaches. Since the RCPSP belongs to the class of NP-hard problems[14], exact algorithms are usually developed to generate benchmark solutions for problem instances beyond real world applications. In comparison, heuristic procedures concentrate on providing an efficient method to calculate an acceptably good solution within a reasonable computational time. Generally, heuristic procedures comprise priority rule based heuristics, meta heuristics (e. g. simulated annealing, tabu search and genetic algorithms), as well as other heuristics, such as truncated branch-and-bound methods and disjunctive arc based methods (Kolisch and Hartmann 2006). The proposed solution procedures in literature are most commonly applied and experimentally investigated based on a set of benchmark test instances, for instance from a project scheduling library (PSPLIB) by Kolisch and Sprecher (Kolisch and Sprecher 1996) or an instance set assembled by Patterson (Patterson 1984). Comprehensive reviews for the RCPSP and its solution procedures can be

[14] For a discussion of the NP-hardness of the RCPSP it is referred to (Klein 1999, 95) and cited literature.

found in (Brucker et al. 1999; Demeulemeester and Herroelen 2002; Kolisch 1996; Kolisch and Hartmann 2006; Kolisch and Padmann 2001).

Despite the theoretical evaluation some practical applications are given in literature to proof the appropriateness of proposed solution procedures for practical planning problems. Moreover, successful implementations in case studies considering various planning contexts are given. In the construction industry, case studies were undertaken, for instance, by Tsubakitani and Deckro (1990) and Chiu and Tsai (2002). Tsubakitani and Deckro originally developed a heuristic for multi-project scheduling under constrained resources for a Japanese operating firm in the housing industry building approximately 6000 custom-order homes per year. Chiu and Tsai developed an efficient search procedure for the resource-constrained multi-project scheduling problem with discounted cash flows (RCMPSP–DCF) and apply it to home building company in Taiwan. Additionally, a successful implementation of the RCPSP with multiple modes was given by Schultmann and Rentz (2002), who applied the model and to deconstruction projects under the consideration of sustainable principles.

4.3 Discussion of results

The contribution of resource-constrained project planning to construction project planning is the improvement of the reliability of project schedules due to the integrated time and capacity planning. It was shown in case studies undertaken by various researchers, that the RCPSP and its extensions can be applied successfully to a variety of different classes of construction projects. It serves not only as a framework for resource allocation in construction project planning but it can also easily be adapted to different project structures and different project environments.

However, due to its complexity, a sole application of resource-constrained methods, as addressed in the preceding sections, leads to inefficient and time consuming scheduling procedures. In response, a combination of the RCPSP and its extensions together with project planning methods such as CPM, MPM or PERT could significantly increase the performance of construction projects. To appropriately integrate resource-constrained project planning into current project planning procedures in construction, a hierarchical project planning approach was developed (see section 4.1.2). In the proposed hierarchical planning approach the objective of tactical project planning is time oriented; i. e. focuses on the early project finish and can be pursued with simple planning approaches. In contrast, the RCPSP is suitable for a more detailed planning on the operational basis of the project and its sub-projects considering various particularities and multiple objectives depending on the context of the project, for instance for construction projects. The proposed combination of both, ‘traditional’ as well as sophisticated project planning approaches contributes to raising the acceptance of more sophisticated planning methods by practitioners and supports the easy application of these usually hard to solve problem structures due to their high number of variables. Future research still has to address the empirical validation of the hierarchical project planning approach in real world projects.

Summarizing, when used in addition to approaches like CPM, MPM and PERT for detailed project planning, resource-constrained project scheduling could improve the reliability and the quality of the schedule due to the integrated resource planning. This includes, for instance, multi-mode or multiple projects as well. Additionally, the RCPSP provides freedom to integrate external constraints (e. g. legislation, market regulations) and multiple objectives. Thus, the RCPSP allows the generation of reliable and applicable schedules even for complex environments.

In addition, the proposed planning approach enlarges the scope of application of RCPSP models. It operates in a static as well as deterministic environment. In projects in practice, however, and especially in construction projects, the supply conditions of resources as well as the duration of the project activities are subject to risks and uncertainties in a non-deterministic environment. Material may arrive late, due dates might have to be changed due to design changes, or additional activities have to be incorporated or dropped due to changing environmental conditions during project progress. Hence, durations of activities might only be rough estimates and are most likely imprecise and change depending on the project environment and project progress. With the rolling horizon of the planning approach these uncertainties could be partly coped with and with the application of stochastic programming, simulation approaches as well as fuzzy scheduling (4.2.6) the reliability of the schedule can be improved.

Nevertheless, it has to be paid attention to the fact that regardless of how sophisticated planning models are, even a nearly perfect planning, considering resource constraints, different environments, uncertainty, vague information etc. can not replace a proper project control.

5 Proposition for the design and operation of construction supply chains

Project success not only depends on an efficient resource allocation during the scheduling of the project. A key issue is also a proper materials management (see section 3.2.2). The construction materials management is related to the materials supply chain of the construction industry. Furthermore, it is based on the construction activities schedule denoting the time, the amount and the location at which construction material or components have to be made available (Ibn-Homaid 2002). Along the material supply chain, different problems occur. These problems comprise, for instance, high inventory holding costs or poor customer response times. The underlying problems, however, to shorten processing times and to lower inventory costs can be tackled with an efficient organization of the communication, information flow and cooperation between the partners of the supply chain, i. e. by methods of SCM. The purpose of this section is therefore to outline the application of selected SCM concepts for construction. Thereby, the focus is put on materials management with special regard on material availability on site and related inventory problems. At first, challenges for the design and operation of construction supply chains are discussed. Afterwards, the focus is shifted to construction SCM by describing the concept and aims as well as presenting major related research work. In the succeeding section, a proposition for the design and operation of construction supply chains is made by revealing potential benefits and risks for construction. A discussion highlights critical issues of the applicability of SCM to construction before the conclusions and a future outlook on research effort finalize the section.

5.1 Challenges for the design and operation of construction supply chains

As revealed in section 3.2.2, a major and most frequent cause of delays in construction projects is the non-availability of material on site (Ibn-Homaid 2002). For instance, a considerable amount of time is spent on site waiting for materials to arrive (see Yeo and Ning 2002). For example, projects are delayed due to problems with the supply of precast concrete components. These problems comprise the *timing of the supply*, *receipt of damaged components* and *improper supply* (Pheng and Chuan 2001).

Generally, construction materials are ordered either very late or too early, while late orders leave the supplier with uncertain demand and high material buffers on-site to ensure a high service level. The placement of too early orders leads to high site inventories which increase risk that materials get stolen, broken or lost (Ala-Risku and Kärkkäinen 2006, 20; Vrijhoef and Koskela 2000). Furthermore, case studies reveal that defective material deliveries account for 8–25 % of the non-completed tasks (Ala-Risku and Kärkkäinen 2006, 21) and costs for materials handling on site are caused by chaotic material deliveries and unsystematic site organization. This usually complemented by an unnecessarily high handling effort due to the procurement of large and inappropriately packaged material; usually material for which discounts had been realized disregarding the additional handling and logistic costs (Vrijhoef and Koskela 2000). Hence, without adequate material management, disturbances construction supply chains with consequences on project cost, schedule, and quality are likely expected to occur (Tserng et al. 2006).

In CSCs the trade-off between the contractor's desire for high material availability and the advantages of inventory reduction on site has to be balanced. On the one hand, 100 % material availability before project start maximizes the flexibility of crew assignment and activity shifts. Hence, construction delays due to late delivery of materials are smoothed out. On the other hand, costs occur for the raise of up-front capital, for inventory holding, and a damage or loss of materials on stock. Hence, the perceived flexibility from 100 % material availability is offset by the inflexibility to quickly respond to design changes and changes in project conditions.

On the one hand, excessive site inventories and material buffers at the site caused by ordering materials and components in advance as a response to high material availability can be avoided by shifting the inventory responsibility upstream to suppliers and by accurate scheduling of material orders when creating the initial project plan (Ala-Risku and Kärkkäinen 2006, 22; Bertelsen and Nielsen 1997; Kärkkäinen et al. 2003; Walsh et al. 2004, 825). On the other hand and in contrast to holding inventories, organizing material management according to the just in time delivery, i. e. supply of materials directly to the site right before assembly, the contractor is put at risk of construction delay due to its dependency on the material suppliers although savings in up-front capital, inventory holding costs, and a reduction in the damage or loss of materials could be achieved (Walsh et al. 2004, 825). To approach these problems, concepts of SCM known from the manufacturing industries can be applied.

5.2 Supply chain management in manufacturing industries

5.2.1 Definitions of supply chain management

SCM found its origins in Japan—in the just in time delivery system of the Toyota production system—and in the field of quality control. From thereon SCM was adopted in many sectors of the traditional manufacturing industries, e. g. automobile industry and electronics. For an overview on the development of SCM refer to (Vrijhoef and Koskela 2000).

Various definitions exist in the literature for *supply chain management*. A selection of definitions is given in Table 5 in increasing order of their complexity.

Table 5: Selected definitions for supply chain management

Author	Definition
(Ellram and Cooper 1990)	"…an integrated philosophy to manage the total flow of distribution channel from the supplier to the ultimate user"
(Harland 1996 cited by Dainty et al. 2001, 164)	"…the management of a network of organizations that are involved in carrying out the business process."
(Johnston 1995 cited by Love et al. 2004, 44)	"...the process of strategically managing the movement and storage of materials, parts and finished inventory from suppliers, through the firm to customers."
(Kranz 1996 cited by Love et al. 2004, 44)	"…the effort involved in producing and delivering a final product from a supplier's supplier to the customers' customer."
(Drucker 1998 cited by Titus and Bröchner 2005, 73)	"…the integration of key business processes from the end user through original suppliers that provides products, services and information that add value for customers and other stakeholders."
(Simchi-Levi et al. 2002, 1)	"…a set of approaches utilised to efficiently integrate suppliers, manufacturers, warehouses, and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize system wide costs while satisfying service level requirements."

As it can be seen, various authors define the term *supply chain management* from different points of view. Whereas the first definitions from Harland (1996), Johnston (1995) and Kranz (1996) briefly define general issues of SCM, the last ones from Drucker (1998) and Simchi-Levi et al. (2002) are much more detailed considering different participants and aims of SCM. However, all of the definitions have in common that SCM looks at the whole network of organizations that are involved. These organizations together create value in the form of products or services, what means that every step towards the end product is included in the considerations: procurement of materials, production stages, assemblies, distribution, sales etc. The main drivers of SCM are the satisfaction of customers as well as the maximization of the total profitability of the entire SC. For a discussion of the term *supply chain management* see, for instance, (Fettke 2007; Halldórson et al. 2003; Seuring 2005).

According to (Halldórson et al. 2003) a supply chain is defined as "…the entity of customer-driven inter-organizational relationship of flow activities. Hence, SCM is the management of the network of organizations involved in value creating activities in terms of products or services. SCM comprises all steps in the SC from the raw material extraction to the client, i. e. extraction of materials, procurement, production stages, assemblies, distribution, sales etc with the aim of maximizing the total profitability of the SC."

In an extended survey on state-of-the-art SCM research Fettke (2007) reveals that empirical studies on objectives pursued with the implementation of SCM reveal two main fields of objectives: strategic and operational. Strategic objectives are (Spekman et al. 1998, 640):

- Customer satisfaction,
- increase in profit,
- guarantee of procurement or sales of a product,
- satisfaction of customer as well as supplier requests,
- decrease in operating costs, and
- achievement of a strategic market position.

Operational objectives according to several studies are (Buer 2003, 75f; Fawcett et al. 2008, 43; Tummala et al. 2006, 185):

- Increase in delivery reliability and respond to customer requests,
- decrease in inventory costs,
- decrease in order fulfillment lead times,
- increase in capacity utilization,
- increase in productivity as well as an
- increase in planning accuracy.

Summarizing, concepts for SCM were generally developed and applied for the manufacturing industries, e. g. electronic goods or automotive industry. In project-based organizations, like construction companies, the approaches for SCM developed so far can not be applied without alterations. Project-based organizations differ from 'traditional' enterprises in terms of products and services which are customer driven and with regard to the uniqueness, uncertainty, and complexity of their business operation. Moreover, many items are only required in low volumes on an infrequent basis and the value of the order may not be of high significance to the supplier (Hicks et al. 2000; McGovern et al. 1999). Apart from their specific characteristic of their products, construction companies often suffer cost and time overruns due to inefficient organization of their business processes, as addressed in section 3.2.2. To overcome these obstacles approaches for SCM known from manufacturing have to be adopted and modified for construction. First studies that have been carried out so far are limited to particular construction applications. An attempt to analyze the applicability of SCM concepts in construction has not yet been conducted.

5.2.2 Framework for strategic and operational supply chain management

A framework for SCM was introduced by Cigolini et al. (2004). They define supply chain strategies which consist of supply chain techniques and tools. The techniques represent the components of SCM which are supported by IT tools (see Figure 20). The strategies were developed for the traditional manufacturing industries, such as automobile industry, pharmacy, textile, electronic equipment or food and beverages industry (e. g. Corsten and Gabriel 2002; Wagner and Meyr 2000).

SCM is often divided into two major decision phases (Cigolini et al. 2004; Fettke 2007; Harrison 2003, 4): Supply chain design (SCD) for strategic planning and supply chain operations or execution (SCE) for the tactical and operational planning.

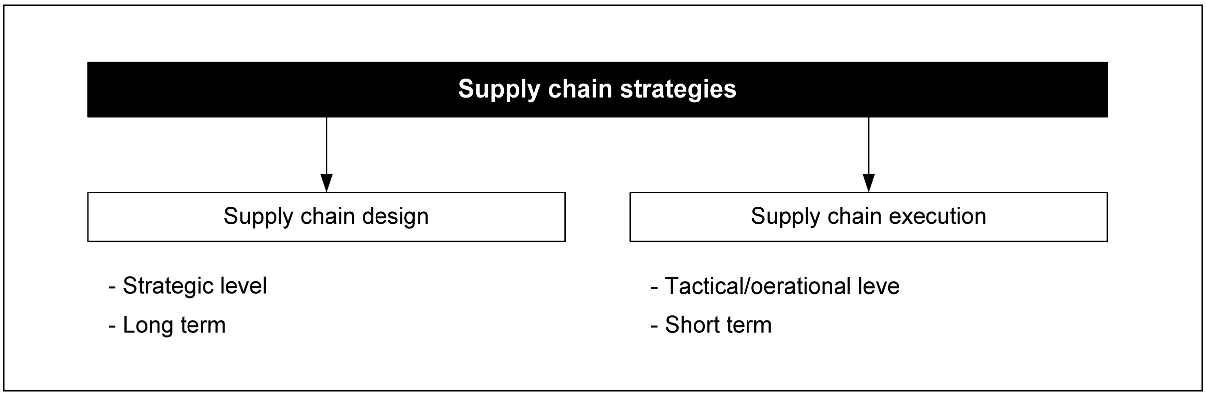

Figure 20: Supply chain strategies

In SCD, sometimes also called supply chain configuration, strategic decisions on the physical structure of the SC for the next several years are made, such as postponement or facilities network redesign. These decisions address the infrastructure of the SC, i. e. the location and capacities of production plants and distribution centers, transportation modes and lanes, production processes used to satisfy customer demand. The time horizon of SCD accounts to many month or years and usually assumes little or even no uncertainty of information (Harrison 2003, 4; Simchi-Levi 2003, 15). In construction, design decisions can influence alternative storage capacities which are—apart from the construction site and related lead times—relevant for material availability, usually applicable if the project volumes for the next years can be estimated.

SCE, sometimes also considered as the term SCM defined in section 5.2.1, focuses on the determination of solutions for tactical and operational planning problems. In particular, decisions on the tactical level are typically updated between once every week, once every month or once every year. They include for instance, local inventory policies and deployment, manufacturing and service schedules, and transportation strategies defining also the frequency in which customers are visited. Production and transportation data are assumed to vary according to know probability distributions, the infrastructure is set to be (almost) fixed. Decisions on the operational level are day-to-day decisions and include for example the generation of schedules for individual orders and according pick lists, the organization of shipments and placement of replenishment orders as well as routing and truck loading. SCE is a short term analysis and spans days, weeks or month, focusing on the implementation of short-term plans (Harrison 2003, 4; Simchi-Levi 2003, 15).

5.2.2.1 Supply chain design

Typical problems addressed in SCD refer to the determination of the manufacturing strategy, the design of the supply base, distribution strategy, outsourcing and the design of products and processes, see Table 6.

Table 6: SCD considerations

SCD issue	Planning problems
Manufacturing Strategy	Number and allocation of plants Products manufactured at each plant Type of process technologies employed Markets served
Supply Base Design	Simultaneous supplier selection for all parts within commodity products Allocation of suppliers to plants
Distribution Strategy	Type of shipment: directly or stock regionally Number and location of distribution centers Allocation of distribution centers to customers Determination of transport mode
Outsourcing	Determination of in-house and outsourced parts of the SC Determination of trade-offs between costs and service
New Product and Process Design	Type of infrastructure when new products are added to the line Determination and allocation of additional sources of supply at which demand point

(Harrison 2003)

According to (Cigolini et al. 2004), the following techniques are perceived to be important for the definition of the structure of the supply chain:

- SC reconfiguration – postponement,
- facilities network redesign,
- warehouse network redesign, and
- transportation fleet design.

SC reconfiguration, also called postponement, aims at improving the product and process design by focusing on the management of inventory, i. e. necessary inventory can be reduced and the variance of materials consumption can be decreased by customizing the products as late as possible (Lee et al. 1993; Nagaraj and Nooyi 1998 cited by Cigolini et al. 2004, 13).

Facilities network redesign deals with the optimization of the number, locations and capacities of production plants (Johnson and Wood 1993 cited by Cigolini et al. 2004, 15). The aim is to decide upon the removal of plants or capacity expansion for higher profitability (Vinelli and Forza 1996 cited by Cigolini et al. 2004, 15) with the objective of a high responsiveness with simultaneously realizing low costs. The appropriate capacity for a facility hereby underlies a trade-off between responsiveness and utilization. Over-capacity leads to a poor utilization with high responsiveness but less capacity leads to low responsiveness (Chopra and Meindl 2006, 115). These decisions have a long-term impact on the whole SC, because expansion or changes of facilities are long term processes. A review on most recent literature on facility location analysis within the context of SCM and a discussion of the general relation between facility location models and strategic supply chain planning is given in (Melo et al. 2008).

Similar to facilities network redesign, *warehouse network redesign* concerns the optimization of the number of warehouses, their location and capacity (Ballou 1987 cited by Cigolini et al. 2004, 14). The aim of warehouse network redesign is to minimize costs for the whole SC while fulfilling service level requirements. In the decision making the trade-off between additional costs for more warehouses but the achievement of higher service levels has to be resolved (Simchi-Levi et al. 2002, 25). Economic impact depending on the increase of warehouses is, for instance (Simchi-Levi et al. 2002, 25):

- An improvement in service level, because the average travel time to the customer gets shorter,
- an increase in inventory costs, because there must be safety stocks at each warehouse,
- an increase in overhead and setup costs,

- a reduction in outbound transportation costs (costs of sending material out of the warehouse), because the ways from the warehouses to the customers are shorter, and
- an increase in inbound transportation costs (costs for bringing material into the warehouse), because there are more warehouses that have to receive smaller amounts.

Transportation fleet design comprises decisions concerning the modes of transportation (Cigolini et al. 2004, 14). These modes are characterized by their capacities, velocities and costs. In particular, modes comprise air, package carrier, trucks, rail, water, pipeline, as well as the option of intermodal transport. Referring to costs only, usually cheaper modes have longer lead-times and require a larger minimum quantity for shipments. The choice of mode is influenced by the characteristics of the products, e. g. pipeline or trucks for liquids depending on quantity. Thereby, a trade-off between transportation and inventory costs exists. Nevertheless, choosing a mode the impact on both inventory costs and responsiveness needs to be considered.

5.2.2.2 Supply chain operations

SCO concepts which are perceived most important for construction are:

- Just in time,
- continuous replenishment,
- vendor managed inventory,
- group purchasing organizations,
- (logistic) category management, and
- transportation optimization.

They help to increase material availability while decreasing site congestion and foster a reduction in transportation costs. Further techniques often mentioned in the context with SCM, such as reserving upstream capacity/stock and techniques for multi-echelon like reordering policies and distribution requirements planning which are applicable for unknown demand are not focused on. Generally, in construction information on future demand is known determined by the design specifications of the final product.

In particular, the aim of *just in time (JIT) delivery* is to reduce inventory levels through a synchronization of transport and consumption (Stadtler and Kilger 2004, 174). JIT means that an activity or the delivery of goods only takes place upon receipt of an order. As decisions are based on true customer demand, suppliers have to react spontaneously to customers requirements. Hence, customers do not need to hold inventory if JIT delivery can be realized with the supplier. The prerequisite for JIT is a fast transmission of customer’s orders and, hence, an appropriate information flow between SC partners (Simchi-Levi et al. 2002, 121–2).

Continuous replenishment is similar to JIT, but solely focuses on the distribution of products (Andraski 1994 cited by Cigolini et al. 2004, 16). Effective continuous replenishment ensures that service levels are met and the retailer decreases its inventory level (Simchi-Levi et al. 2002, 154). Therefore, vendors and retailers fix time intervals for replenishment. The retailer must provide the vendor with data about his inventory level. Based on this data the vendor prepares the appropriate shipments for the next delivery so that a specific level of inventory is maintained at the retailer's warehouse (Chopra and Meindl 2006, 518). The retailer buys the amount of goods needed to replenish its stocks and is therefore the owner of the inventory at its store/warehouse (Simchi-Levi et al. 2002, 154).

Similar to continuous replenishment is *vendor managed inventory (VMI)*. Applying VMI, not the retailer but the vendor is the owner of the inventory until the goods are finally sold. The vendor is responsible for a sufficient number of goods at the retailers stock and has to take the items back when they remain unsold (Chopra and Meindl 2006, 518). The advantage for the retailer is the shifted risk of unsold items to the vendor. However, the retailer must provide the vendor with correct data on the inventory levels to ensure proper replenishment (Chopra and Meindl 2006, 518).

Group purchasing aims at optimizing the procurement through purchasing goods in groups, i. e. different companies order their required materials or components together. Purchasing higher amounts, they can most likely gain discounts and reduce transportation costs by exploiting economies of scale (Cigolini et al. 2004, 15).

(Logistic) category management is applied in companies with different product categories that require different production and logistic concepts, for example food and non-food articles. These companies summarize their products to product groups for which the same production and logistic approaches can be applied and hence planning effort could be reduced (Cigolini et al. 2004, 15).

The aim of the *transportation optimization technique* is to find the lowest-cost routing of products from the production/assembly plants to the warehouses or customers (Ballou 1987 cited by Cigolini et al. 2004, 15). This technique especially applies to companies with a complex transportation network because of geographic expansion or multi-echelon warehousing (Blumenfeld et al. 1987; Cigolini et al. 2004, 16).

5.3 Adoption of supply chain management to construction

5.3.1 Characteristics of construction supply chain management

Construction Supply Chain Management (CSCM) is characterized by the integration of key construction business processes, from the demands of client, design to construction, and key members of construction supply chain, including the client, architects and consultants, the main contractor, sub-contractor and supplier of materials and components. CSCM focuses on how firms utilize their suppliers' processes, technology and capability to enhance competitive advantage. It can be regarded as "…a management philosophy that extends traditional intra-enterprise activities by bringing trading partners together with the common goal of optimization and efficiency. CSCM emphasizes on long-term win-win, cooperative relationships between stakeholders in systemic perspective. Its ultimate goal is to improve construction performance and add client value at less cost." (Xue et al. 2007, 152)

CSCM aims at four dimensions (Vrijhoef and Koskela 2000, 172):

1. Improvement of the total flow of materials and components between suppliers and contractors,
2. reduction of costs, especially those related to logistics, lead time, and inventory,
3. transfer of on-site activities to the SC and reducing total installed cost and duration by avoiding inferior conditions on site, or achieving wider concurrency between activities barred by technical dependencies on site, and
4. integration of on-site production and management of the SC.

Thereby, a critical issue for a successful construction project is the material delivery process and materials management, i. e. the assurance of material availability for project execution without holding unnecessary inventory, as materials inventory on the one hand incurs extra inventory costs and on the other hand causes serious construction problems, such as site congestion as well the deterioration of the quality of the materials (Ala-Risku and Kärkkäinen 2006, 25; Tserng et al. 2006, 395).

Two conditions for efficient materials management are:

1. The transparency of material availability for site inventories and other stages of the supply chain, and
2. short response times along the supply chain demanded by short time-span of material planning (Ala-Risku and Kärkkäinen 2006).

CSCM shall ensure material availability on site and reduced inventory costs—on site as well as in the depository of the contractor where it holds material on stock; i. e. it supports that those materials and components are supplied in adequate quality in the required quantity, at the appropriate place and within an adequate time. This causes a reduction of costs for faulty or wrong deliveries and helps to decrease on-site congestions caused by workspace conflicts between construction activities and materials inventory. CSCM could further initiate a decrease in personnel costs and reduce extra control and planning effort in purchasing decisions by shifting the responsibility for the material availability to the supplier and enabling an automation of the materials management (e. g. Tserng et al. 2006).

5.3.2 Existing work on construction supply chain management

A first initiative for SCM in construction can be seen in the Latham report in 1994 (Latham 1994). It was the first publication that drew attention to the need for improvements of the construction industry by implementing concepts originating from SCM. A so-called 'win-win situation' for all parties involved by teamwork is suggested as optimum, because fairness among project participants is essential for project success (Latham 1994, V). Furthermore, Latham (1994) discusses surveys that showed a significant cost reduction by a greater use of standard components or off-site prefabrication (Latham 1994, 63). In 1998, the Egan report 'Rethinking Construction' from the so called Construction Task Force was issued. In the report it was claimed that the construction industry was not as different from the manufacturing industries as always said. For example, houses are products that are essentially repeated, so is the process of construction itself. Thus, in the opinion of the authors processes could be improved because of these repetitions (Egan 1998, 18). In 2002, the report 'Accelerating Change' was published by the Strategic Forum for Construction, chaired by Egan, to reaffirm the principles that were set out in 'Rethinking Construction' (Strategic Forum for Construction 2002, 7). It showed the progress in SCM implementation in construction since the Egan report. More than 1000 construction organizations were involved in the initiative and analyses of the various demonstration projects show that the achievements were remarkable compared with the industry average (Strategic Forum for Construction 2002, 15).

Since these three reports were issued, numerous researches on CSCM have been done so far and monographs have been published. These monographs published are, for instance, (London 2008; Olsson 2000) and (Oakland and Marosszeky 2006). Scientific articles published in recent years are of different nature. Most of the articles contain general recommendations based on expert studies, especially focusing organizational aspects of partnering, for instance, (Aulinger 2003; Beach et al. 2005; Cheng et al. 2004; Errasti et al.

2007; Phua and Rowlinson 2004; Ronchi 2006; Teller and Kotzab 2003; Windischer and Grote 2003) and supply chain integration, for example, (Briscoe et al. 2001; Briscoe et al. 2004; Dainty et al. 2001; Love et al. 2002). Further literature addresses the creation of a seamless SCM model for construction (Love et al. 2004) and delivery systems in construction, such as BOT etc. (e. g. Oyetunji and Anderson 2007; Palaneeswaran et al. 2001), as introduced in section 3.1.

Furthermore, a new framework/model for the improvement of a special task, for example procurement, is introduced and it is theoretically explained how SCM can eliminate problems to reach higher profits while meeting the customers requirements, for instance, (Kumaraswamy et al. 2000; Yao-Wu and Xiao-Long 2004; Yeo and Ning 2002). Some works identify problems and show how improvements can be reached applying new techniques, for example, (Mahmoud-Jouini 2000; Vrijhoef and Koskela 1999) or by the application of information technology (IT) in the construction industry (Cheng et al. 2001). Furthermore, critical perspectives on other work or new frameworks that were published are given, for instance in Green and May (2003).

Few migrations of practices have been observed between manufacturing and construction industries in terms of materials management (Palaneeswaran et al. 2001). A concept already applied in practice is the so called just in time delivery of components. Furthermore, knowledge transfer from mass-production has been conducted to housing considering construction as a manufacturing process by developing pre-assembly and modular housing (Barlow et al. 2003; Gann 1996; Gibb 2001; Gibb and Isack 2003; Naim and Barlow 2003). However, common construction projects are unique and dependent on a bewildering array of contextual variables and participants (Palaneeswaran et al. 2001). Apart from the given and perceived major representatives of research in CSCM and additional research effort on partnering and networking in construction, there has been no thorough analysis of the application of concepts from SCM to improve efficiency of construction projects in terms of material availability, inventory holding, and a smooth construction process.

5.3.3 Construction supply chain design

The definition of construction supply chain design (CSCD) depends on the responsibilities and positioning of the material suppliers, sub-contractors and contractors within the CSC. A supplier might seek to control the CSC to increase market share and stabilize their demand through development of a larger risk pool. In contrast, the contractor's primary motivation is to seek control of a SC to exert control over lead time and improve their ability to successfully resolve the matching problem between material availability and material demand on site. Usually, general contractors are service providers and, hence, have limited influence on the material chain. Instead, the location and ownership of inventory is mainly a problem faced by sub-contractors who might wish to control their material streams (Walsh et al. 2004, 825). The potentials, risks, benefits as well as prerequisites for the application of SCD approaches in construction are summarized in Table 7.

Table 7: CSC design approaches

Supply Chain Design	**Material**	**Supplier: Delivery**	**Contractor: Sourcing**
Design for SCM - Postponement	• Standardized housing, pre-fabricated buildings • Standardized components • E. g. windows, doors	How: • Establishment of standardized production processes • Establishment of contractual relationship with contractors (customer) and suppliers (raw material)	How: • Use of standardized components
		Benefits: • Promised sales rates • High planning stability due to improved demand forecasts for construction materials production and resource procurement	Benefits: • Easy replacement of worn out, broken parts • Less dependency on a single supplier, multiple sourcing possible, due to standardization • Realization of discounts ordering high volumes for various projects • High material availability
		Risks: –	Risks: • Loss of individuality
		Prerequisites: e. g. strong contractual relationship, IT support etc.	
Facilities network redesign	• Standardized construction materials and components • E. g. bricks, concrete	How: • Applies to manufacturing plants • Location close to places were high construction activity is expected to occur in the future	How: • Applies to branch offices, plant depot and housing for construction workers • Location close to places were projects take place, usually temporary • Possibility of renting
		Benefits: • Decrease in transport distances and in transportation costs	Benefits: • Decrease in transport distances and in transportation costs
		Risks: • High investments in manufacturing plants and exposure to risk in case of shift of construction activities	Risks: • High investments in facilities and exposure to risk in case of shift of construction activities
		Prerequisites: • High demand forecast reliability	Prerequisites: • High planning reliability about business activity in the near future

Table 7: CSC design approaches (continued)

Supply Chain Design	Material	Supplier: Delivery	Contractor: Sourcing
Warehouse network redesign	• Standardized construction materials and components • E. g. brick, concrete	How: • Location of warehouses close to places were high construction activity is expected to occur in the future	How: • Location of warehouses close to were projects take place, usually temporary • Possibility of renting
	• Electric and non-electric components ordered in high amounts to realize discounts and/or material availability • E. g. air conditioning systems, heating systems, process measuring and control technology	Benefits: • Decrease in transport distances and in transportation costs	Benefits: • Guarantee of material availability due to supplier independent material buffer • Decrease in transport distances and in transportation costs • Realization of discounts • Reduced storage space on site, reduced site congestion
		Risks: • High investments in warehouses and exposure to risk in case of shift of construction activities	Risks: • High investments in warehouses and exposure to risk in case of shift of construction activities
		Prerequisites: • High demand forecast reliability	Prerequisites: • High planning reliability about business activity in the near future
Transportation fleet design	• All construction materials and components	How: • Selection of transport modes depending on construction material • Addresses logistic system models • Applies to transport from manufacturing plant to warehouse, from warehouse to the site, from the manufacturing plant to the site	How: • Selection of transport modes • Applies to transport from warehouse to the site, from the site to the warehouse, on-site logistics
		Risks: • Little choice in transport mode • Mode determined by size, consistency, weight and requested delivery time as well as accessibility of site or warehouse	
		Prerequisites: • Availability of appropriate transport systems	

Regarding the particular problems in CSCD, *postponement* in traditional construction[15], is applicable in terms of standardization[16] of components. While standardization cannot be applied in the shell-phase for components with specific dimensions (e. g. foundations, walls), the use of standardized end items in the completion-phase of the project, for instance doors, windows, electrical fittings, and the design of bath rooms or even the dimensional grid for the facility enhances CSC performance. Contractors can achieve economies of scale in the procurement of components by ordering larger amounts of standardized regularly used components, also for different projects, and store them in a warehouse (see warehouse network redesign). A side effect is reduced installation time for standardized components because of learning effects (Winch, 2002, p. 304).

Facilities network redesign for a construction contractor is rather complicated due to its unique character of on-site production. Classical production plants as typical for traditional manufacturing cannot be found in the individual housing industry. However, facilities network redesign is applicable to the number, location and capacity of branch offices including bureaus and stores for equipment of the contractor. The construction material suppliers employ facilities network redesign for the location of manufacturing plants. The objective of the decision on the facilities network design is driven by transport distances and costs of bulky equipment either the materials or equipment storage to the construction sites. If the contractor runs various projects in a far distance from the office either equipment is transported to the site causing high transport costs or it is rented leading to underutilization of own equipment.

The *warehouse network redesign* is applicable to both, material suppliers as well as construction enterprises. Material suppliers can benefit from warehouse network redesign to establish warehouses in areas where high construction activity is expected to occur in the next years regarding long term planning to ensure high service levels in material availability. Additionally, construction contractors benefit from warehouse network redesign by allocating warehouses used to store procured material in high amounts due to own forecasts of construction activity and material buffers they establish to realize discounts on huge amounts and ensure material availability. Thereby, construction contractors tend to rent warehouses for the time before actual assembly of the material or components on site. Warehouse network redesign can help reduce storage space on-site due to less congestion on-site and quicker delivery times due to more accurate planning of the own construction projects as well as

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[15] Note: Not valid for construction as a manufacturing process, pre-assembly and modular housing. See for instance (Barlow et al. 2003; Gann 1996; Gibb 2001; Gibb and Isack 2003; Naim and Barlow 2003).

[16] Pre-engineering in construction is also a concept of standardization. The customer can choose a building out of a given set of buildings which are already pre-engineered and construction on site can start immediately (Vrijhoef and Koskela 2000, 172).

possible decrease on material costs due to the realization of discounts for the procurement of huge amounts of material.

Analyzing the design of the *transportation fleet* a connection is drawn at the interface between the material storage of the supplier or contractor and the construction side. Transports concern the equipment from the plant depot to the construction site, transports of materials or components from the suppliers to the construction site and on-site logistics. Usually, the choice of transport mode is determined by the type of equipment or material transported for instance low-loading trucks for the transport of excavators, trucks for smaller tools or gravel, mixer conveyors for concrete etc.

5.3.4 Construction supply chain operations

After having identified possibilities of the application of approaches for SC design in the construction industry, the focus is shifted towards instruments on the operational level in construction in the following. Table 8 briefly summarizes the applicability of SC operations and executions techniques, benefits and risks as well as major prerequisites for its successful introduction to construction.

The *JIT delivery* is already applied in construction projects. Usually JIT is the only way procurement, especially of customized construction material, can be managed as on most construction sites storage space for materials or components is rare. Hence, with the achievement of JIT delivery for on-site material delivery, temporary on-site storage, i. e. site congestion, double handling as well as maintenance can be avoided (Yeo and Ning 2002, 257). For example, pre-fabricated components like pillars are very big and bulky and, thus, must directly be build in after arrival at the construction site, i. e. a synchronization of transport and consumption is indispensable. Yeo and Ning (2002, 257) propose the use of just in time delivery for on-site material delivery with the aim to avoid temporary on-site storage, double handling and maintenance. Furthermore, JIT raises the flexibility in responding to design changes (Walsh et al. 2004, 825). However, the current situations show that the industry still lacks site readiness due to delays in site progress and suffers unpredictable deliveries as well as installation rates so that fabricators have to maintain large inventories and materials and components on site have to be handled more than once. This is due to the reason that mainly the planning itself cannot assure that preceding work packages are completed whereas project progress is not properly communicated to related SC members. This requests the availability of a schedule reliably determining the finish and start of construction activities.

Table 8: CSC operations and execution

Supply Chain Operations or Execution	**Material**	**Supplier: Delivery**	**Contractor: Sourcing**
Just in time	• Cost-intensive components with known demand • Usually one-time demand	How: • Delivery of component on customer order directly to the site	How: • Order of component with set delivery date
		Benefits • Detailed planning of production possible • Reduction of inventory	Benefits/Risks: • Reduced site congestion • Reduced on and off-site inventory and inventory costs
		Risks • Risk of late delivery if production is distorted • Risk of non availability of equipment for unloading or site-access	Risks: • Risk of non-availability of material and components due to supplier problems
		Prerequisites: • Contractual agreement • Site readiness, access to site and available unloading equipment and workforce	Prerequisites: • Contractual agreement • Reliability of supplier in terms of time and quality
Continuous replenishment	• Standardized construction materials • E. g. bricks, concrete, sand, soil • Continuous/enduring demand during project phases	How: • Delivery of material to warehouse or directly to the site of the contractor • Replenish if certain inventory level is reached or a fixed time interval has passed • Guarantee of material availability and quality standard	How: • Provide material supplier with necessary information about inventory levels and future demand • Assign a warehouse or storage space on site to the supplier
		Benefits: • Inter-organizational, more flexible planning of production and delivery	Benefits: • Reduced planning effort for material procurement • Reduced material handling costs
		Risks: • Liability for non-availability of materials due to delivery problem	Risks: • Non availability of designated storage space • Less flexibility in changing storage space for a supplier • Dependency on supplier
		Prerequisites: • Transparency of date about inventory level and demand • Long-term contracts with clients • IT support	Prerequisites: • Reliability of supplier in terms of service, time and quality

Table 8: CSC operations and execution (continued)

Supply Chain Operations or Execution	Material	Supplier: Delivery	Contractor: Sourcing
Vendor managed-inventory	• Standardized construction materials • E. g. bricks, concrete, sand, soil • Continuous/enduring demand during project	How: • Delivery of material to warehouse or directly to the site • Management of the inventory in warehouse or site of the contractor • Guarantee of material availability and quality standard Benefits: • Inter-organizational, more flexible planning of production and delivery • Risk of unsold and probably not resalable material Risk: • Liability for non-availability of materials due to delivery problem • Risk of unsold and probably not resalable material Prerequisites: • IT support • Long-term contracts with clients	How: • Provide material supplier necessary information about inventory levels and forthcoming demand • Assign a warehouse or storage space on site to the supplier Benefits: • Reduced planning effort for material procurement • Reduced material handling costs • Risk of unsold items shifted to supplier Risks: • Dependency on the supplier Prerequisites: • Reliability of supplier in terms of service, time and quality
Group purchasing organizations	• Standardized construction materials • E. g. bricks, concrete, sand, soil		How: • Procurement of large amounts for several projects within one firm Benefits: • Realization of discounts for large amounts of materials and components • Reduction of transportation costs due to larger amounts ordered Risks: • Changing construction sites hamper long-term planning Prerequisites: • Long-term forecast of project portfolio • Good communication process

Table 8: CSC operations and execution (continued)

Supply Chain Operations or Execution	Material	Supplier: Delivery	Contractor: Sourcing
(Logistic) category management	• Standardized construction materials and components • E. g. bulk materials, piece goods	How: • Delivery of material and components to warehouse or directly to the site of the contractor	How: • Delivery of material and components from the warehouse to the site, from the site to the warehouse or on-site
		Benefits: • High capacity utilization of transport vehicles • Reduced transportation costs	
Transportation optimization	• All construction materials components	How: • Finding optimal routing decision to deliver materials and/or components to warehouses and sites of various contractors • Match amount and time of demand of the various contractors	How: • Finding optimal routing decision to deliver materials and/or components from central storage to construction sites, on-site, from site to warehouse
		Benefits: • Reduced transport costs Prerequisites: • High amount of similar materials and components to which the same logistic models apply	

Although the construction industry is usually characterized by an absence of continuous production process like in the manufacturing or process industries, *continuous replenishment* can be applied whenever linear or repetitive construction projects like highway or high-rise building construction occur. Its potential is especially seen in large scale projects with a number of similar work packages over a longer period, e. g. masonry or pavement works. Construction enterprises already use storage silos on site for e. g. mortar and directly pick up the material from the silo. A continuous replenishment program can ensure the sufficient material availability and reduce work breaks due to a lack of material on site. However, evaluation is still needed to declare whether significant cost savings will be achievable due to the short time frame of projects and the necessary establishment of an IT infrastructure to ensure reliable information transfer on inventory to the supplier.

According to continuous replenishment, *VMI* could be applied for similar cases. Still, it has to be questioned if the condition of the supplier’s ownership and take back responsibility is liable in practice, as construction materials once delivered to the construction site are exposed to environmental impacts such as weather and thievery. However, vendor management of site materials at a warehouse would reduce the materials inventory at construction sites and help reduce site congestion and has already been implemented exemplarily for steel bar production and supply operations in a resource supply chain planning system for construction projects to minimize the integrated inventory costs (Tserng et al. 2006). However, the application of VMI to standard materials and components makes it easier to handle situations were a surplus in material remaining at the end of the construction is likely to occur. On the one hand, suppliers might offer reductions in restocking charges due to the better chance to resale the materials and components and on the other hand, if the materials are not deteriorated they could be easily resold to other construction and engineering enterprises due to its standard character (Kini 1999, 34).

Although, *group purchasing* in construction might be possible for the procurement of larger amounts of standardized construction materials and components with other firms, it is usually not practicable due to the project character of construction and the changing production sites as well as highly unstable amount of required materials and components in each project. However, if a construction enterprise holds several projects with longer durations at the same time in its project portfolio group purchasing would be beneficial if the amount of material or components required exceeds a certain limit to achieve economies of scale regarding transportation costs and to realize quantity discounts. Prerequisite for group purchasing in a multi project environment of a construction enterprise is an efficient communication process between planners on the amount and time of demand to set material orders. Closely related to group purchasing would be the CSC design technique of warehouse network redesign to centrally store construction materials and components for several projects.

(Logistic) category management addresses the delivery of the final product to the customer. In construction, this refers to the transport of construction materials and components from the supplier to the warehouse or site of the construction contractor or to the transport of construction materials and components from the warehouse to the site or on-site supervised by the construction contractor. However, as buildings consist of a heterogeneous mix of materials and components for which usually predetermined production, storage and transportation constraints exist, category management would be rather difficult and not appropriate to implement, unless a materials supplier has to service several construction contractors with similar material at the same time.

Transportation optimization techniques are also applicable in the construction industry. In construction, constant changes in production environments and the location of sites results in complex and changing transportation network for the supplier as well as for the construction contractor. Therefore, a cost-optimal routing must be achieved by also considering constraints like the delivery of materials and components within given time windows. However, due to the unstable environment in construction these techniques do not seem to offer the same benefits in lead time reduction and cost saving like in the traditional manufacturing industries and have to be adjusted.

5.4 Impacts on the design and operation of construction supply chains

5.4.1 Logistic systems for material delivery

The application of SCM in construction depends on the way the material delivery is organized from the supplier to the construction site or the respective destination. Common delivery types and related materials, also referred to as logistic system models, are given in Table 9. Additionally, these system models are applicable for components like doors, windows or heating, ventilation, air conditioning and refrigeration (HVACR).

Table 9: Logistic systems and suitable building materials

Delivery type	Material
Directly to construction sites	Construction steel, precast concrete unit, building woodwork, cement, gypsum and gypsum elements, insulation materials (order) Terrazzo products, technological outfit (adjudication by tender) finishing materials, other materials (by phone)
To construction sites and then to central store	Sheet, ceramic brick, belite, building paper, foils, aggregate, lime
Central store with checking of stock	Technical gases, cement, insulating materials, sanitary system materials, electrical system materials, foamed polystyrene, sawn timber
Central store and then to construction sites	Paints and glues, terracotta and glaze, floor finish, glass, wood and wood based elements
Directly to construction sites from auxiliary plant	Concrete, technical gases, metal materials

(Sobotka 2000, 186)

The two most typical logistic systems in construction are ‘To construction sites and then to central store’ and ‘Central store and then to construction sites’. The most suitable materials for the application of SCM in construction are bulk materials which require stock on site and are consumed in roughly known but still variable amount as well as materials with known amount and specification, high value and high on-site space requirements of storage. Bulk materials refer to materials such as concrete, insulation materials, aggregate, lime, technical gases, cement and few metal materials. High value and materials which require large space on site are, for instance, construction steel and pre-cast concrete units.

Current logistics practice involves the construction or site manager sending an order to the purchasing department if the stock of materials on site reaches a certain level (Sobotka 2000).

This causes additional permanently occurring control effort for the observation of the stock level.

5.4.2 Material and component characteristics

The characteristics of the construction material or component influence the organization of transport as well as inventory management both for the supplier as well as for the construction contractor. The classification of construction materials and components in Table 10 supports the determination of adequate use of SC approaches which imply transport and storage requirements as well as requirements for the inventory control process of the materials and components. The applied criteria and there values are:

- State of aggregation: liquid, solid, gaseous
- environmental safety: hazardous, non-hazardous
- type: bulk material, piece goods
- standardization: standardized, individual
- size of product (in relation to transport vehicle): small, large
- resistance (risk of deterioration due to climatic influence): none, heat, sunlight, water
- consumption: constant, variable, once

Additionally, transport as well as inventory management are further differentiated. Two relevant issues for the organization of the transport are the chosen mode, given by road, water, railway, air or mixed mode, as well as the chosen packaging option, for instance, containers, palettes or tanks. Inventory management refers to storage requirements, i. e. on-site or in a warehouse and possible exposition to the environment or the necessity to cover the materials and components, as well as to order types given with refill, individual or delivery upon receipt of order, so called JIT.

Thereby, the cross (X) in Table 10 highlights the relevancy of the criteria for transport and inventory management and indicate whether the characteristic exerts an influence on the transport of construction material and components as well as on the inventory management or not.

Furthermore, the accessibility of facilities and the site influence the transport mode. For instance, if a facility or construction site is located in the middle of a country without access to railway and water, these two transport modes are to be excluded from the choice. Additionally, the transport mode itself influences the packaging, for instance, only particular containers or pallets are permitted to be transported by plane.

Table 10: Influence of construction materials on transport and inventory management

		Transport		Inventory management	
Characteristic	**Value**	**Mode**	**Packaging option**	**Storage**	**Order types**
State of aggregation	- Liquid - Solid - Gaseous	X	X	X	
Environmental safety	- Hazardous - Non-hazardous	X	X	X	
Type	- Bulk material - Piece goods	X	X	X	X
Standardization	- Standardized - Individual			X	X
Size	- Small - Large	X	X		X
Resistance -Risk of deterioration due to climatic influences	- None - Heat, sunlight, water		X	X	X
Consumption	- Constant - Variable - Once				X

5.5 Discussion of results

In the preceding sections it was shown, that the efficiency of materials management in construction projects could be improved by applying concepts of SCM. Therefore, potential applications of SCM concepts for the design and operation of construction supply chains were highlighted and their benefits and risks both for construction contractors as well as for material suppliers were revealed. It was not intended, however, to give a comprehensive overview on all aspects of SCM.

As construction material suppliers are defined as part of the manufacturing industries most SC concepts suitable for mass production are applicable by additionally considering uncertain demand pattern in construction and hence, coping with shorter planning horizons. The evaluation of SCM concepts for construction reveals that some SCM concepts from the manufacturing industries are already adapted. Still, it is to note that the adoption of SCM in the construction industry is characterized by a significant number of limitations and inconsistencies (Saad et al. 2002).

Regarding the operational CSCM, field installation crews face the unique matching problem that a significant fraction of materials and components delivered to the construction site must be precisely delivered to their installation location. In contrast, engineering and design organizations, suppliers and construction managers often ignore the unique matching problem of the construction site workers which requires exact timely allocation of materials and resources. Furthermore, although contractors are held liable for completion dates, they usually become involved in the delivery process too late to be able to control the upstream site activities. Concluding, contractors force the earliest possible delivery of materials to the site rather than a delivery process corresponding to the planned installation dates to reduce on-site congestions and decrease inventory (Tommelein 1998, 279; Walsh et al. 2004).

Additionally, it is to note, this work does not contain considerations about the interrelation and possible integration of the procurement of construction materials and the corresponding construction processes. Long lead times of procurement and delivery times to the site after an order may delay activities behind the initial schedule starting time. Hence, after the initial construction schedule and material requirements plan, compatibility should be established by rescheduling the construction activities, i. e. the starting dates of the construction activities should depend on the time constraints deriving from the actual delivery dates of the construction material or components.

Furthermore, the construction industry ‘suffers’ its unstable project environment and temporary project relationships among the partners of the CSC. With this regard, although a complete application of SCM concepts as referred to in this thesis is not expected in the short term, i. e. might be considered as impossible or impractical, changing institutional and project relationships between the participants of the CSC might enable more efficient construction project planning in the future. Yet it has to be shown, whether the trend for individual housing remains in the future or if a shift towards more industrial housing occurs. With this respect, concepts like lean and agile construction are discussed. For related work see, for instance, (Al-Sudairi 2007; Naim and Barlow 2003).

Concluding, the implementation of the concepts of SCM in construction cannot happen isolated but usually comprises a bundle of concepts pursued jointly; i. e. although the foundation for successful SCM in construction is laid by a move from partnering to more collaborative relationships and integrated processes in construction the next step to be taken is the rethinking of existing process structures in construction projects. This section takes a step towards the planning of the CSC by highlighting opportunities to apply, adopt and modify certain well-known SC techniques. Thereby, the outcomes of this conceptual approach have to be empirically validated in the future. This would be achieved by conducting surveys among industry professionals occupied with materials procurement and site management regarding current and future potentials of the adoption of concepts of SCM in construction.

6 Sustainable end-of-life management of construction products

As pointed out in previous sections 3.2 and 4.2, current project planning approaches address the planning of construction projects mainly with respect to time and cost objectives. Taking into account the growing importance of sustainability (see section 6.1) it becomes obvious that targets beyond time and costs have to be addressed in the future. For instance, focusing on deconstruction projects, environmental objectives, as aimed at with the establishment of closed-loop supply chains, need to become part of project planning. Hence, project planning procedures as common in construction practice significantly need to be upgraded or innovated. Thereby, the focus of project planning has to be shifted to aspects like resource or energy efficiency, topics heavily discussed in science, politics and economics with respect to the need for sustainable development. While energy efficiency is addressed in section 8, this section focuses on aspects related to resource. Thus, in the following, current accomplishments in Germany with respect to C&D waste treatment are highlighted and the role of sustainability in construction as well as the relevancy of closed-loop material flows in construction is discussed in more detail. Based upon this, section 7 will then set up planning concepts of reverse logistic operations as relevant for the operation of construction projects.

6.1 Need for sustainability

In recent discussions about climatic change the enforcement of environmental conscious behavior and sustainability of human actions is addressed. In response to the Kyoto protocol (UNFCCC 1997) and its central instruments, the clean development mechanism and joint implementation, various countries have already begun to implement mechanisms laid down by the Kyoto process, and enforce the awareness of sustainability of human actions. In a wider sense, the concept of sustainability can be described as the endeavor to ensure the achievement of economic growth without unreasonably exploiting the resource base, polluting the environment or upsetting any existing ecosystem. Therefore, entities like countries seek to decisions on the micro- as well as on the macro-level are in accordance with the objective of an environmentally friendly development. In detail this means, that the concept of sustainability involves the assessment of all the costs and benefits related to economic activities including externalities, for the efficient allocation of resources and an improvement in quality of life (Ofori 1992).

The construction industry plays a key role putting the concept of sustainability into practice. Although essential for economic and social development, the construction industry is a major consumer of natural resources and potential polluter to the environment. Approximately 30–40 % of global energy consumption as well as 20–30 % of greenhouse gas emissions can be traced back to the construction industry (UNEP 2007).

The negative effects of construction activities can be categorized as follows (Ramachandran 1991):

- Resource deterioration: depletion of forest resources by the use of timber; dereliction of land caused by quarrying; extraction of sand, clay and other deposits such as limestone; use of energy in the production and transportation of materials and in site construction activity;
- Physical disruption of ecosystems and long-term climatic changes: diversion of natural waterways caused by dams, loss of flora and fauna, and upsetting of the ecological balance with possible health hazards; noise pollution caused by buildings in urban areas; affection of stability of fragile hillsides by highway construction;
- Chemical pollution: particles released in the production and transportation of materials such as cement and quarry products; pollutants produced in the production of building materials; fibers released during working with asbestos products; accidental spillage of chemicals on site and careless disposal of waste.

Therefore, sustainability in construction has become a key factor for the successful completion of construction projects and criteria of sustainability have to be incorporated into the planning and execution of projects. From these remarks it becomes obvious that the construction industry must actively react in a positive manner to environmental issues. Actions to be undertaken include (Ofori 1992; Yang et al. 2005):

- Arresting the depletion of resources, e. g. timber and clay, through economic use of resources as well as recovery of materials and the use of renewable varieties and the development of alternative materials;
- preventing and arresting pollution by a proper waste management, the development and use of non-polluting materials, as well as by applying efficient techniques for construction, maintenance and demolition; low pollution or no-waste technologies;
- exploring energy sources for the extraction of raw materials and the production of materials, the construction activity as well as for the use, maintenance and deconstruction of buildings;
- reduce the energy consumption during construction, use and maintenance of buildings.

Research about sustainability in construction has up to now mainly focused on the design and construction phases, the sustainability of buildings materials, for instance, their ability to efficiently use natural resources such as sun light and water and their recovery, their potentials of avoiding harmful or hazardous emissions as well as their suitability for reuse, refurbishing or recycling. However, sustainable construction does not only refer to the design of the building, but also to the construction, use, maintenance, and deconstruction phase of the building life cycle. Thus, not only the design itself has to meet ecological requirements but also the succeeding phases from construction to deconstruction processes at the end of the life cycle. The highest amount of C&D waste over the life cycle of the building occurs during deconstruction. Taking into account limited dumping capacities, the depletion of scarce resources (e. g. wood, metal and natural gravel), the increasing amount of energy and resource consumption for the production of building materials, and emissions and hazardous substances released into the environment, the aim of sustainable construction should be to strive for closed-loop material flows, i. e. recover deconstructed material such that the material accumulated at the end-of-life of buildings can be lead back into the material flow in the same or different condition and functionality after recovery. This is particularly realized in closed-loop supply chains.

6.2 Construction and demolition waste as an example

6.2.1 Classification of construction and demolition waste

Compared with the manufacturing industries, material stewardship in the construction industry bears much more difficulties. These difficulties emerge from the individuality of buildings, i. e. their uniqueness and wide variety of constituent parts and materials. According to Kibert et al. (2000), five general component categories of houses can be distinguished:

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-inplace 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, also referred to as C&D waste, likewise arises during the erection or renovation of buildings. In Germany, these materials are classified according to the European Waste Catalogue (EWC) (European Commission 2002). It contains a number of different waste descriptions, e. g. for wastes from inorganic chemical processes, waste from the photographic industry as well C&D wastes (including excavated soil from contaminated sites). According to the EWC, construction and demolition waste is grouped in section 17 00 00 comprising the materials listed in the appendix 0.

For statistical considerations, the following five types of C&D Waste are differentiated:

1. Construction and demolition debris: concrete, bricks, tiles and ceramics, mixtures of, or separate fractions of the aforementioned, except those containing dangerous substances
2. Road construction waste: bituminous mixtures except mixtures containing coal tar
3. Excavated earth: soil and stones, dredging spoil, track ballast, all excluding dangerous substances
4. Gypsum-based construction material: gypsum-based construction materials except those containing dangerous substances
5. Construction waste:
   - wood, glass, plastic
   - copper, bronze, brass, aluminum, zinc, iron and steel, tin and mixed metal
   - cables, except those containing dangerous substances, oil and tar
   - insulation materials, excluding those consisting of or containing dangerous substances
   - mixed C&D waste, except those containing mercury and phosphate bonded ceramic (PBC)

6.2.2 Accomplishments of construction and demolition waste recovery in Germany

Considering the implementation of waste management and recovery of C&D waste, it can be seen that progress has been made in various European countries during the last decades. In Germany, for instance, the Federal Statistical Office reports that around 86 % (161.764 million tons) of all accumulating C&D waste (187.478 million tons) were being recovered, with 0.5 % in combustion (0.884 million tons) with heat recovery and 99.5 % in product/material recovery (160.880 million tons) in 2004. The remaining 25.714 million tons of C&D waste were either land-filled (98.8 %) or incinerated (0.2 %); only a small amount of C&D waste was treated for disposal (Statistisches Bundesamt 2006). In 2006, around 173.678 million tons (88 %) of the 193.374 million tons C&D waste accumulated were recovered. More detailed, 90 % of the 187.361 million tons of non-hazardous C&D waste and 61 % of the 9.013 million tons of hazardous C&D waste were recovered (Statistisches Bundesamt 2008b).

The main industry driven organization in the field of C&D waste treatment in Germany is the Consortium of the Construction Recycling and Waste Management Industry (ARGE KWTB, 'Arbeitsgemeinschaft Kreislaufwirtschaftsträger Bau'). It is a consortium of trade associations of the construction industry, e. g. Central association of the German construction industry (ZDB, 'Zentralverband des deutschen Baugewerbes') and the Confederation of recycling construction materials (BRB; 'Bundesvereinigung Recycling-Baustoffe').

In 1996, the ARGE KWTB commenced a voluntary commitment with the Federal Environment Ministry for the Environment, Nature Conservation and Nuclear Safety in Germany, to achieve a 50 % decrease in the amount of disposed of C&D waste in Germany. In 2005 the construction industry has achieved their 10-year voluntary commitment (since 1996) for the 5^{th} time with a long term Recycling Quota of 70.1 % and a long term Recovery Quota of 88.7 %. Nevertheless, it has to be noticed that these figures do not reflect the quality of recovery in terms of recycling or reuse options. However, although the figures of the 5^{th} monitoring report of the ARGE are still subject to interpretation, they provide a more detailed insight into the accumulation and recycling, reuse and disposal of C&D waste than the Federal Statistical Office in Germany. According to the report of the ARGE the disposal of reusable C&D waste has decreased significantly during the last years. In average, 218 tons of mineral C&D waste accumulated each year in the period from 1995 to 2005 consisting of approximately 2/3 excavated earth and 1/3 C&D debris, road construction waste, and construction waste (ARGE KWTB 2007, 12). Thereby, in Germany, only 10 % of C&D debris is disposed of currently (1997: 50 %).

In 2004, C&D waste accounted to 200.7 million tons. These 200.7 million tons comprised 128.3 million tons (63.9 %) excavated earth and 72.4 million tons (36.1 %) consisting of construction and demolition debris (50.5 million tons: 25.2 %), road construction waste (19.7 million tons: 9.8 %) gypsum-based construction material (0.28 million tons: 0.2 %), and construction waste (1.9 million tons: 0.9 %) (ARGE KWTB 2007, 15).

Out of these 72.4 million tons of mineral C&D waste 49.6 million tons of recycling construction materials haven been manufactured which represents a recycling quota of 68.5 %. Thereby, 20.4 million of the 49.6 million tons of recycling construction materials have been produced in stationary plants and 29.2 million tons in mobile or semi mobile recycling facilities (ARGE KWTB 2007, 16–7).

The recovery and disposition of mineral C&D waste can further be analyzed. The first source for recycling construction materials is *C&D debris*. The disposition of the 50.5 million tons of C&D debris is shown in Figure 21. As can be seen, 31.1 million tons were recycled in 2004. 12.2 million tons were directly reused in projects funded by public authorities (3.8 million tons) and in aboveground mining (8.4 million tons) and 4.6 million tons were land filled.

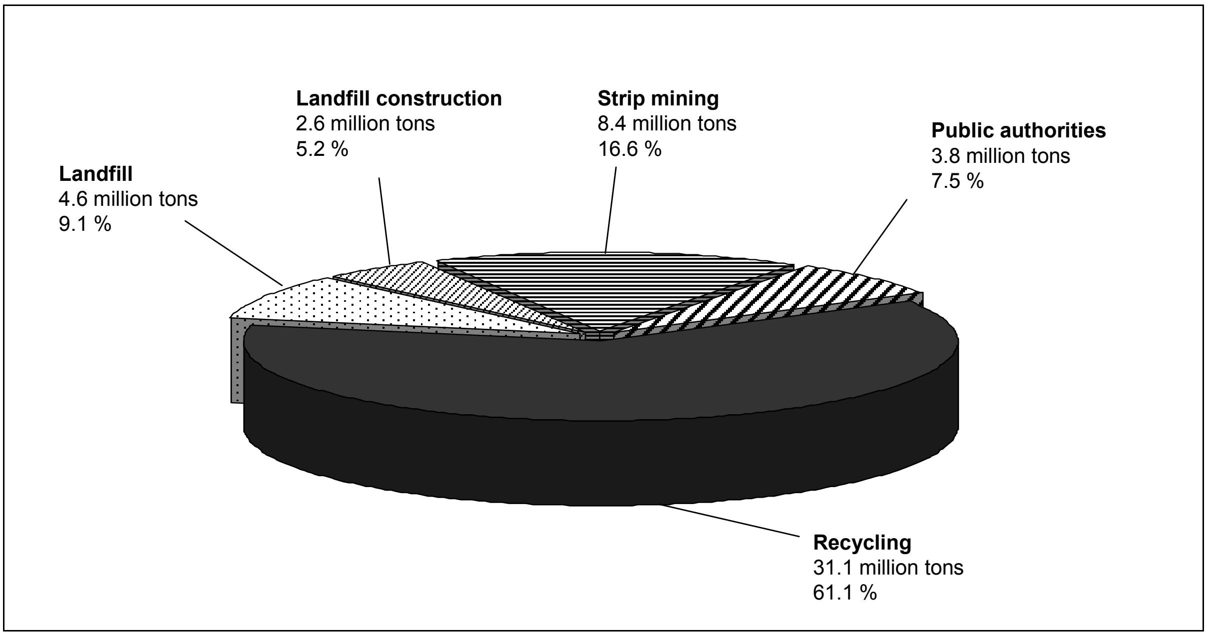

Figure 21: Disposition C&D debris in 2004

(ARGE KWTB 2007, 17)

The second source for recycling construction materials is road construction waste. According to the 5th monitoring report of the ARGE, 18.4 million (93.4 %) of the accumulated 19.7 million tons were recycled in 2004. Around 200 000 tones (1.0 %) were land filled, as shown in Figure 22 (ARGE KWTB 2007, 19).

The accumulation of construction waste in 2004 with 1.9 million tons has decreased since 2002 (4.3 million tons of construction waste) due to the progress made in selective dismantling and collection of recoverable construction waste during the last years. However, a huge amount of construction waste (1.4 million tons, 73.7 %) was disposed off with 1.4 million tons (73.7 %) while only 0.1 million tons were recycled (5.3 %) and 0.4 million tons (21.0 %) were used in strip mining. Further analyzing the 0.28 million tons of gypsum-based construction material accumulated in 2004, 210 000 tons were used for strip mining and 560 tons in landfill construction while 70 000 tons were land filled (ARGE KWTB 2007, 19–20).

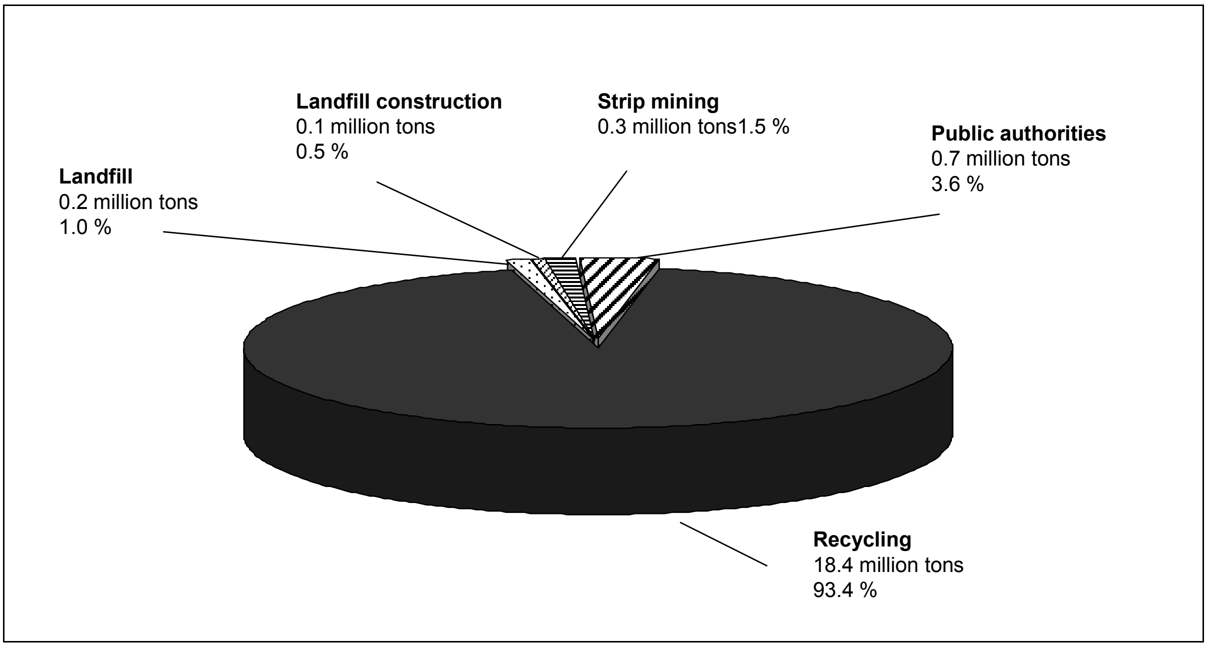

Figure 22: Disposition road construction waste in 2004

(ARGE KWTB 2007, 19)

A detailed investigation of the disposition of excavated earth in Figure 23 shows, that 68.0 million tons (53.0 %) were used in strip mining in 2004, 28.3 million tons were used by public authorities. Recycling of excavated earth amounted to 9.1 million tons (7.1 %) while 15.7 million tons (12.2 %) of the 128.3 million tons of excavated earth were land filled.

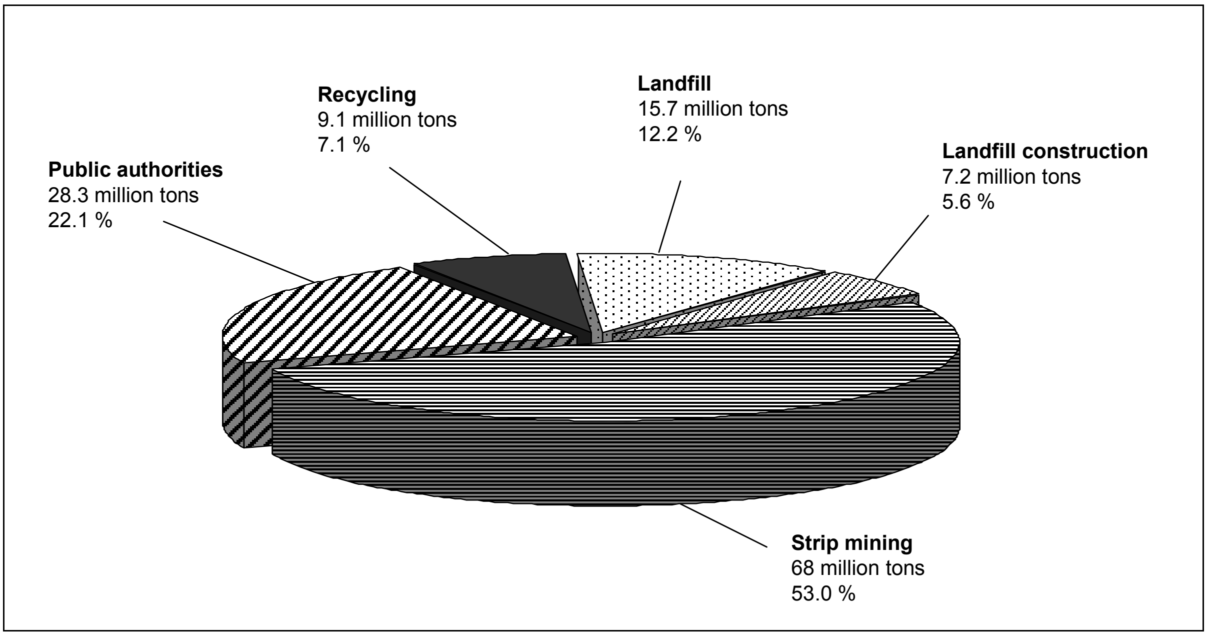

Figure 23: Disposition of excavated earth in 2004

(ARGE KWTB 2007, 19)

The analysis of the disposition of C&D waste shows, that considerable amount of waste could be recycled. As already addressed 49.6 million tons of recycling construction materials were produced in 2004. The use of these recycling construction materials is independent from its composition whereas the composition can be influenced by the type of deconstruction technique applied, the separation of the C&D waste as well as by the technology of the reprocessing plant. With this regard, the opportunity for high quality recovery increases with the degree of material separation of C&D waste (ARGE KWTB 2007, 21).

As Figure 24 shows, 32.9 million tons were used in road construction while 12.3 million tons were used in earth-moving, generally with the lowest requirements in material composition. Remaining 2.0 million tons (4 %) were used for purposes like gardening and land shaping and 2.4 million tons could be used for the high quality application as aggregate, three times as high as in 2002.

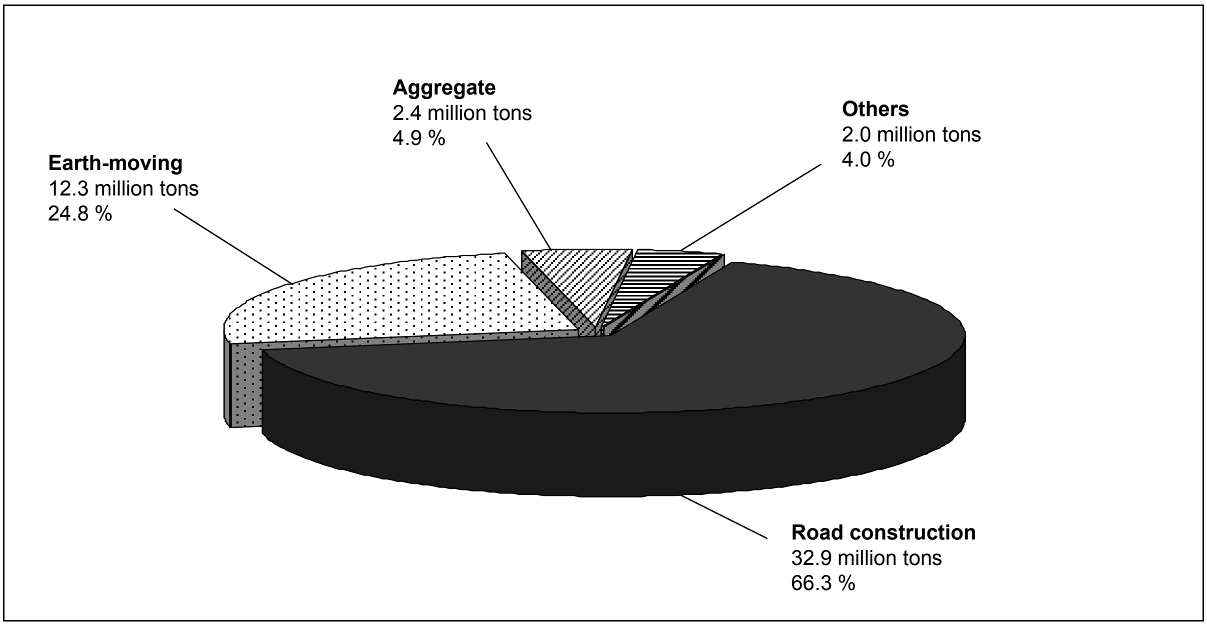

Figure 24: Applications for recycling construction material

(ARGE KWTB 2007, 19)

As a decoupling of the accumulated C&D waste from construction investments can be observed in Germany, it can be concluded that the market for mineral C&D waste develops to a stand-alone market segment. Thereby, Table 11 summarizes the current state of C&D waste recovery (10-year average) in Germany according to the 5th monitoring report of the ARGE (ARGE KWTB 2007).

Table 11: Current state of C&D waste recovery (10-year average)

C&D waste	Recycling	Direct Reuse	Recovery quota (1995–2005)
C&D debris	69.3 % 37.9 million tons	20.5 % 11.2 million tons	89.8 %
Road construction waste	86.3 % 15.7 million tons	11.5 % 2.1 million tons	97.8 %
Construction waste	26.3 % 1.5 million tons	21.1 % 1.2 million tons	47.4 %

Of the approximately 80 million tons of mineral C&D waste (C&D debris, road construction waste, construction waste, excluding excavated earth) accumulated during each year in the 10-year average, ca. 55 million tons were recycled, 15 million tons were directly reused, and approximately 10 million tons are still disposed of although recovery options exist. Potentials for recoverable C&D waste for resource preservation are, hence, found in 15.6 million tons excavated earth and 5.6 million tons C&D debris.

6.2.3 Laws and regulations in Germany

Legislation in the field of waste management has quite a long history in Germany. The *Law on the Prevention and Disposal of Waste*[17] of 27 August 1986 (AbfG 1986) outlined for the first time the principles for the transition from disposal to waste management. Accordingly to this law, the first aim must be the prevention of waste. If prevention is not possible, the composition of waste must be improved in order to permit reuse or recycling.

In July 1994, the *Act for Promoting Closed Substance Cycle Waste Management and Ensuring Environmentally Compatible Waste Disposal*[18] (KrW-/AbfG 1994), also called *Waste Avoidance, Recovery and Disposal Act* or *Closed Substance Cycle and Waste Management Act* was issued by the German parliament. This Act implements the European Council Directive 91/156/EEC of 18 March 1991 (The Council of the European Communities 1991a) (revised Framework Directive on Waste, amending Council Directive 75/442/EEC (The Council of the European Communities 1975)) and of Council Directive 94/31/EC of 27 June 1994 for amendment of Directive 91/689/EEC (The Council of the European Communities 1991b) on hazardous waste into national legislation. The Waste Avoidance, Recovery and Disposal Act came into force two years after promulgation, on October 7th, 1996.

[17] Abfallgesetz, AbfG
[18] Kreislaufwirtschafts- und Abfallgesetz, KrW-/AbfG

The act contains the basic principles of German waste management and closed-loop recycling strategies. Several principles for waste management were introduced, for example product responsibility and a new hierarchy for waste treatment. The product responsibility of the Waste Avoidance, Recovery and Disposal Act is the assigned responsibility to the producer for the waste arising from their products, i. e. *extended producer responsibility* (EPR).

The hierarchy of the Act assigns priority on waste prevention according to the maxims that:

- The avoidance of waste is better than the recycling of waste,
- the waste that cannot be prevented should be recovered, and
- the disposal of waste is only allowed when neither prevention nor recovery is feasible or economically reasonable.

In order to comply with the principle objectives, waste designed for recovery is to be kept separate and treated separately (Art. 5 KrW-/AbfG). Art. 7, 23 and 24 KrW-/AbfG authorize the federal government to enact administrative orders and statutory ordinances with the aim of enforcing prevention and recovery to reduce contamination on wastes. The supplementary subsidiary regulations of the Waste Avoidance, Recovery and Disposal Act consist of various ordinances. These ordinances comprise ordinances that restructure supervision under waste management law and align it with EU law and ordinances that create a basis for further deregulation of supervision.

One of the major general administrative orders concerning construction and demolition waste is the *Technical Instruction for Municipal Waste* ('TA Siedlungsabfall') (TASi 1993) that is originally based on Art. 14 of the former Law on the Prevention and Disposal of Waste of 27th August 1986 (AbfG 1986). The German Technical Instruction for Municipal Waste specifies the treatment and disposal of waste and deals with major waste streams, such as domestic waste and building and demolition waste. The goals of this administrative order are set to:

- Recycle unavoidable waste,
- reduce the toxicity of waste, and
- ensure that an environmentally friendly treatment or disposal of waste is maintained.

C&D waste should be collected and prepared for recovery separately at the place of arising. The responsible municipalities should encourage the utilization of mobile or semi-mobile recovery installations. It also contains requirements concerning the disposal of waste. Fractions which do not meet the requirements set out in the TA Siedlungsabfall will not be allowed to be land filled without further treatment.

The federal states (German Bundesländer) count on their own and more specific laws and regulations on waste. Some states have already introduced topics for demolition requiring organized dismantling and separation of waste on-site or at specialized treatment facilities. The municipalities or local authorities have further regulations like demolition permits or dismantling ordinances. In some cities it is already compulsory to add a deconstruction plan presenting the phases of preparation, the method of deconstruction or demolition and detailed information on the recycling of the various materials when demolition permits are required.

Furthermore, standards of the German institution for standardization (DIN, 'Deutsches Institut für Normung') have been issued in Germany regulating construction and deconstruction work. In November 2006, the DIN 18459 (DIN 2006a) setting general standards for *demolition and deconstruction work* came into force. The DIN 18459 is a supplement to the DIN 18299 (DIN 2006b) which regulates general and contracting issues regarding construction work of any kind. The DIN 18459 concerns, besides the selective or complete deconstruction of construction work, the extraction, storage and transportation of the deconstruction materials and components (classified according to the EWC).

Additionally, guidelines have been published by various authorities. For instance, the *Guideline for Sustainable Construction*[19] (BMVBS 2001) issued by the German Federal Ministry of Transport, Building and Urban Affairs[20]. This guideline addresses the sustainable construction throughout the whole life cycle of buildings; i. e. the minimization of energy and resource consumption as well as the decrease if negative environmental impact. In particular, this comprises, for instance:

- The reduction of energy consumption and operating resources,
- the avoidance of transport costs for construction materials and components, and
- the use of renewable and recoverable construction materials and components.

Further guidelines for the sustainable deconstruction of buildings are the *Arbeitshilfen Recycling* (BMVBS 1998) and the *Construction Products Directive* (Council Directive 89/106/EEC)[21] (European Commission 1989) and their amendments. The *Arbeitshilfen Recycling* have been issued for the persons in charge of public construction projects. The use of a common terminology of the *Richtlinien für die Durchführung von Bauaufgaben des Bundes* (RBBau) (BMVBS 2007) as well as the *Fee Structure for Architects and Engineers*[22] (HOAI 1976) ensures applicability for every construction projects with waste accumulation.

[19] Leitfaden Nachhaltiges Bauen
[20] Bundesministerium für Verkehr, Bau und Stadtentwicklung, BMVBS
[21] Bauproduktenrichtlinie, BPR
[22] Honorarordnung für Architekten und Ingenieure, HOAI

6.2.4 Product recovery management in construction

6.2.4.1 Challenges in product recovery and related work

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, thereby to reduce the amount of waste at the end of a product's life cycle as well as to avoid or at least reduce the rate of the depletion of resources (Lambert and Gupta 2005; Thierry et al. 1995). The need for PRM is triggered, for instance, by the increasing awareness and interest of the public in the environment and conscious governmental policy decisions on industrial and economic activities. This development is mainly driven by current discussions on sustainable development denunciating resource depletion and harm to nature and the environment by waste and pollution, as well as scarce landfill space and the resulting undesired economic increase in landfill costs (Lee et al. 1995; Ofori 1992).

Efforts to initiate closed-loop material flows in the construction industry have mainly focused on the recovery of waste material from underground engineering (Symonds et al. 1999). In this sector, recovery strategies have already been implemented successfully in many countries. However, problems occur with the handling of C&D waste and materials from the building construction sector arising from the deconstruction, modification or renovation of buildings. These problems especially occur in the existing building stock, where the long time-lag between the initial design and construction of the building and the final deconstruction at the end of its lifetime causes high uncertainty about the composition of buildings, i. e. deconstruction planning faces severe problems, especially when the building has not been designed and constructed with the intention to recover its used components and materials (TeDorsthorst et al. 2000). However, not just the uncertainty of composition but also the complexity of the final product and the variety of materials (e. g. metals, ceramics, concrete, masonry, bricks, timer, natural stone, plastics) and components (e. g. heating systems, piping) add to the enormous planning effort in recovery or recycling planning in deconstruction projects and hamper a proper recovery (Schultmann 2003). Research on recovery of waste from building deconstruction has mainly focused on deconstruction and recovery techniques (e. g. Kuo 2006; Tam and Tam 2006), the use of various building materials and components after recovery (e. g. Rao et al. 2007), the implementation of waste management and recovery of building materials in particular countries (e. g. Begum et al. 2007; Duran et al. 2006; Fatta et al. 2003; Rodríguez et al. 2007) as well as on life cycle assessment, energy and emergy analysis of buildings, their components and building materials (e. g. Buhé et al. 1995; Crawley and Aho 1999; Emmanuel 2004; Erlandsson and Borg 2003; Fay et al. 2000; Irurah and Holm 1999; Mithraratne and Vale 2004; Mora 2007; Ozel and Kohler 2004; Pulselli et al. 2007; Richard et al. 2007; Thormark 2000; Treloar et al. 2000;

Venkatarama Reddy and Jagadish 2003). Recently, an attempt was made towards the definition of the broader concept of closed-loop material cycle construction (Sassi 2008).

6.2.4.2 Terminology of recovery strategies for materials and components

Although various research efforts on the recovery of buildings, components and their material have been undertaken, there is still no common understanding of terms such as *recycling*, *recovery*, and *reuse* in construction. For instance, Thormark (2000) divides the umbrella term *recycling* into *reuse*, *material recycling* and *combustion with heat recovery*. While reuse considers the reuse of material with the same function, material recycling addresses the use of recycled materials in open or closed-loops for various purposes. In comparison, Brown and Buranakarn (2003) differentiate three recycle trajectories: material recycle, by-product use, and adaptive reuse. Material recycle is considered as the standard type of recycling where the material is used again for the same purpose. By-product use exists if a by-product of a process is used to manufacture something different; whereas adaptive reuse considers the reuse of a material after recycling for a different purpose. In contrast to Thormark (2000) and Brown and Buranakarn (2003), Mora (2007) addresses the possibilities of reusing components and materials by either recycling or recovering, embracing the options of recycling and recovering in the term *reusing*.

For the development of the integrated deconstruction-recovery planning approach, it is necessary to introduce a unifying understanding of the terms related to product recovery in construction. Concepts for the recovery of products and materials have already been studied extensively for the manufacturing industries. Various recovery concepts for simple and complex products such as batteries and cars have been developed (e. g. Daniel et al. 2003; Schultmann et al. 2006b). Hence, based on a classification of recovery options for the manufacturing industries by Thierry et al. (1995), a classification scheme for recovery in construction is developed.

Thierry et al. (1995) distinguish the management of end-of-life products (EOLPs) into direct reuse, PRM and waste management. While PRM consists of repairing, refurbishing, remanufacturing, cannibalization, or recycling of EOLPs, waste management addresses the incineration or landfill, as depicted in Figure 25.

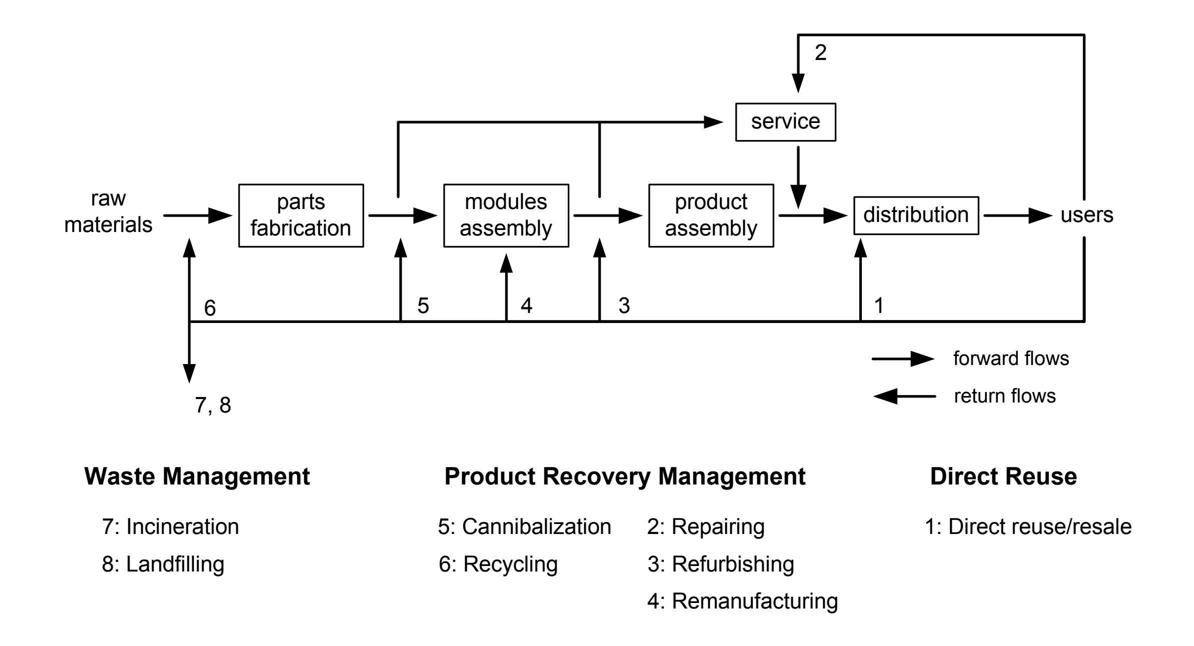

Figure 25: Product recovery management in the manufacturing industries

(Thierry et al. 1995)

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 effort and can be easily performed at the customer's location or at manufacturer-controlled repair centers. *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 ones. 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 disassembled and all modules and parts 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. With the recovery strategy of *cannibalization* the used products are selectively disassembled and potentially reusable parts are inspected and used in the repair, refurbishing, and remanufacturing of other products and components. Obviously, refurbishing, repair, remanufacturing, and cannibalization are based on the product level and their main objective is to preserve the identity and functionality of used products and their components on high standard. However, *recycling* is processed on the material level and is characterized by a loss of identity and functionality of the product and/or its components. Hence, recycling comes into operation where used products and components are disassembled into parts. These parts are further separated into material categories. The recycled materials are thereafter reused in the production of new parts.

By analyzing the component categories of buildings, it becomes obvious that the material flow in construction consists of a variety of component and material flows, each comprised of more or less complex products (e. g. boilers versus lumber or concrete). Waste and recovery management for some EOL components in a building already exist due to their production in the manufacturing industries. These products fall under the EPR. Legal compliance is ensured by environmental regulations, in Europe, e. g. EU Directive 2002/96/EC on waste electrical and electronic equipment (WEEE) (European Parliament and the Council of the European Union 2003) and amendments. According to this directive producers are responsible for the take-back, recycling and disposal of their products (see also section 6.3.2). Although buildings are far less likely to have their components returned to the original manufacturer for take-back at the end of their lives, EPR could be applied to building components which are routinely replaced in maintenance and renovation activities during the building life cycle (e. g. lifts, heaters, cooling apparatus) (Kibert et al. 2000). However, the majority of a building's mass is not easily deconstructed and concentrating on construction-specific building components and materials, e. g. brick, concrete, plastic, and timber, modifications of strategies for EOLP treatment in manufacturing have to be made. Therefore, a further classification for PRM options is made. As depicted in Figure 26, product recovery cannot just address the reuse and recovery of components and materials, but also the recovery of energy value of materials by *incineration* or *combustion with heat recovery* and *composting*. Hence, if none of the existing reuse and recovery options repair, refurbish, remanufacture, and recycling can be applied, energy recovery could be processed for a suitable material before final disposal (Thormark 2000). For instance, in Germany, one of the major general administrative orders concerning C&D waste is the TA Siedlungsabfall (see section 6.2.3). According to the TA Siedlungsabfall (TASi 1993), recovery has to be processed before final disposal; *land filling* is only allowed for materials that contain less than 5 % of organic fractions.

Based on the recovery strategies discussed for the manufacturing industries, a classification scheme is proposed for the construction industry. Figure 26 shows a new approach to categorize recovery options for construction components and materials. Thereby, different recovery options exist in dependency on the components and materials, which are classified in section 6.2.1.

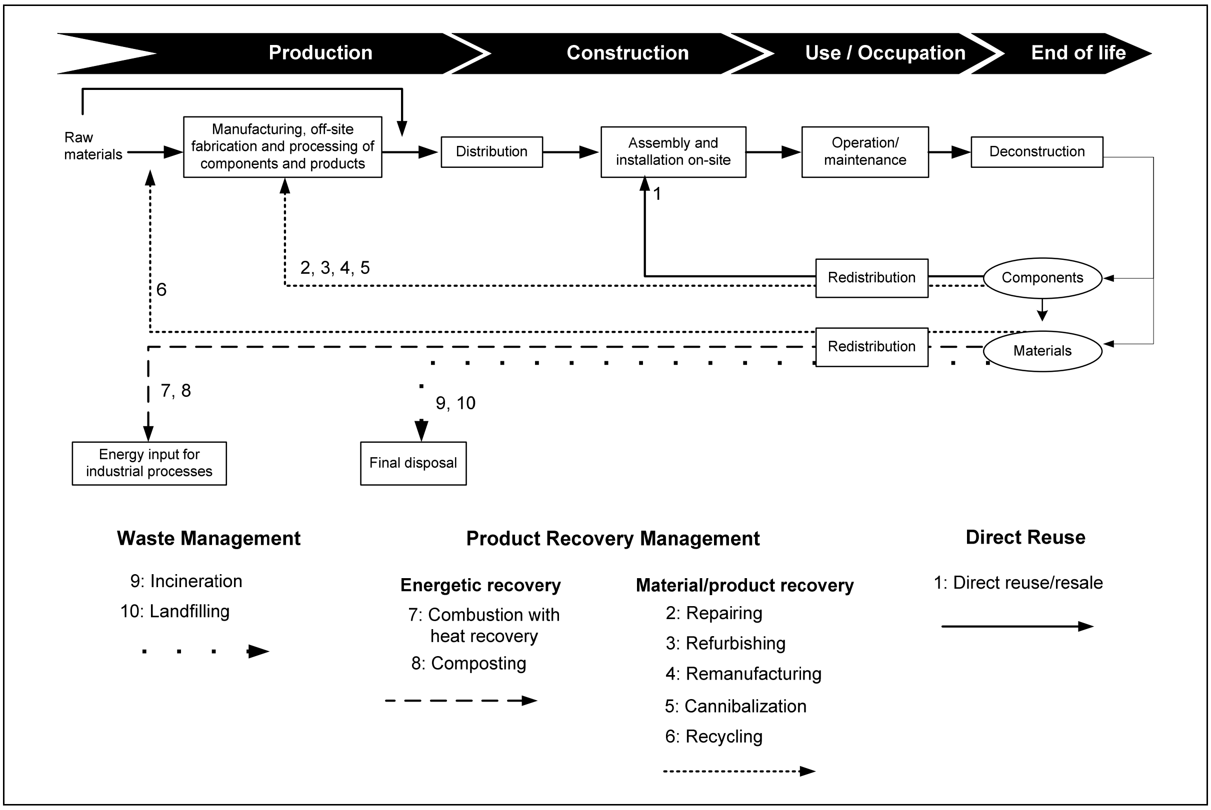

Figure 26: Recovery strategies in the building construction sector

Category 1 components, such as boilers, valves, and windows, can be easily deconstructed. They can be reused or resold after having been repaired, refurbished or remanufactured. In addition, components in category 2 can be either directly reused, repaired, refurbished or remanufactured if their quality after deconstruction is sufficiently high. If the quality of category 1 and 2 components is not sufficiently high, recycling can take place. After recycling, glass can, for instance, be ground into powder, polished, or burned to ash and used as glass fiber in tiles or as cement replacement. In contrast, components and materials of category 3 can be either recycled or, if possible, incinerated or land-filled, for instance cold recycling or heat generation of asphalt and use as recycled asphalt or asphalt aggregate. The same holds true for category 4 components, if, for instance, metal piping and ductwork are not reused in another building object. Plastic can, for example, be converted into powder by cryogenic milling or crushed into aggregate to be used as recycled plastic or landfill drainage (Kibert et al. 2000; Tam and Tam 2006). Materials in category 5 can only be recycled, incinerated or land-filled. Usually these materials are subject to regulations on the treatment of hazardous substances and materials as, for example, contained in manufactured, site-installed, low-mass products such as paints, sealers, or varnishes (Kibert et al. 2000). This means that direct reuse (1) of components appears when they are redistributed into the construction process of new buildings (e. g. bricks, windows, doors, and structural steel, wood or metal trusses) and are site-installed or site-assembled again to become a direct part of the building. Repairing (2), refurbishing (3), and remanufacturing (4) occur for components that are redistributed to the manufacturing plant and off-site production where they are either repaired, refurbished or remanufactured, e. g. boilers, valves, windows, but also components such as structural steel or engineered wood products (Kibert et al., 2000). Cannibalization (5) can be processed for components in manufacturing processes (e. g. valves, boilers), whereas recycling (6) is solely possible for materials. Hence, components have to be dismantled before recycling can be processed. Afterwards, the recycled materials can be used for various purposes. If a recovery at the materials/product level is not possible, options of energy recovery can be applied: combustion with heat recovery (7) and composting (8) (Marchettini et al. 2007; Thormark 2000).

For an overview of recovery options for construction materials and further utilization after recovery, such as asphalt, brick, concrete, glass, plastic, and timber, see Thormark (2000) and Tam and Tam (Tam and Tam 2006). Detailed results are given in Klang et al. (2003). They developed and evaluated a model to analyze the environmental, economic and social aspects of the re-use and recovery of C&D waste and revealed that the recycling of steel and re-use of sanitary porcelain showed a potential contribution to sustainable development in all of the three aspects. Preparing bricks for re-use showed the largest potential for eco-efficiency, but had negative effects on sustainability from the social perspective of health and the working environment (Klang et al. 2003). The application of recycling and recovery process has further been proven to be successful in practice for deconstruction projects in Dobel and Mulhouse, Elsaß (Ruch et al. 1997).

However, reuse and recovery will be hampered if the building is completely demolished. In this case, recovery and recycling is only possible after a time-consuming selection and separation of valuable material from the rubble (Schultmann 2005). In order to gain components and materials in a high degree of diversification, selective deconstruction can help raise the quality of materials under the focus of sustainability. Therefore, in the following a measured to determine the sustainability in terms of energy efficiency of deconstruction is introduced. This measure is called the energy-savings value. The energy-savings value describes the amount of energy saved by reusing or recovering a component or a building material and using it as a recovered material for the same or another purpose in comparison with production from primary resources. The energy-savings value is assigned to every component and material and is included in the integrated deconstruction-recovery planning model for deconstruction projects, which is developed in section 8.

6.2.4.3 Limitations of product recovery

The implementation of reverse flows in the construction industry as depicted in Figure 26 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 be both positive and negative and vary considerably with the type of the recovery process and type of material chosen. Benefits result, among others, from saved energy in the production process of new input materials and less environmental pollution. However, re-use and recycling do not necessarily result in ecological sustainability as sometimes the effort to recycle causes severe environmental impacts itself. These negative impacts include additional energy consumption as well as environmental burdens for the recovery of deconstructed components and materials. 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 the recovery processes itself. For this reason, it is important to maintain a life cycle perspective when evaluating waste management measures (Klang et al. 2003, 320).

For an evaluation of the environmental impacts caused by industrial processes, refer to the well-known approaches from life cycle assessment (LCA)—a method that has developed rapidly over the last years—and eco balancing, especially with respect to energy consumption during recovery and transport (see 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 a positive eco balance is supported by not increasing the gross sum of energy use.

In addition to the negative ecological impacts of deconstruction projects, economic objectives might also hamper the realization of sustainable deconstruction and recovery of components and materials. To decide whether the recovery of a material (which includes costs for selective dismantling, transport of components and material, as well as those for the recovery itself) is economically justifiable, these factors have to be known in advance and be considered in deconstruction project planning (Schultmann 1998; Schultmann and Rentz 2002). Furthermore, quality changes might occur during the recovery and recycling of C&D waste and recovered construction materials and components might not always measure up to modern quality and environmental standards, for instance bricks with regard to crack-formation and thermal conductivity (Klang et al. 2003, 324). Hence, the substitution of construction materials and components with recovered or recycled materials might force to add additional materials to retain quality requirements such as insulation standards (Thormark 2007, 763).

6.2.4.4 Measuring the advantageousness of product recovery

A measure for the advantageousness of reuse and recovery of building components and materials has to consider the full life cycle of the material flow to consider environmental effects of a component or material from extraction of raw materials, production, operation, replacement, repair and final disposal or recovery (Wernik 2002). In contrast, recovery quotas in statistics are usually measured in mass, as illustrated before. However, mass provides only a weak indicator of environmental sustainability as increasing amounts of reused and recovered components do not necessarily imply a lower negative ecological impact.

An appropriate method for the measurement of the environmental burden of a product or process throughout its life cycle by identifying and quantifying materials and energy used as well as released to the environment is LCA, as mentioned in section 6.2.4.3. It covers the assessment of the environmental impact from the extraction of raw materials, their transportation, manufacturing, use, reuse, maintenance, as well as recycling and final disposal. Most LCA studies today cover the principles laid out in a series of standards from the International Organization for Standardization (ISO) and especially refer to the 14040 series (ISO 1998; ISO 2000a; ISO 2000b) within the broader ISO 14000 category of standards on environmental management (e. g. Batterman 2004; Bouman et al. 2000; Fay et al. 2000). Thereby, an appropriate measure for the environmental burden of a product or process, without complicating the determination of the impact by measuring emissions, energy consumption and waste accumulation during the life cycle, is energy.

With respect to the necessity of shifting 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 sustainable deconstruction project planning is developed in section 8 by 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 with respect to energy efficiency. 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. Thereby, in order to follow the purpose of deconstruction, i. e. to recover as many components, modules and materials of a building for reuse or recycling as possible, companies involved in the deconstruction process have to be regarded as suppliers of components and materials (Guy and Shell 2002).

6.3 Closed-loop supply chain management

6.3.1 Closed-loop supply chains

In addition to forward supply chains, as depicted in section 2.3, closed-loop supply chains also comprise the reverse flow of products, its components and materials, as mentioned before. These closed-loop supply chains are, according to Fleischmann et al. (2000, 659) and Faucheux and Nicolai (1998 cited by Krikke et al. 2002, 62–3) characterized by several aspects:

- Environmental drivers become relevant in addition to cost and service.
- Higher system complexity exists due to the increased number of goods and its potential interaction between collection and (re-)distribution, e. g. combined transportation in closed-loop networks depending on the specific recovery process.
- Uncertainty about the supply (collection) side of the system in terms of volume, quality, composition, and timing is inherent.
- Push-pull nature due to the often occurring mismatch between supply and demand; i. e. the production (supply of used products) is not coupled with the demand (producer's requirements).
- Numerous suppliers face few customers considering used products as raw materials or input for the reverse chain. In contrast to the forward chain more sources of raw materials exist while the raw materials enter the reverse chain at small or at no cost. Additionally, although the backward flows seem to be inexpensive or for free, the value of return flows is usually low and may be limited only to a small fraction.
- Unexplored market opportunities related to environmental requirements offer opportunities for the creation of new markets or the reorganization of existing ones.

Hereby, Fleischmann et al. (2000) state that product recovery not only reverses the product stream with the consequence that there are many supply sources (collection points, e. g. retailers) and few demand points (recovery facilities, disposal sites), but that the design of product recovery networks is complicated by the high uncertainty in many factors (e. g. demand forecast for recovered products and materials appears to be difficult due to the lack of data in recently developing markets for recovered products, availability of used products on the disposer market, timing, quantity and quality of used product) and a reliable planning of collection and recovery may therefore be a difficult task (Fleischmann et al. 2000, 658–9).

As closed-loop supply chains can be considered as an extension of traditional forward supply chains, the management of closed-loop supply chains includes, in addition to the traditional forward supply chain processes, the following activities:

- Product acquisition: collection of products from end users,
- reverse logistics: movement of products from pint of use to final disposition,
- testing, sorting, and disposition: determination of product condition and most efficient recovery option in terms of economic incentives,
- recovery: regaining value of used product, and
- remarketing: creation and exploitation of markets, final distribution.

In some works, the activities of closed-loop SCM focusing on the management of the reverse chain are also referred to as reverse logistic phases (see section 6.3.3.1).

6.3.2 General drivers for the establishment of closed-loop supply chains

The *drivers* for the involvement of companies into closed-loop supply chain activities and especially in reverse logistic activities for end-of-life returns are differentiated into profit, legislation as well as corporate citizenship (Dekker et al. 2004; Schultmann et al. 2006b).

The profit-oriented drivers comprise direct as well as indirect benefits. While direct benefits can be achieved by returning products and their use as substitute for new input materials (for instance metal scrap for steel) as well as by cost reductions for disposal and new raw materials procurement, indirect benefits are expected from the established ‘green image’ of the enterprise, improved customer and supplier relations as well as the anticipation of legislation. Especially the indirect benefits refer to the movement of sustainable development and the increasing awareness of different stakeholders, for instance, the government, the common public, non-governmental institutions as well as interest groups to act environmentally friendly. Among others, typical tasks are to preserve natural resources, to reduce green house gas emissions, and to prevent global warming. This holds true especially for the legislation for end-of-life products and wastes and social acceptance of the enterprise in the public. Despite the profit-oriented drivers, legislative acts might force companies to take action in reverse logistics. These range from encouraging source reduction and recycling activities to mandating specific actions to divert solid waste from disposal facilities and include (Rhyner 1998, 350):

- Banning specific materials such as yard waste, tires, automobile batteries, motor oil, large appliances, and recyclable materials from landfills,
- banning or taxing specific non-recyclable product packages,

- providing loans and grants to municipalities to offset costs of implementing recycling programs,
- encouraging market development for the collected recyclable materials by requiring governmental agencies to purchase products manufactured with a significant content of post-consumer waste, and
- providing tax credits and other financial incentives to businesses developing products or changing processes to use post-consumer materials as raw materials.

In particular, this also comprises the EPR where producers, in their role as manufacturer of goods, are legally obliged to take back and recycle their goods (see also section 6.2.4.2). Examples in Europe are the EU Directive 2002/96/EC on WEEE (European Parliament and the Council of the European Union 2003) as well as the manufacturers' responsibility for the take back certain products like batteries as laid down in the EU Directive 2006/66/EC (European Parliament and the Council of the European Union 2006) or cars defined in the EU Directive 2005/64/EC (European Parliament and the Council of the European Union 2005). In addition to profit-oriented and legislative drivers, an enterprise is also dependent on the 'license to operate' issued by its stakeholders. This especially refers to the expectation of the company's environment that enterprises behave social as well as environmental conscious. Disregarding this issue might result in unfavorable influences on companies' business operations by its environment, i. e. its stakeholders.

The motivation for construction companies to participate in the establishment of closed-loop material cycles is likely the same as in the manufacturing industries. Regarding profit-orientation, a reduction of costs for disposal by selective deconstruction and separation of C&D waste can be realized. Additional gains are expected from the resale or recovery of valuable components and materials, for instance deconstructed aluminum framed windows, steel bars, wood, or bricks. Legislative pressure is put on the enterprises by construction specific legislation. In particular, this legislation comprises regulations for the handling of C&D waste. In Europe, this is mainly laid down in the European Council Directive 91/156/EEC (The Council of the European Communities 1991a) (revised Framework Directive on Waste, amending Council Directive 75/442/EEC (The Council of the European Communities 1975)) and Council Directive 91/689/EEC on Hazardous Waste (The Council of the European Communities 1991b), amended by national legislation as Closed Substance Cycle and Waste Management Act (KrW-/AbfG 1994) in Germany (see section 6.2.3).

While the first two drivers for reverse logistic tasks focus on economic and legal aspects, the third factor addresses social consideration. Due to environmental concerns, also construction enterprises face pressure to act according to the principle of sustainability, i. e. waste avoidance and reuse in order to foster resource preservation and emission avoidance. The 'green image' gained by environmentally friendly business operations can help to win the favor of the public and, in some way, can be considered as external pressure from stakeholders exerted on companies to establish closed-loop supply chains (Álvarez-Gil et al. 2007).

6.3.3 Reverse logistics

6.3.3.1 Phases of reverse logistics

Reverse logistics is not only considered to comprise logistic activities to move products from the point of use to the point of disposition but the phases from product acquisition to remarketing. For the manufacturing industries they are differentiated according to their chronological order into (Fleischmann et al. 2000, 657):

- Collection,
- inspection/Separation,
- re-processing,
- disposal, and
- re-distribution.

These phases are linked by transport and storage activities, as Figure 27 illustrates[23].

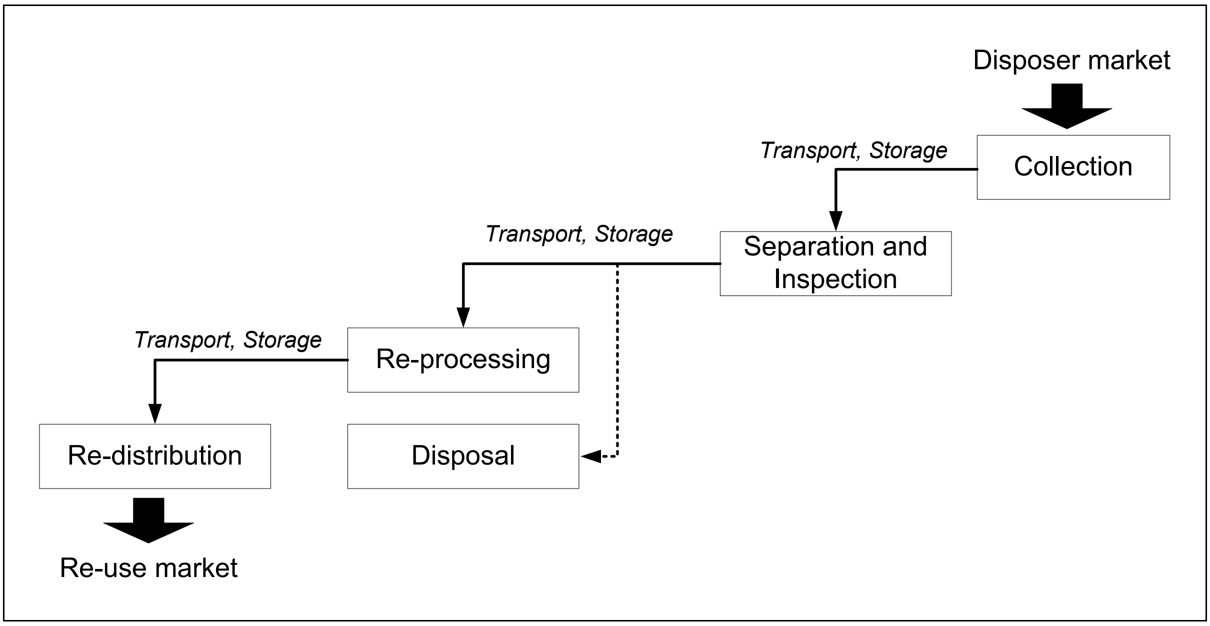

Figure 27: Stages of reverse logistics in the manufacturing industries

[23] Reverse logistic phases in construction are further dealt with in section 7.

Collection comprises all activities necessary to make products available and physically moving them to locations or facilities were further treatment takes place. Well known examples are the take back of electrical and electronic equipment as well as used batteries and cars (e. g. Daniel et al. 2003; Schultmann et al. 2006b). Briefly, the collection includes the activities purchasing, transportation, and storage (Fleischmann et al. 2000, 657). The design of the collection system is especially important for managerial implications of the organization of reverse logistics operations in construction. Therefore, section 6.3.3.4 closer analysis of the design of collection system with respect to construction.

Inspection/Separation includes all operations for the determination of the type of re-usability of a product. Therefore, the flow of used products is separated according to the various re-covery or disposal options, e. g. inspection of goods for hazardous substances. The inspection and separation span disassembling, shredding, testing, sorting, and storing the products within the reverse logistic process (Fleischmann et al. 2000, 657).

The recovery of a used product for further use in the same or another constitution is defined as *re-processing*. Re-processing or recovering as addressed in section 6.2.4.2 represents activities such as recycling, repair, or remanufacturing. Additionally, cleaning, replacement, and re-assembly activities are included (Fleischmann et al. 2000, 657).

In comparison, disposal is applied to products not suitable for recovery due to technical or economic reasons; for instance, rejected products during separation level due to excessive repair effort or products without market potential due to their age. Thereby, disposal includes transportation, land filling, as well as incineration (Fleischmann et al. 2000, 657–8).

After re-processing, products are re-distributed to the potential market place and future customers. Re-distribution encompasses the steps sales, transportation but also storage activities; e. g. sale of recycled materials or refurbished electronic equipment (Fleischmann et al. 2000, 658).

As pointed out before, logistics, transportation and storage activities are not considered as single stages but rather as linking activities between the stages in Figure 27. Nevertheless, transportation and storage activity are usually required between each of the stages and are limited by a number of constraints, such as the availability and capacity of transport vehicles or storage space and inventory requirements. Thereby, transport and storage processes, like in the manufacturing industries, also take place between all stages of reverse logistics in construction and significantly contribute to the complexity of the problem of establishing closed-loop construction supply chains.

6.3.3.2 Existing work on reverse logistics

The research field of reverse logistics has attracted intensive research efforts during the last years. Its application covers a wide variety of activities from different industries. Thereby, reverse logistics can, among others, be defined according to the Reverse Logistics Executive Council as "…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…" (RLEC 2008).

Comprehensive overviews on reverse logistics are given, for instance, in Dekker et al. (2004), Dyckhoff et al. (2004), and Maede et al. (2007). Case studies and other industry related work, concentrate on the organization of reverse logistic tasks, for example, in the automotive industry (e. g. Schultmann et al. 2006b), in the industry for electrical and electronic equipment (e. g. Walther and Spengler 2005), in the publishing industry (e. g. Wu and Cheng 2006), or the design of a logistics network for recycling sand from processing construction waste (Barros et al. 1998). A cross-industry study is undertaken in Kumar and Putnam (2008). Other research addresses issues of the organization of reverse logistics in the context of closed-loop supply chains and reverse SCM (Boulton and The Stiller Group 2005; Ferguson 2001; Jayaraman et al. 2003; Kovács et al. 2006; Krumwiede and Sheu 2002; Pochampally and Gupta 2005; Srivastava and Srivastava 2006; Tibben-Lembke 2002) and the design and organization of reverse logistics networks (e. g. Fleischmann et al. 2000; Jayaraman et al. 2003; Srivastava 2008). In addition, some papers also provide overviews on literature and current research status (e. g. Rubio et al. 2008) and conducted case studies in the field of reverse logistics, which are only briefly referred to in this thesis. These papers comprise, for instance, Fleischmann et al. (1997) giving on overview on quantitative models for reverse logistics, Fleischmann et al. (2000) highlighting conducted case studies, and Dowlatshai (2005), who is developing a framework for effective design and implementation of remanufacturing/recycling operations in reverse logistics after analyzing various case studies. A more recent literature review on green supply-chain management and, hence, also on reverse logistics can be found in (Srivastava 2007).

The construction industry, however, has not yet attracted much research concerning the organization of reverse logistic tasks (Schultmann and Sunke 2007b). The return or take-back of C&D waste at the end-of-life of a building or during repair and renovation processes has not been subject to reverse logistic concepts.

Therefore, discussing reverse logistics, the following aspects need to be taken into consideration (Dekker et al. 2004):

1. General drivers, i. e. motivation of enterprises to take action in closed-loop material flows and reverse logistics,
2. reasons for product returns,
3. characteristics of product returns,
4. processes carried out in logistics with the aim of recovering value in terms of recovery options and collection systems, and
5. reverse chain actors.

While general drivers for the expansion of operations with respect to the establishment of closed-loop material flows and reverse logistics as well as reasons for product return have been stressed in section 6.3.2, the characteristics of returned products, the related processes carried out as well as the corresponding reverse chain actors are highlighted in the following. Thereby, a discussion of these characteristics with special regard on construction is given in section 6.4.

6.3.3.3 Characteristics of product returns

Reverse logistics in general comprises the reverse flow of goods from the end consumer back to the manufacturer, i. e. including processes after take back of products. This might happen because of several reasons. Generally, three return stages of products can be differentiated: manufacturing returns, distribution returns, and customer returns. Manufacturing returns comprise returns because of a material surplus, returns from quality controls or production leftovers or by-products. Distribution returns might be product recalls, business-to-business (B2B) commercial returns (e. g. unsold products, damaged delivery), and functional returns, such as distribution items or packaging. In comparison, customer returns are, e. g., reimbursement guarantees, i. e. business-to-consumer commercial returns, warranty or service returns (maintenance and repair), or end-of-use (e. g. returnable bottles or leased cars) and end-of-life returns (Dekker et al. 2004).

Thereby, performing reverse logistic activities depends on the characteristics of the returned product. These include (Dekker et al. 2004):

1. Composition,
2. deterioration, and
3. use pattern of the product.

The product composition describes factors like the presence of hazardous materials, the material heterogeneity of the product and the size of the product. The size of the product has significant impact on the transport and handling of the product, e. g. choice of appropriate mode of transportation as well as means of transport. Deterioration of a product considers the intrinsic deterioration of a product, i. e. aging during its use, the homogeneity of deterioration, i. e. if all parts age equally, and the economic deterioration, which addresses the decline of the value of the product, for instance, outdated products like old computer technology. The use pattern of a product is especially relevant for the collection phase of the product. It comprises issues like the location, i. e. different locations and effort for collection, intensity and duration of use.

Product returns in construction, as considered in the following, refer to end-of-life components and materials of constructs, i. e. to C&D waste. Thereby, the composition as well as the degree of deterioration is of major importance for the opportunities for recovery of the products as well as for the organization of reverse logistic operations in construction projects.

6.3.3.4 Collection systems

The collection phase is the first step in the management of reverse logistics tasks. Designing the collection system, i. e. the handover from the generator of the used products to the recovery network, has to meet the criteria of efficiency, i. e. a meaningful direction of used products and the avoidance of these products turning into (particularly unwanted) waste streams. Besides offering a cost efficient service, this means on the one hand that the collection has to work conveniently and time reliable. On the other hand, the collection and transport system have to be aligned according to the recovery option of the product and hence, appropriate and safe transport vehicles. In particular, the following aspects, as depicted in Figure 28, have to be considered (Beullens 2004, 299):

- Collection infrastructure,
- collection policy,
- combination level of the collection, and
- characteristics of the collection vehicles.

The *collection infrastructure* describes the points at which a handover of used products takes place. Generally, it can be differentiated between on-site collection, collection from unmanned drop-off sites and staffed and smart drop-off sites. In *on-site collection,* used products are collected at the location of the supplier (i. e. the generator). It is most commonly used for enterprises or for curbside collection from households, e. g. domestic waste, plastics and paper. *Unmanned drop-off site collection* occurs if the generator delivers the goods containers at special locations in its neighborhood. It is usually applied to households and used as substitute for curbside collection, e. g. glass or textiles. On *staffed drop-off sites* stuff supervises the delivery and, hence, can ensure a more convenient and higher quality separation and collection in comparison to on-site and unmanned drop-off site collection. Examples are second-hand shops, municipal collection depots (e. g. for furniture) and regular shops or retailers. Smart drop-off sites are unmanned drop-off sites but are additionally equipped with IT, such as radio frequency identification (RFID) and telematics to sort products according to their characteristics (e. g. color of glass). Currently, they are applied to reusable packaging and recyclables such as bottles or tin cans (Beullens 2004, 300). The application of RFID techniques in construction is discussed in (Schultmann and Sunke 2008).

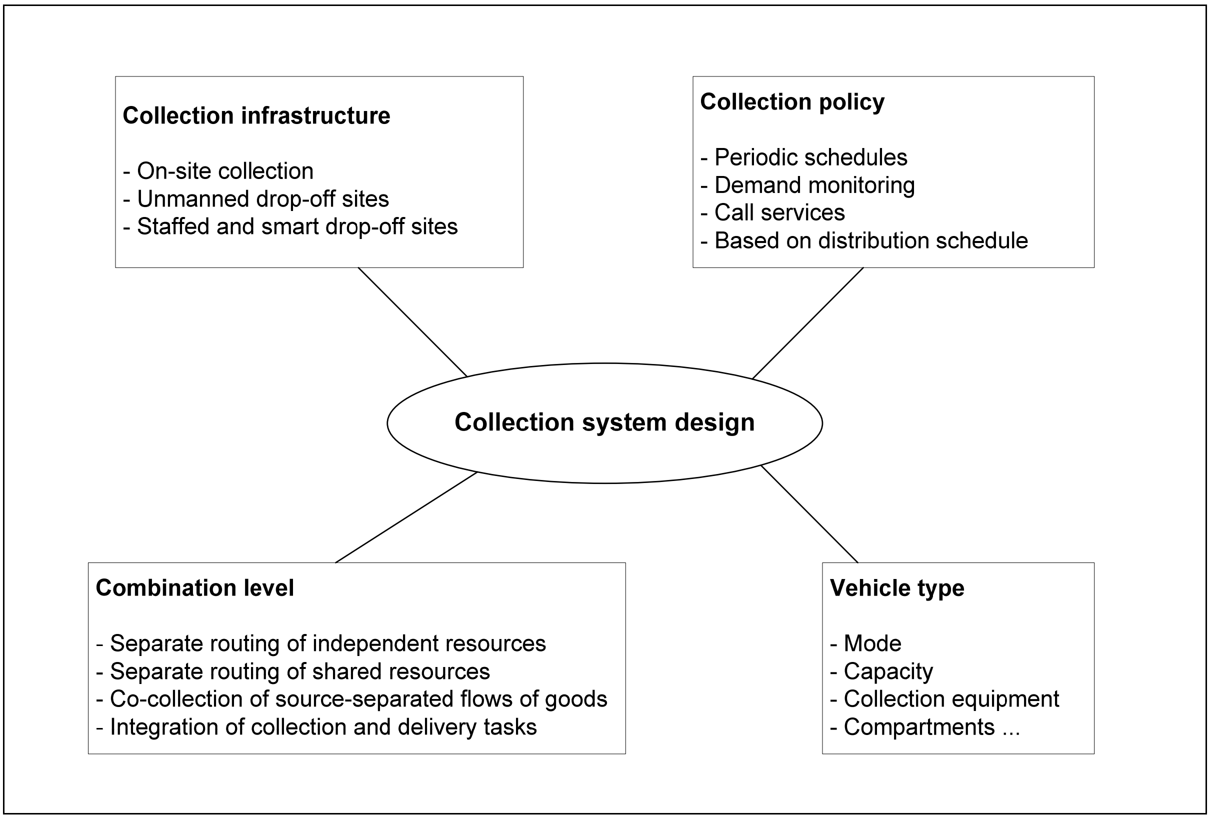

Figure 28: Factors impacting collection system design

The *collection policy* defines the time points of collection from the collection point and volume to be collected. The collection time can be determined either via periodic schedules, by monitoring demand, by call services or can be triggered by a distribution schedule. For collection based on a *periodic schedule*, collection points are repeatedly serviced with routine visits during specified periods, e. g. curbside collection. *Monitoring demand* the generation rate of used products is monitored on smart drop-off sites and information on capacity utilization of the storage space at the collection point is transferred to the collector, who then initiates a dynamic route planning. *Call services* are applicable to collections from staffed drop-off-sites, where the collector is informed by the staff if a collection is necessary. In case delivery and collection of goods are integrated processes, the time of collection is determined by the distribution schedule, defining when a customer at a collection point or in the neighborhood should be serviced, e. g. delivery of refrigerator and pickup of used one (Beullens 2004, 300).

The *combination level* is the way in which services related to different flows of goods can be combined. Here it is differentiated between (Beullens 2004, 300−1):

- Separate routing of independent resources,
- separate routing of shared resources,
- co-collection of source-separated flows of goods, and
- integration of collection and delivery tasks.

While *separating routing of independent resources* means that a fleet of vehicles with single compartments collects one flow of products which can be heterogeneous, the *separation of the routing of shared resources* defines a combination level where two or more classes of product flows are picked up by the same crew and/or fleet of vehicles while distinct classes of products are never within the same vehicle. This means, that one particular vehicle is assigned to one particular class of products. An assignment to another product class can only take place after unloading—cleaning and setting up, if necessary—of the vehicle for a new route. In comparison, a *co-collection of source-separated flows* allows the simultaneous collection of two or more product classes within the same vehicle. Usually, multi-compartment vehicles are used. If *collection and delivery tasks are integrated* either mixing of deliveries and collections, backhauling, and partial mixing can be processed. Using mixing the deliveries and collections can be made randomly as long as capacity constraints of the vehicle or satisfied. This might however not always be feasible, either due legal requirements or due to the high effort for re-arrangement of deliveries and collections during the tour. Therefore, backhauling presents an appropriate alternative; i. e. deliveries are made before the collection can take place. In case of enough shuffling space on the vehicle mixing and backhauling can be combined. Therefore a capacity level is set below which mixing is allowed. Hence, deliveries take place until enough volume is available for shuffling and then collections can take place until the capacity level is exceeded again as long as there are still deliveries on the vehicle. After unloading all deliveries collections can fill up the whole capacity of the vehicle.

The *vehicle type* used to collect used products depends on the type of the goods or waste flow. Therefore, it is to determine, e. g. which mode can be applied, how many compartments are necessary, which equipment needs to be on board and how much capacity is needed.

6.3.3.5 Reverse chain actors

A distinction of actors or responsible parties in reverse logistics activities can be made between (e. g. Dekker et al. 2004; Fleischmann et al. 1997, 4):

- Forward supply chain actors,
- specialized reverse chain actors, and
- opportunistic actors.

In particular, forward supply chain actors are e. g. original equipment manufacturer (OEM), wholesalers or retailers and logistics service providers, and independent intermediaries, while specialized recovery enterprises comprise e. g. secondary material dealers and material recovery facilities, third party reverse logistics service providers, and governmental institutions, like municipalities taking care of waste collection.

6.4 Discussion of results

With respect to the high negative impact the construction industry exerts on the environment, sustainability in construction is a topic with high interests for all stakeholders of construction projects. Thereby, an efficient approach to implement sustainability in construction is the establishment of closed loop supply chains and C&D waste management.

The responsibility for C&D waste management in deconstruction projects is usually assigned to the general contractor, i. e. the construction enterprise or the responsible sub-contractor. Concluding, the contractor or sub-contractor has to organize the disposal of waste. The aim of the contractor is to reduce disposal costs. This is usually realized by selective deconstruction and a high degree of C&D waste separation. Thereby, the major collection infrastructure is on-site collection, i. e. C&D waste is sorted and stored on-site or in transportable devices, for instance in containers, until it is collected. After deconstruction and sorting, either the contractor delivers the waste to recovery facilities or disposal sites against a fee or directly contracts with a specialized reverse chain actor, e. g. a recycling company, who picks up the containers of C&D waste on site for money and resells, recovers or disposes the C&D waste itself. Thereby, the contractor usually sets orders (call services) to the waste management company to request pick up of C&D waste to avoid site congestion. As deconstruction projects are usually conducted using selective dismantling, i. e. C&D waste is separated right after deconstruction, the collection takes place as separate routing of shared resources. This means, that one vehicle collects one particular waste type, for instance wood or bricks. Additionally, in case of collection of C&D waste in containers, the delivery task of an empty container might be combined with the preceding pickup of a full container from the construction site. After the collection and transport to the recovery facilities or direct consumers in case of direct reuse, recovered components and materials are lead back into the material cycle, either as low quality material for road construction or as input for other production processes, such as glass or aluminum or insulation manufacturing.

Especially for reverse chain actors, the efficient transport of C&D waste is difficult. In contrast to the manufacturing, the location of the deconstruction sites is varying and usually the only accessible way is road transport mode. Hence, trucks with special equipment (for instance, special hangers to safely store deconstructed windows for resale) or container trucks are used. Thereby, also the composition of C&D waste hampers efficient reverse logistic activities. The size and quality of C&D waste is usually not standardized and the waste often contains unexpected hazardous substances. Deadheads cannot be avoided due to the missing planning certainty with respect to the forecast of the amount, place and time of the pickup of goods or collection from the construction sites and usually different role of the actor (a recycling plant usually does not deliver a deconstruction site with recovered components or recycled material). Instead, pick up tours have to be calculated every time an order is made by a contractor and complicated vehicle routing problems occur every time a new order arrives.

Summarizing, depending on the actors involved in reverse logistics processes in construction different networks of collection points (supply sources) and recovery facilities or disposal sites (demand points) for C&D waste exist. If third party service providers are authorized with the pickup and recovery or disposal C&D waste, from the viewpoint of these service providers, numerous collection points (construction sites) exist and difficult transport problems, i. e. vehicle routing problems, occur. If the construction operator itself is responsible for the collection and transport of C&D waste to the recovery facility or disposal site against some charge, easy network structures and planning problems occur. However, this situation only occurs for very small deconstruction projects usually processed by small construction enterprises, which are most commonly engaged in regional business and contracts with private persons.

It can be concluded, that the main structural difference between the construction industry and the manufacturing industries regarding the take back of products, i. e. waste, does not refer to waste treatment or recovery processes, but to the organization of the collection and the design of logistic processes from the building site to the recovery facilities due to the special characteristics of the construction industry and its products.

Concentrating on the analysis of reverse logistics concerning C&D waste, recovery strategies for C&D waste have already been discussed intensively in literature. This comprises, for instance, research on deconstruction and recovery techniques (e. g. Kuo 2006; Tam and Tam

2006; Thormark 2000) and the use of various building materials and components after recovery (e. g. Rao et al. 2007). Therefore, in the following, the focus is shifted to the organization of operational logistic tasks, i. e. the collection of C&D waste at the deconstruction site and its transport to recovery facilities or disposal sites. Hereby, the statement of Fleischmann et al. (2000) (see section 6.3.1) especially holds true for construction, where common problems occurring are to be found in transportation activities, i. e. inefficient route planning and empty truck loads, so called deadheads.

These problems result from the characteristics of the construction industry, which differs from the manufacturing industries in many points. Among them are the complex and heterogeneous structure of the product, the long life time of the product and its immobility, the uncertain and non static waste accumulation in deconstruction projects, as well as the varying locations of construction sites (see section 2.1), i. e. varying collection points but only a few recovery facilities and disposal sites as addressed before. Considering these particularities planning models for reverse logistic operations are stressed and adopted to the logistic planning problems faced in C&D waste management in section 7.

7 Planning models for reverse logistics operations in construction

The reduction of waste through the establishment of closed-loop material flows has an important role in creating a more sustainable built environment. Especially in deconstruction projects, participants could take advantage of the application of waste management and recovery strategies while adhering to the principle of *sustainable construction*. In comparison with the construction of a building, the deconstruction process is characterized by a reverse process structure; i. e. while 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, i. e. C&D waste. After deconstruction C&D waste can be separated into its main components at the construction site before the collection and transport to the recovery facilities take place or at recovery facilities, depending on its composition and volume. The two main actors involved in the organization of these reverse logistic processes are the *contractor*, also considered being the client requesting service, and all parties responsible for the recovery of C&D waste, here named the *waste management company* (WMC). Both parties have to solve complex planning problems with respect to the C&D waste to be collected. These planning problems can be formally described in planning models for logistic operations in construction with respect to the particular planning objectives of each party and imposed constraints. Thereby, these formal description of planning problems and the introduction of models for the organization of reverse logistics operations is unique for the construction industry. For the purpose of theory developing they need to be addressed in detail to foster the understanding of the underlying set of problems.

Hence, after the general description of the planning problems in construction in section 7.1, constraints on the planning problems with material accumulation and implications for site storage and collection are addressed in section 7.2. Following, various quantitative planning models for reverse logistic operations in (de-)construction are introduced in sections 7.3 to 7.7. These models are either especially designed for a particular planning context or are based on existing models for reverse logistic operations which are extended. Finally, an approach for integrated project scheduling and reverse logistic planning is introduced in section 7.8. This approach pays respect to the fact, that the timely organization of reverse logistic activities depends on the schedule which determines the time of the accumulation of waste and necessary schedule adjustments if C&D waste pickup cannot be processed at the time indicated as necessary by the schedule. Thereby, both perspectives, the one of the contractor as well as the one of the WMC, are integrated by means of feedback loops.

7.1 General structure of the reverse logistic planning problem in construction

C&D waste consists of different material fractions. From a logistical point of view, these materials or truck loads have to be transported to a recovery facility or landfill. The material fractions can be separated according to value, volume or potential for recovery. For an overview and material fractions arising during construction and deconstruction processes it is referred to the EWC (see section 6.2.1). Thereby it is to note, the major part of C&D waste arises during the deconstruction of buildings.

The separated material fractions are either stored on site or in storage facilities before the collection and transport to recovery facilities for further treatment or to landfills take place. While recovery processes for construction materials are well established and, hence, are not subject of this chapter, the focus will be drawn on the organization of the transport logistics from the source of origin of construction material fractions, i. e. the construction site, to the next step down the process chain. Thus, the focus lies on the connection between construction sites and the recycling or recovery facilities, as highlighted in Figure 29.[24]

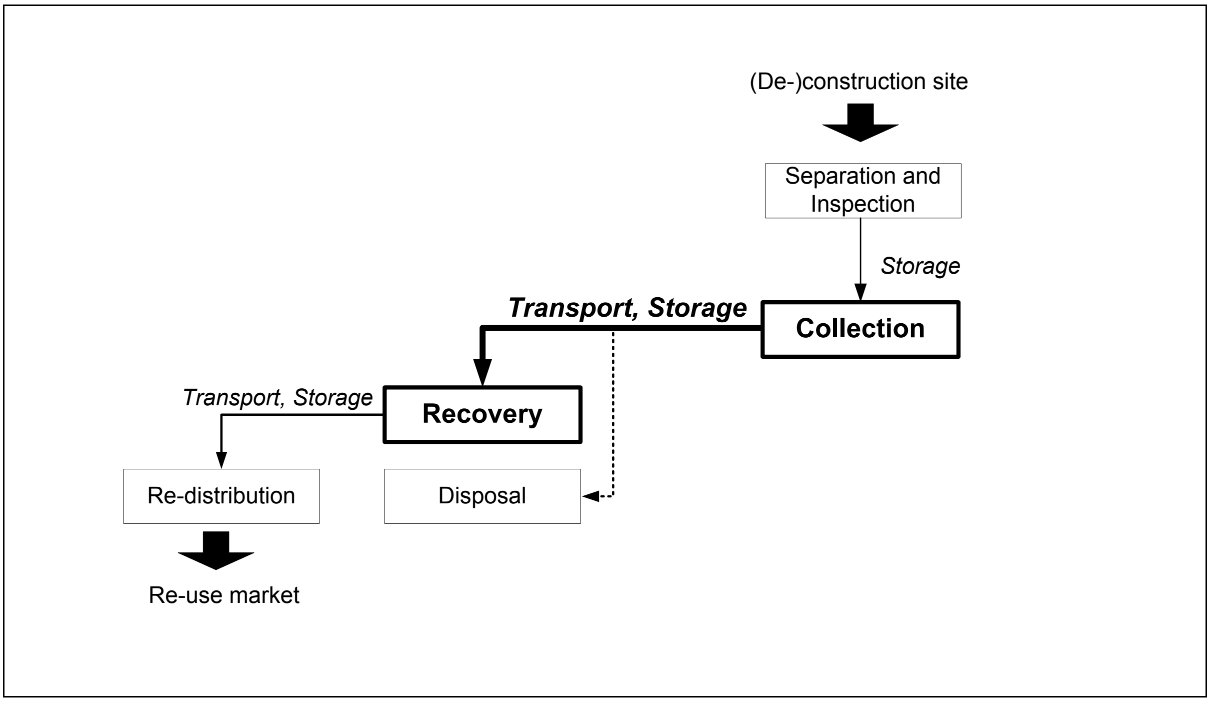

Figure 29: Focus of the reverse logistic planning problem in construction

The organization of logistic activities between construction sites and recycling or recovering facilities on the one hand involves different parties with different roles in the collection

[24] In contrast to construction, a discussion of reverse logistic phases in the manufacturing industries is given in section 6.3.3.1.

planning and on the other hand has to pay respect to the type of C&D waste to be collected. Regarding requirements for the collection and transport of C&D waste it can be distinguished between:

- Bulk material, and
- low volume material.

Bulk materials comprise materials such as concrete, wood or insulation materials which are accumulating in high amounts when buildings are demolished or deconstructed. Usually, waste management companies undertake the collection and transport to the recovery facility or to land fills.

In contrast to bulk materials, certain fractions of C&D waste accumulate in low amounts, e. g. copper or aluminum. These can be further distinguished into hazardous and valuable materials. While the focus for collection of hazardous material, such as tarred products or asbestos, is drawn to safety issues and proper disposal, the collection of valuable material, however, has first to follow the objective of preventing thievery and deterioration. Especially in the future, a trend is expected that valuable materials gain increasing importance due to resource deterioration and their high value as input material for common manufacturing processes. Figure 30 reflects the perspectives of the WMC and of the contractor on this optimization problem.

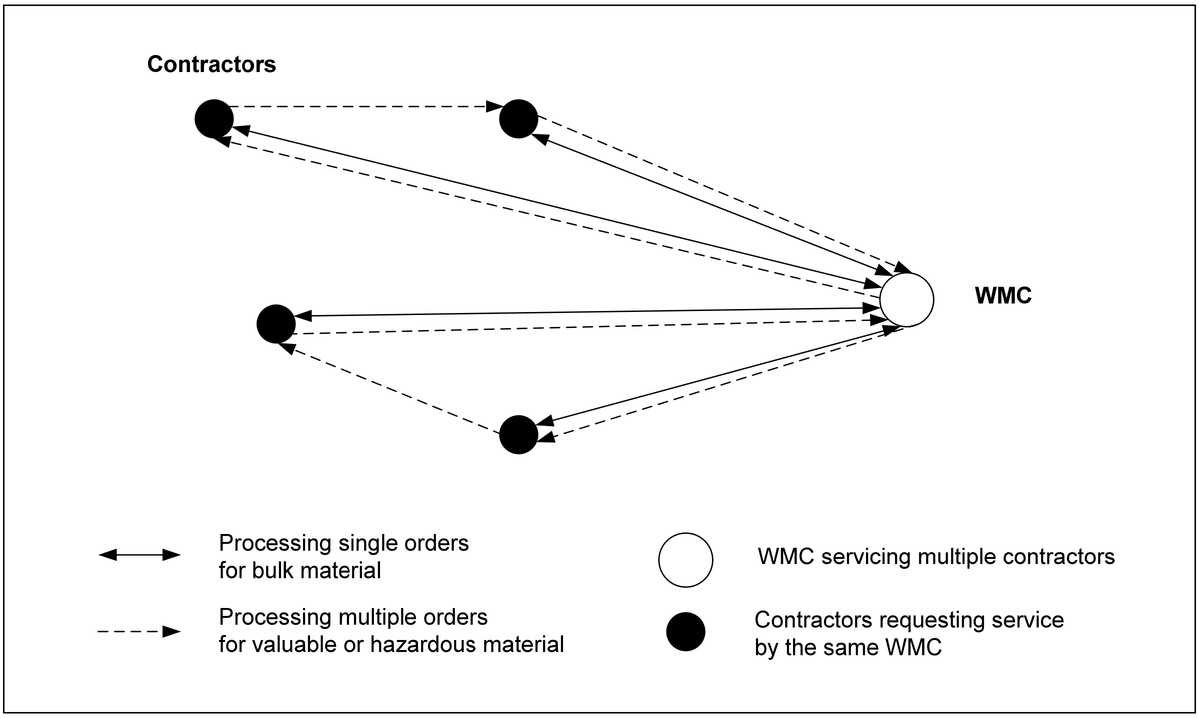

Figure 30: General structure of the material collection problem in construction

From the perspective of the WMC, multiple contractors could be serviced. If bulk material is to be collected, usually full truck loads can be picked up at each contractor, i. e. a single order is processed for each contractor (represented by the bi-directional arc). In contrast, for valuable or hazardous material, underutilization of the vehicle of the WMC might occur due to the lower amounts of material. Thus, in this case the WMC could service multiple contractors in one tour, as shown by the uni-directional dashed arc. The perspective of the contractor, as focused on in this section, is somewhat different. As it can be assumed that a contractor has already made its final choice on the WMC before planning the collection of material, the contractor's planning decisions refer to only one available WMC. Hence, cases where a contractor might choose out of several WMCs to request service are excluded from further considerations.

The objectives of the contractor as well as of the WMC are somewhat adverse. While construction contractors usually seek to have their site clean at minimum costs not exceeding maximum available space on site, WMCs try to minimize their transportation costs while servicing as many clients as possible, i. e. maximizing their profits. However, the contractor usually reports to the WMC when to pick up a certain amount of a material type and does not take into consideration the available amount of vehicles and related capacities of the WMC, i. e. the capacity utilization of the WMC. Hence, the WMC can rarely define optimal routings for the vehicles nor can it properly assign vehicle capacities to contractor's orders in accordance to the available number of vehicles.

Concluding, it is reasonable to develop a model which includes both, the contractor's as well as the WMC's view. Doing so, complex optimization problems would arise due to the highly unstable planning environment and short time orders. For simplification purposes, the optimization problem is decomposed in this approach. According to the structure of the collection problem in construction projects as depicted in Figure 30, planning problems for a particular party can be differentiated concerning the material fractions bulk material and valuable or hazardous material.

For bulk as well as for valuable and hazardous material, Table 12 and Table 13 give a brief summary on the related planning problems according to their constraints, required data, objectives, and results of planning for both, the construction contractor as well as for the WMC.

Table 12 shows the perspective of the contractor and the WMC regarding the underlying reverse logistic planning tasks for bulk material. From the available information, three planning problems are developed and introduced in the preceding sections:

1. Contractor's multi vehicle multi material assignment problem (section 7.3)
2. Waste management company's vehicle assignment problem (section 7.4)
3. Waste management company's roll-on roll-off planning problem (section 7.5)

Table 12: Reverse logistics planning tasks for bulk materials

Bulk materials		Construction contractor	WMC
E. g. concrete wood, insulation	**Planning problems**	• Contractor's multi vehicle multi material assignment problem	• WMC's vehicle assignment problem • WMC's roll-on roll-off planning problem
	Constraints	• On-site storage space	• Vehicle capacity in terms of volume and weight • Number and type of vehicles • On-site storage space of contractor • Time windows for collection of containers for roll-on roll-off planning
	Available data	• Time and amount of material accumulation for each material type • Capacities of containers and vehicles which can be ordered	• Time and amount of material accumulation for each material type • Number of clients and related information
	Objectives	• Clean construction site • Minimal disposal costs	• Clean construction site according to contractors requirements • Minimal transportation costs
	Results of planning	• Collection time points and capacity of related vehicle as basis for order to WMC	• Collection time points and related vehicle • Routing information for container collection for roll-on roll-off planning

Table 13 concentrates on the planning problems which arise for valuable and hazardous construction materials. It is to note, that referring to the collection of valuable or hazardous material the construction contractor defines the time windows for the collection. These serve as input data for the determination of optimal routing decision to be made by the WMC.

Two cases can be differentiated according to the information available:

1. Information available on the amount of material and time window for the pickup, and
2. information available on the time and amount of material accumulation as well as on the capacity of storage facilities.

Each of the two cases implies different planning approaches. While in the first case, an appropriate representation of the planning problem is given by the Vehicle Routing Problem with Time Windows (VRPTW), the second case represents an Inventory Routing Problem (IRP). Hence, in the following, the two planning problems are addressed in detail and their potential for reverse logistics in construction is revealed. Therefore, the theoretical concepts of the VRPTW as well as of the IRP are introduced, before special focus is put on the VRPTW which is adapted to the reverse logistics context in construction. In particular, this comprises the following planning problems for the collection of valuable and hazardous material:

1. Waste management company's multi day vehicle routing problem with time windows (section 7.6.2)
2. Waste management company's inventory routing problem (section 7.7)

Table 13: Reverse logistics planning tasks for valuable and hazardous materials

Low volume materials and components		**Construction Contractor**	**WMC**
Hazardous material E. g. tarred products, asbestos	**Planning problems**		• WMC's multi day vehicle routing problem with time windows • WMC's inventory routing problem
Valuable material Gain importance in the future due to resource deterioration and its high value as input material for production processes	**Constraints**	• Soft constraint: On-site storage space constraint	• (Short) time windows for collection due to safety/ disposal requirements imposed by contractor, long inventory holding times often forbidden by contractor • Limited availability of vehicles and capacities
Façade elements, roofing, cladding : aluminum, copper	**Available data**	• Time and amount of material accumulation	• Multiple construction sites • Time and amount of material accumulation
Pipes, cables: cooper Intelligent façade elements	**Objectives**	• Safety and proper disposal • Costs material usually determined by WMC	• Safety and proper disposal • Minimization of transportation costs
with photovoltaic technique: silicon	**Results of planning**		• Pickup times, related vehicles and routing

7.2 Implications for the use of site storage space and vehicle capacities

During construction and deconstruction projects, different material fractions arise in different volumes and have to be stored before final collection; i. e. the fractions impose constraints on the formulation of models for the aforementioned planning problems. On the one hand these constraints refer to the available and usually limited storage space on site and on the other hand on the number and characteristic of available vehicles for collection.

7.2.1 Constraints on site storage space

During a construction and especially during a deconstruction project, several material fractions accumulate which have to be collected from site. Some of the fractions can be stored and transported together, while others have to be separated and treated independently. Material fractions, which can be stored and transported together, are denoted as material type *g*. During a (de-)construction project, to each of these material types a particular storage space has to be assigned on site. There, the material remains until it is picked up from site and transported to a recovery facility.

This storage space is generally limited and thereby characterized by a maximum capacity, which cannot be exceeded. Hence, in order not to exceed scheduled activity times, material fractions have to be picked up latest when the maximum capacity of the storage is reached, or for reasons of site security, as soon as the accumulation of that particular material finishes. Thereby, the schedule generated for construction activities determines the starting times ST_j and finishing times FT_j of (de-)construction activities *j*, i. e. the schedule also implicates the time of material accumulation.[25] This means, that the schedule set up for (de-)construction works by the timely organization of the collection of material is fixed.[26]

In order not to disrupt the existing schedule, it is necessary to determine the time at which the maximum capacity of the storage space on site will be exceeded to be able to request collection in time. Thereby, for the determination of the time at which the available space on site denoted as $V_g^{\max}$ will be exceeded by material type *g*, an *activity material accumulation function* $V_{jg}(t)$ has to be introduced first. This activity material accumulation function $V_{jg}(t)$ describes the amount of material *g* accumulated during activity *j* in dependency on the time *t* in volume [m³][27].

[25] The schedule can be set up based on the RCPSP, introduced in section 4.2.1.

[26] A complement can be found in materials management, where the procurement and delivery of material is based on the schedule for the construction project.

[27] Note, that *g* generally comprises bulk material. Thus, volume is the most appropriate unit.

To describe the underlying planning problem the following parameters are used:

g : material type g accumulating in (de-)construction project, $g = 1,...,G$

v_{jg} : total volume of material type g accumulating during processing of activity j [m³]

l_g : density of material type g [kg/m³]

$V_g^{\max}$: maximum available storage space on site or in warehouse for material type g [m³]

ST_j : starting time of activity j determined by schedule

FT_j : finishing time of activity j determined by schedule

$V_{jg}(t)$: activity material accumulation function, $t = 1,...,T$

$V_g(t)$: material accumulation function, $t = 1,...,T$

In reality, these materials do not only accumulate at the finishing time FT_j of an activity but during its execution. For the following considerations it is therefore assumed that material accumulates continuously when an activity j is active, thus, according to a linear function between ST_j and FT_j. Concluding, the activity material accumulation function can be characterized by three parts which are separated by the two points $P_1(ST_j, 0)$ and $P_2(FT_j, v_{jg})$ with $P(x,y)$ as depicted in Figure 31.

Point $P_1(ST_j, 0)$ separates the non-active phase $(0 \le t < ST_j)$, hence, zero material accumulation, of activity j from the active phase $(ST_j \le t \le FT_j)$ with linear material accumulation. Point $P_2(FT_j, v_{jg})$ separates the active period of deconstruction activity j from the non-active phase $(FT_j < t \le T)$ after the finish of activity j with the amount of material v_{jg} remaining constant.

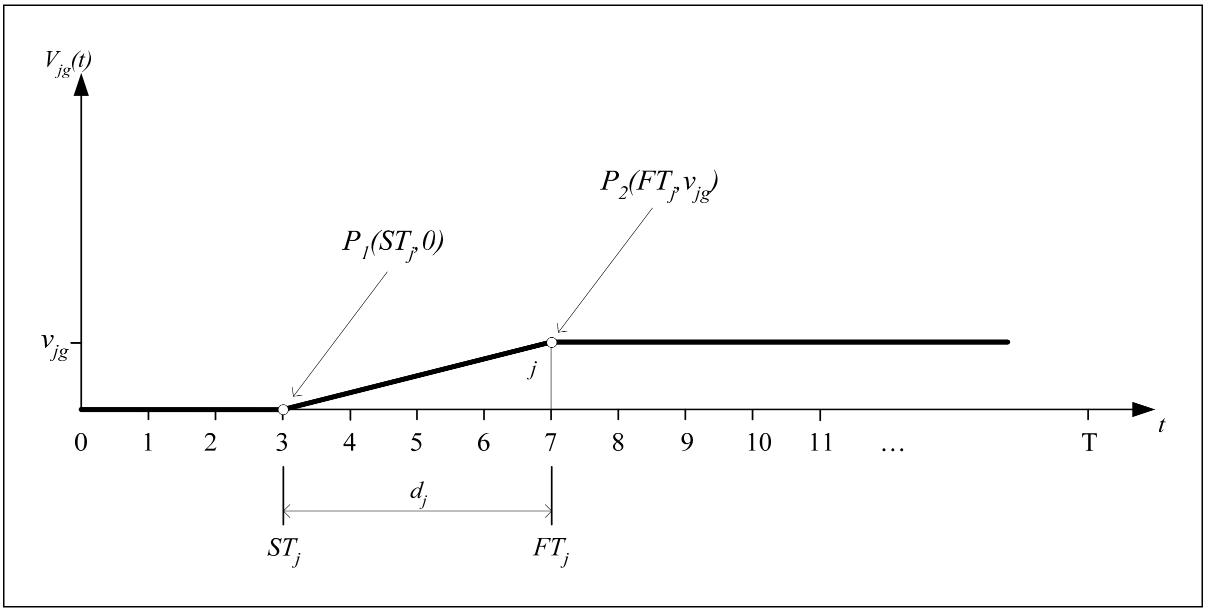

Figure 31: Material accumulation of activity *j* (example)

The linear part of the piecewise linear activity material accumulation function $V_{jg}(t)$ within the time window ST_j and FT_j is determined with the help of the well known equations from linear algebra:

$$f(x) = y = m \cdot x + n$$

with $P_1(x_1, y_1)$ and $P_2(x_2, y_2)$

$$m = \frac{\Delta y}{\Delta x} = \frac{y_2 - y_1}{x_2 - x_1}$$

with P(x,y) in $f(x)$

$$y = m \cdot x + n$$
$$n = y - m \cdot x$$

Hence, the variables of linear part of $V_{jg}(t)$ can be derived with the given points $P_1(ST_j, 0)$ and $P_2(FT_j, v_{jg})$ as follows:

$$V_{jg}(t) = m \cdot t + n \tag{7.1}$$

$$m = \frac{\Delta y}{\Delta x} = \frac{v_{jg}}{d_j} \tag{7.2}$$

with $P_1(ST_j, 0)$ in $V_{jg}(t)$

$$0 = \frac{v_{jg}}{d_j} \cdot ST_j + n \tag{7.3}$$

$$n = -\frac{v_{jg}}{d_j} \cdot ST_j \tag{7.4}$$

The linear term of $V_{jg}(t)$ follows with:

$$V_{jg}(t) = v_{jg} \cdot \left(\frac{t - ST_j}{d_j} \right) \tag{7.5}$$

Distinguishing between the different intervals $V_{jg}(t)$ is obtained as:

$$V_{jg}(t) = \begin{cases} v_{jg} \cdot \left(\frac{t - ST_j}{d_j} \right) & \text{for } ST_j \leq t \leq FT_j \\ 0 & \text{for } t < ST_j \\ v_{jg} & \text{for } t > FT_j \end{cases} \quad (7.6)$$

Generally, in (de-)construction projects several activities j are processed in parallel. Accordingly, to determine the volume of material type g which has been accumulated on a storage space, additional functions $V_g(t)$ have to be formulated for each material type g. The material accumulation function $V_g(t)$ describes the amount of material type g which has been accumulated by performing all activities j, $j=1,\ldots, J$, during project progress until t. Therefore, as Figure 32 shows for the example of 3 activities $j=1, 2, 3$, $V_g(t)$ is the sum over the activity material accumulation functions $V_{jg}(t)$ at time t, as given in equation 7.7.

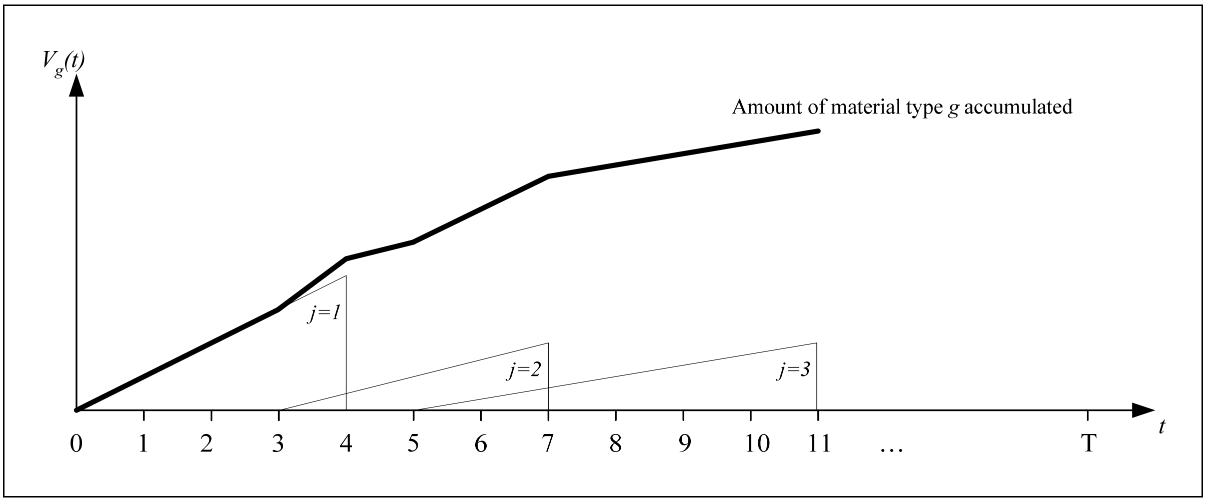

Figure 32: Material type accumulation at time *t* with parallel activities (example)

$$V_g(t) = \sum_{j=1}^{J} V_{jg}(t) \qquad g = 1,\ldots,G \quad (7.7)$$

Usually in (de-)construction, a particular material type *g* does not accumulate over the whole project horizon and is not generated by all activities *j*, i. e. material type *g* only arises during the processing of certain activities. Hence, the first time $\underline{T_g}$ this material actively accumulates is calculated with:

$$\underline{T_g} = \min\left\{ST_j\right\} \qquad g = 1,...,G, j \in \Upsilon_g \qquad (7.8)$$

and the last time $\overline{T_g}$ this material type *g* accumulates is determined with[28]:

$$\overline{T_g} = \max\left\{FT_j\right\} \qquad g = 1,...,G, j \in \Upsilon_g \qquad (7.9)$$

with

$\underline{T_g}$: first time at which material type g activily accumulates

$\overline{T_g}$: last time at which material type g activily accumulates before its amount on site remains constant

Υ_g : set of jobs j which generate material type g

To determine the total amount of material type *g* having accumulated until project end *T*, the subsequent equation 7.10 follows:

$$V_g(T) = \sum_{j=1}^{J} v_{jg} \qquad g = 1,...,G \qquad (7.10)$$

In the formulas (7.1)–(7.10), *t* is given by the construction project schedule. If the schedule is generated using the RCPSP, as introduced in section 4.2, $t \in \mathbb{N}$. In contrast, $V_g(t)$ spans the positive real numbers $\mathbb{R}^+$. For the easier representation of the introduced models, the formal description of $V_g(t)$ is changed into V_{gt} in the following. Thereby the condition $V_{gt} \in \mathbb{R}^+$ still holds.

7.2.2 Constraints on vehicle capacities

In the preceding section 7.2.1, the constraints on the storage space were discussed disregarding limited capacity of vehicles. In general, it is unlikely that the capacity of vehicles, both in terms of volume and load, corresponds to the capacity of the storage space on site; i. e. a collection at t^*, exactly at that time when storage space is exceeded will most

[28] The use of $\underline{T_g}$ and $\overline{T_g}$ will be illustrated in section 7.3.

probably not be realizable. This means, that constraints on the capacity of the transport vehicle k also have to be considered for the logistic planning problems in (de-)construction projects. These constraints are:

1. Volume or space constraints with $V_k^{\max}$ denoting the maximum available volume of vehicle k in $[\text{m}^3]$, and
2. the maximum load $L_k^{\max}$ representing the maximum available load of vehicle k in terms of material weight measured in $[\text{kg}]$ or $[\text{t}]$.

Thereby, the trade-off between the objective of full capacity utilization and the fulfillment of orders for the collection of the material has to be balanced and the orders have to be adjusted to the vehicle capacity. Also, the relation between the maximum load and maximum volume of the vehicles have to be considered; i. e. if the maximum volume of a vehicle is not yet exceeded, but the maximum load of the vehicle has already been reached, remaining material has to be picked up by an additional vehicle.

For the formal description of the constraints on the vehicle capacity the following additional parameters are introduced:

k	:	vehicle k, $k = 1,...,K$
l_g	:	density of material type g $[\text{kg/m}^3]$
$V_k^{\max}$	:	maximum volume of vehicle k $[\text{m}^3]$
$L_k^{\max}$	:	maximum load of vehicle k $[\text{kg}]$
L_{gt}	:	weight of material type g at time t resulting from V_{gt}
$\overline{V_{gk}^{col}}$	:	maximum volume of material type g which can be collected by vehicle k according to load restrictions
V_{gt}^{rem}	:	volume of remaining material type g on site at t
Q_k	:	number of available vehicles k, here set to 1, k denotes a particular vehicle

To match the weight of the material to be collected with the maximum available load $L_k^{\max}$ of the vehicle, it is necessary to calculate the weight L_{gt} of the total material accumulated at t with l_g defining the density of material type g [kg/m³]:

$$L_{gt} = l_g \cdot V_{gt} \qquad g = 1,...,G \qquad (7.11)$$

Furthermore, the maximum amount of material $\overline{V_{gk}^{col}}$ which can be collected by vehicle k is equal to:

$$\overline{V_{gk}^{col}} = \min\left\{V_k^{\max};\frac{L_k^{\max}}{l_g}\right\} \qquad g=1,...,G;k=1,...,K \qquad (7.12)$$

Hence, if the maximum amount of material $\overline{V_{gk}^{col}}$ is collected by vehicle k at time t, the volume V_{gt}^{rem} of the remaining material type g on site at time t is the difference between all material type g accumulated and the amount of all pickups taken place until t:

$$V_{gt}^{rem} = V_{gt} - \sum_{\tau=1}^{t}\sum_{k=1}^{K} s_{kg\tau}\cdot\overline{V_{gk}^{col}} \qquad t=1,...,T;g=1,...,G \qquad (7.13)$$

with the new decision variable:

$$s_{kgt}: \begin{cases} 1 & \text{, if vehicle } k \text{ collects material type } g \text{ at time } t \\ 0 & \text{, else} \end{cases}$$

7.3 Contractor's multi vehicle multi material assignment problem for bulk material

7.3.1 General model formulation

In (de-)construction projects, the contractor holds the information on type, time and amount of material accumulation and places orders on the pickup of these materials. Usually, the contractor can choose out of different pickup options represented by different vehicles with defined capacities available from a WMC. With this respect, the task of the contractor is to determine the collection time of the different material fractions and the related vehicles by matching the different material types accumulating with the capacity of the vehicle subject to its objective function. The resulting problem is called multi vehicle multi material assignment problem (MVMMAP). In the MVMMAP, the objective function depicts the aim of the contractor to minimize disposal costs and is constrained by the available storage space—making regular transports necessary to avoid site congestion and project disturbances—and by capacity constraints of the vehicle.

As stated in section 7.2, it is assumed that processing a construction activity j a certain amount of material type g accumulates. This material is specified in terms of volume and weight. Again, V_{gt} describes the amount of material type g accumulated during the project. Furthermore, for each material type g the time at which the amount of this material last actively grows is given by $\overline{T_g}$ (see section 7.2.1). Different types of material can be stored on site, while it is assumed that one material type *g* is assigned to only one storage space and one storage space is assigned to only one material type *g*. This assumption applies to most cases in practice.

As the contractor usually does not pay attention to the number of vehicles available to the WMC (see section 7.1), the number of vehicles of a particular capacity is assumed to be unlimited. For bulk materials it is furthermore assumed that the storage capacities and demands to be picked up are sufficiently large relative to the capacity of the vehicle, hence, it is beneficial to pick up full vehicle loads. Additionally, vehicles have to arrive latest, when the available space for material on the site $V_g^{\max}$ is to be congested; otherwise, (de-)construction construction activities would have to stop and wait until the remaining material has been collected.

In the model which is developed in the following, the granularity of the time period *t* (see section 4.2.1) is chosen according to the input data from the project schedule; i. e. time intervals of one day are perceived to be sufficient to represent real world instances. This is also justified by the fact, that material accumulation is not always processed as a linear function and, hence, uncertainties in material accumulation have to be expected. These uncertainties would even more impact the quality of the output if time intervals were shorter[29].

The underlying assumptions of the resulting planning problem are listed in the following:

1. Materials are stored on-site.
2. Transport requirements to be dealt with are vehicle capacity constraints.
3. Inventory requirements comprise available storage space on site.
4. Requirements regarding transport mode, regulations on the transport and storage of hazardous substances and safety issues are neglected. Especially, transport modes are chosen according to the type of material and existing transport regulations.
5. Collection costs are considered. They comprise transport costs as well as disposal costs. Collection costs c_{kg}^{col} arise for each vehicle and each material type.
6. It is assumed that collection costs rise in relation to the distances travelled. Therefore, distances from facility/land fill are implicitly considered in the collection costs and, hence, do not need to be considered explicitly in the MVMMAP.
7. The number of available vehicles is assumed to be unlimited. Thereby, k denotes a particular vehicle with a defined capacity in terms of volume and load.

[29] Uncertainties in project planning are discussed in detail in section 4.2.6.

8. Only vehicles with single compartment are considered, i. e. a vehicle can only collect and transport one material type *g* at a time.
9. The planning horizon is divided into planning periods of one day length.
10. Setup times of vehicles are neglected.

The objective of the MVMMAP (7.14)–(7.18) pursued by the contractor might be the minimization of the collection costs *C* for all materials on site. It is to note, that minimizing the collection costs, it is also ensured that the number of pickups is minimized as costs for collection usually correspond to the amount of material picked up. This objective can be formulated as:

$$MIN \;\; \mathrm{C} = \sum_{g=1}^{G} \sum_{k=1}^{K} \sum_{t=1}^{T} c_{kg}^{col} \cdot s_{kgt} \tag{7.14}$$

with

c_{kg}^{col} : collection costs for material type g with vehicle k assuming full capacity utilization

s_{kgt} : $\begin{cases} 1 & \text{, if vehicle } k \text{ collects material type } g \text{ at time } t \\ 0 & \text{, else (as introduced in section 7.2.2)} \end{cases}$

Note, in the MVMMAP different vehicles *k* can refer to resources that are identical in volume and load. Thus, in order to model unlimited vehicle availability, a sufficiently high number of vehicles *k* have to be introduced.

The objective function (7.14) is subject to a number of constraints.

Storage space

At each time *t* the maximum available storage space $V_g^{\max}$ is not allowed to be exceeded by the remaining material. The remaining volume of material type *g* on the site is defined as the difference between the total of all accumulated material V_{gt} from the beginning of the project until *t* and the amount *X* of material type *g* already collected until time *t* by vehicles *k*, thus:

$$X = \sum_{\tau=1}^{t} \sum_{k=1}^{K} \overline{V_{kg}^{col}} \cdot s_{kg\tau} \tag{7.15}$$

Now the constraints on the storage space follow with[30]:

$$V_{gt} - \sum_{\tau=1}^{t}\sum_{k=1}^{K}\overline{V_{kg}^{col}} \cdot s_{kg\tau} \le V_{g}^{\max} \qquad t = 1,...,T;\ g = 1,...,G \tag{7.16}$$

Empty storage space at project finish

To avoid congestions and to enhance worker security on site the contractor usually seeks to clear the site as soon as the accumulation of material type *g* has been finished. Thus, material type *g* has to be collected finally at the given time $\overline{T_g}$ to clear the storage space. Usually, the remaining material $V_{g\overline{T_g}}^{rem}$ on site at $\overline{T_g}$ will not exactly match the capacities of the available vehicles. Concluding, an underutilization of the vehicle usually occurs for the last pickup. Accordingly, to guarantee that all material is collected a slack variable $u_g, u_g \le 0$ has to be introduced to allow underutilization of the vehicle used for the last pickup. This requirement is necessary, as it is assumed in the calculation of the remaining material on site, that the full capacity in terms of either volume or load of the vehicle $\overline{V_{kg}^{col}}$ is collected in one pickup.

$$V_{g\overline{T_g}} - \sum_{\tau=1}^{\overline{T_g}}\sum_{k=1}^{K}\overline{V_{kg}^{col}} \cdot s_{kg\tau} + u_g = 0 \qquad g = 1,...,G \tag{7.17}$$

These constraints also hold for the case, that material type *g* accumulates in such small amounts that $V_g^{\max}$ would never be exceeded and the capacity of a vehicle would never be fully utilized. For this case it is referred to section 7.6 dealing with the vehicle routing problem, where improved capacity utilization can be achieved by servicing multiple customers with the same vehicle.

Binary decision variable

$$s_{kgt} \in \{0,1\} \qquad k = 1,...,K;\ g = 1,...,G;\ t = 1,...,T \tag{7.18}$$

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[30] These constraints (7.16) already include the constraints on the vehicle volume and vehicle load, as $\overline{V_{kg}^{col}}$ is calculated taking $V_k^{\max}$ and $L_k^{\max}$ into consideration.

The complete MVMMAP is formulated as:

$$MIN \quad C=\sum_{g=1}^{G}\sum_{k=1}^{K}\sum_{t=1}^{T} c_{kg}^{col} \cdot s_{kgt} \tag{7.19}$$

subject to

$$V_{gt} - \sum_{\tau=1}^{t}\sum_{k=1}^{K} \overline{V_{kg}^{col}} \cdot s_{kg\tau} \le V_{g}^{\max} \qquad t=1,...,T;\ g=1,...,G \tag{7.20}$$

$$V_{g\overline{T_g}} - \sum_{\tau=1}^{\overline{T_g}}\sum_{k=1}^{K} \overline{V_{kg}^{col}} \cdot s_{kg\tau} + u_g = 0 \qquad g=1,...,G \tag{7.21}$$

$$s_{kgt} \in \{0,1\} \qquad k=1,...,K;\ g=1,...,G;\ t=1,...,T \tag{7.22}$$

7.3.2 Multi vehicle multi material assignment problem with consolidated storage

In the preceding model (7.19)–(7.22) it was assumed that one material type *g* is assigned to one storage space and one storage space is assigned to exactly one material type *g* throughout the whole project. However, storage space might be used by several material types during the project, i. e. consolidated, which enables a more efficient utilization of storage. In the following, two cases for consolidated storage space are considered:

1. Case 1: Succeeding, non-overlapping use of one particular storage space by multiple material types *g*
2. Case 2: Simultaneous use of one particular storage space by multiple material types *g*

Solving the MVMMAP with consolidated storage space the introduced objective function (7.19) and constraints (7.20)–(7.22) of the MVMMAP remain the same. Instead, the input data of the model have to be modified. In the following it is shown, how the input data of the model can be transformed to serve case one and case two of consolidated storage space use.

In the case of *succeeding use of one storage space i* particular material types *g* are assigned to exactly the same storage space on site. In this case, however, material types *g* accumulate at different times *t*, i. e. within the time frame $t=\underline{T_g},...,\overline{T_g}$, which are distinct for $g=1,...,G$ and non-overlapping.

Figure 33 exemplarily depicts the use of one particular storage space *i* during project progress by material types *g=1*, *g=4*, and *g=8*.

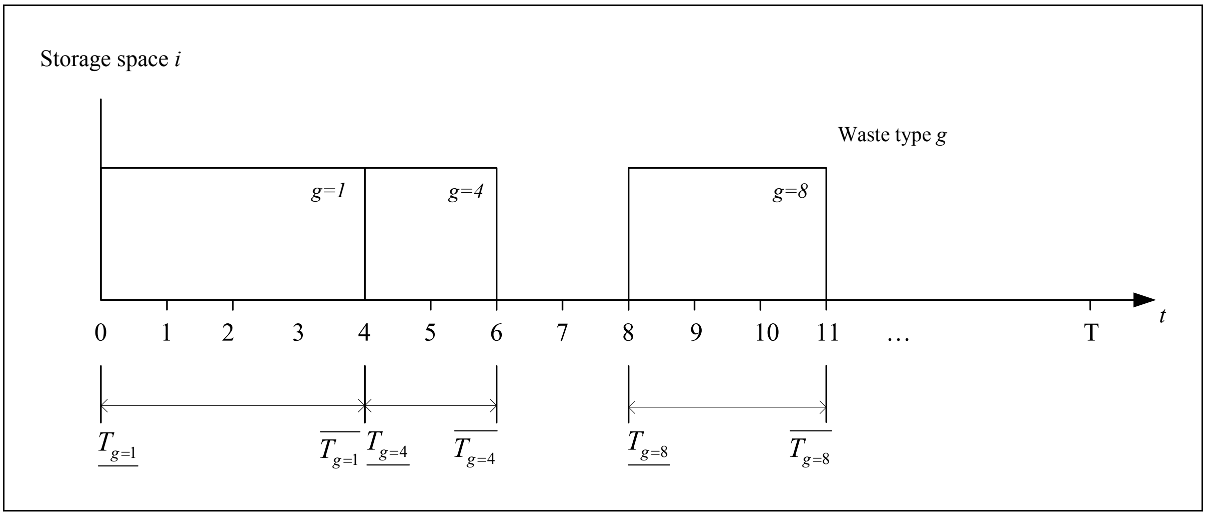

Figure 33: Utilization of storage space by succeeding accumulating material types

The time frame is determined by the starting and finishing times of the activities *j* which generate the material type *g* and, hence, result from the schedule (see section 7.2.1). Concluding, they have to be given as input data to the MVMMAP. Thereby, the particular space is subdivided into virtual storage spaces which are assigned to each material type g; i. e. V_g^{max} with *g=1*, *g=4*, and *g=8* denotes the maximum volume of the identical storage space, while knowing from the RCPSP solution, that *g=1*, *g=4*, and *g=8* never arise at the same time.

In case two with *simultaneous use of storage space*, V_g^{max} again denotes the storage space reserved for a particular material type *g*, e. g. wood, bricks, or glass. During (de-)construction projects, material types exist, which accumulate in small amounts. Usually, unless being valuable or containing hazardous substances, it is not reasonably to sort and store these material types on site separately. They are rather stored together at one location on site—for instance in a container—before pickup, selection and sorting in the recovery facility. Thus, a new material type *g* could be defined comprising all mixable materials. To this material type, storage space V_g^{max} is assigned and treated as common material type *g* in the model, i. e. several material types *g* can be stored at the same location at one time.

7.4 Waste management company's vehicle assignment problem for bulk material

In section 7.3, the material collection problem (7.19)–(7.22) was analyzed from the perspective of the construction contractor. From the viewpoint of the construction contractor it is not relevant, whether the WMC is able to optimize its vehicle capacities and match it to the customer's demand who requested the pickup of material in order to minimize overall collection costs. Hence, the underlying assumption in the preceding problems is that vehicles with different capacity are available in unlimited amount. The cooperation between the construction contractor and the WMC focuses on the orders of the contractor and the related information about the time and amount of material being requested to be collected by the WMC, whereas vehicle capacity constraints are not relevant. As a consequence, the WMC takes over a passive role in responding to the orders of the customers, assuming that an order can be fulfilled at any point in time.

In contrast, if the WMC's perspective is taken into consideration, limited availability of vehicles becomes a predominant issue which needs to be considered in detail. The WMC's perspective has to take into account that not only one particular contractor needs to be serviced but several contractors request material pickup. Thereby, one vehicle can collect material more than once during the planning horizon. Furthermore, a vehicle is generally unavailable for several periods after pickup, i. e. setup times occur. In the models introduced in sections 7.4.1 and 7.4.2, these setup times comprise time for uploading and transport of material to recovery facilities, unloading, cleaning if necessary and for deadheads back to the same or another site for further collection.

For the consideration of setup times it is necessary to change the granularity of the model (see section 4.2.1). In the model (7.19)–(7.22) a planning period comprised one full day. Setup times are usually measured in hours or minutes. Hence, the planning periods have to be adjusted. For this particular application a duration of 1 hour is perceived to be appropriate. Shorter time intervals (minutes or seconds) might better depict real world instances; however, due to uncertainties in waste accumulation and uncertain durations for collection, transport, unloading and cleaning the output of the model could more easily be disturbed. For the transformation of the 1-day planning periods it is assumed that a working day consists of 12 hours. This means, that the (de-)construction site as well as the collection can take place during 12 hours each working day, for instance, from 6:00 AM to 18:00 AM. The assumption, that both, the operation of the site as well as the collection activities take place during the same time interval is necessary to model the waste accumulation as well as the collection and related setup-times in one model. For instance for 1-day period a planning horizon of 2 weeks, comprising 10 working days is modeled as $t = 1,\ 2,\ 3, ...,\ 10$. Considering the same planning horizon with 1-hour planning periods, each day containing 12 working hours, the planning horizon comprises 120 hours, i. e. 120 elements $t = 1,\ 2,\ 3, ...,\ 120$.

Again it is assumed, that one vehicle only collects one particular material type g comprising bulk materials only; i. e. the full vehicle capacity is utilized for one pickup. Exceptions exist for the last pickup, where underutilization might occur (see equations (7.21)). The remaining capacity could be fully utilized if another (de-)construction site is serviced were materials could be collected. This situation is discussed in relation with vehicle routing problems (see section 7.6) and is, however, not considered in the following model.

In the following, two extensions of the formerly introduced model (7.19)–(7.22) are developed. The first extension refers to servicing one particular contractor and its construction site and allocation of the pool of vehicles considering setup times. The second extension further amends the model and introduces multiple construction contractors to the material collection problem.

7.4.1 Single contractor vehicle assignment problem with setup times

Generally, in real world applications of the collection of materials the number of available vehicles is limited over the planning horizon. Furthermore, a vehicle can be used more than once over the planning horizon. Thus, modeling the pickup of material from a (de-)construction site, setup times have to be considered. The resulting problem is the single contractor vehicle assignment problem with setup times (SCVAPST). In the SCVAPST, each vehicle is treated separately to assign a particular setup time to every vehicle. Therefore, additional constraints have to be introduced.

Number of collections

Assuming, that vehicle k can only collect one material type g at a time t, the following additional constraints derive:

$$\sum_{g=1}^{G} s_{kgt} \leq 1 \qquad t = 1,...,T;\ k = 1,...,K \qquad (7.23)$$

Setup times

Assuming that a vehicle is reused after pickup and delivery of material over the planning horizon, it has to be ensured that the next pickup first takes place after the defined setup time has passed. The following constraints (7.24) have to be introduced

$$\sum_{g=1}^{G} s_{kgt} + \sum_{\pi=t}^{t+d_k^{setup}-1} \sum_{g=1}^{G} s_{kg\pi} \leq 1 \qquad t = 1,...,T;\ k = 1,...,K \qquad (7.24)$$

with

d_k^{setup} : setup time of vehicle k, i.e. number of unavailable periods of vehicle k

Now, the SCVAPST is written as:

$$MIN \quad C=\sum_{g=1}^{G}\sum_{k=1}^{K}\sum_{t=1}^{T} c_{kg}^{col} \cdot s_{kgt} \tag{7.25}$$

subject to

$$V_{gt} - \sum_{\tau=1}^{t}\sum_{k=1}^{K} \overline{V_{kg}^{col}} \cdot s_{kg\tau} \le V_g^{\max} \qquad t=1,...,T;\ g=1,...,G \tag{7.26}$$

$$V_{g\overline{T_g}} - \sum_{\tau=1}^{\overline{T_g}}\sum_{k=1}^{K} \overline{V_{kg}^{col}} \cdot s_{kg\tau} + u_g = 0 \qquad g=1,...,G \tag{7.27}$$

$$\sum_{g=1}^{G} s_{kgt} \le 1 \qquad t=1,...,T;\ k=1,...,K \tag{7.28}$$

$$\sum_{g=1}^{G} s_{kgt} + \sum_{\pi=t}^{t+d_k^{setup}-1}\sum_{g=1}^{G} s_{kg\pi} \le 1 \qquad t=1,...,T;\ k=1,...,K \tag{7.29}$$

$$s_{kgt} \in \{0,1\} \qquad k=1,...,K;\ g=1,...,G;\ t=1,...,T \tag{7.30}$$

7.4.2 Multiple contractor vehicle assignment problem with setup times

Usually, a WMC has to service multiple construction contractors during its planning horizon and material has to be picked up from several (de-)construction sites or clients. Each construction site is denoted by i, $i=1,...,I$, which corresponds to (de-)construction projects in the RCPSP (see section 4.2.1). Hence, material accumulation functions V_{igt} exist for each *i*.

In the multiple contractor vehicle assignment problem with setup times (MCVAPST) the objective of the WMC is to minimize the collection costs over the planning horizon for servicing all clients. Hence, considering multiple collection points the objective function (7.19) changes into:

$$MIN \quad C=\sum_{i=1}^{I}\sum_{g=1}^{G}\sum_{k=1}^{K}\sum_{t=1}^{T} c_{kig}^{col} \cdot s_{kigt} \tag{7.31}$$

with

c_{kig}^{col} : collection costs for waste type g with vehicle k assuming full capacity utilisation of vehicle k of client i

This objective function is subject to the following constraints:

Storage space

At each time t the maximum available storage space $V_{ig}^{\max}$ at a (de-)construction site i is not allowed to be exceeded by the remaining material. The remaining material is the difference between the total of all accumulated material V_{igt} from the beginning of the project until t and the amount Y of material already collected until time t by vehicles k, calculated with:

$$Y = \sum_{\tau=1}^{t} \sum_{k=1}^{K} \overline{V_{kig}^{col}} \cdot s_{kgi\tau} \tag{7.32}$$

Now constraints (7.16) of the MWMMAP alter into constraints:

$$V_{igt} - \sum_{\tau=1}^{t} \sum_{k=1}^{K} \overline{V_{kig}^{col}} \cdot s_{kig\tau} \leq V_{ig}^{\max} \qquad i = 1,...,I;\ t = 1,...,T;\ g = 1,...,G \tag{7.33}$$

Empty storage space at project finish

In the calculation of the remaining material on site it is assumed, that the full capacity $\overline{V_{kig}^{col}}$ in terms of either volume or load of the vehicle is collected in one pickup. In reality, the last pickup will most likely not match the maximum capacity of the vehicle, hence, underutilization is allowed by introducing a slack variable u_{ig}, $u_{ig} \leq 0$ and changing constraints (7.21) of the MWMVAP into:

$$V_{igt} - \sum_{\tau=1}^{t} \sum_{k=1}^{K} \overline{V_{kig}^{col}} \cdot s_{kig\tau} + u_{ig} = 0 \qquad i = 1,...,I;\ g = 1,...,G;\ t = T \tag{7.34}$$

If it is furthermore assumed, that a storage space is used succeedingly for different material types g during project progress and that one vehicle can only pickup one particular material type g at a time, the storage has to be cleared of material type g right at the time of last material accumulation, $\overline{T_{ig}}$. Now the preceding constraints (7.34) alter into:

$$V_{ig\overline{T_{ig}}} - \sum_{\tau=1}^{\overline{T_{ig}}} \sum_{k=1}^{K} \overline{V_{kig}^{col}} \cdot s_{kig\tau} + u_{ig} = 0 \qquad i = 1,...,I;\ g = 1,...,G \tag{7.35}$$

Number of collections

Furthermore, vehicle k can only collect one material type g from one particular client i at a time t

$$\sum_{i=1}^{I}\sum_{g=1}^{G} s_{kigt} \leq 1 \qquad t = 1,...,T;\ k = 1,...,K \qquad (7.36)$$

Setup times

To consider setup times it is necessary, that the available amount of vehicle k is set to 1 in order to always address a particular vehicle which is prohibited to service other sites during its setup time. Thereby, vehicle k can service customers in different order once having delivered the collected material. In reality, the setup time depends on the order in which the customers are serviced due to their varying distance from the recovery facility; i. e. must be given as d_{ijk}^{setup} . Now the following constraints follow:[31]

$$\sum_{g=1}^{G} s_{kjgt} + \sum_{j=1}^{J_i}\sum_{g=1}^{G} s_{kjg\pi} \sum_{\pi=t}^{t+d_{ijk}^{setup}-1} \leq 1 \qquad i = 1,...,I;\ t = 1,...,T;\ k = 1,...,K \qquad (7.37)$$

with

j : client serviced after client $i, j \in J_i$
with $J \in J_i$ denoting all clients which can be serviced after i,
i is also part of J_i, as client i can be serviced successively by the same vehicle

Binary decision variable

$$s_{kigt} \in \{0,1\} \qquad k = 1,...,K;\ i = 1,...,I;\ g = 1,...,G;\ t = 1,...,T \qquad (7.38)$$

with

$$s_{kigt} : \begin{cases} 1 & \text{, if a vehicle of vehicle type } k \text{ collects waste type } g \text{ at time } t \text{ from client } i \\ 0 & \text{, else} \end{cases}$$

[31] In the RCPSP (section 4.2.1), j denoted the job j of a project. Now j denotes the succeeding construction contractor serviced by vehicle k.

Following, the complete MCVAPST is written as:

$$MIN \quad C=\sum_{i=1}^{I}\sum_{g=1}^{G}\sum_{k=1}^{K}\sum_{t=1}^{T} c_{kig}^{col}\cdot s_{kigt} \tag{7.39}$$

subject to

$$V_{igt}-\sum_{\tau=1}^{t}\sum_{k=1}^{K}\overline{V_{kig}^{col}}\cdot s_{kig\tau}\le V_{ig}^{\max} \qquad i=1,...,I;\ t=1,...,T;\ g=1,...,G \tag{7.40}$$

$$V_{ig\overline{T_{ig}}}-\sum_{\tau=1}^{\overline{T_{ig}}}\sum_{k=1}^{K}\overline{V_{kig}^{col}}\cdot s_{kig\tau}+u_{ig}=0 \qquad i=1,...,I;\ g=1,...,G \tag{7.41}$$

$$\sum_{i=1}^{I}\sum_{g=1}^{G}s_{kigt}\le 1 \qquad t=1,...,T;\ k=1,...,K \tag{7.42}$$

$$\sum_{i=1}^{I}\sum_{g=1}^{G}s_{kjgt}+\sum_{\pi=t}^{t+d_k^{setup}-1}\sum_{j=1}^{J_i}\sum_{g=1}^{G}s_{kjg\pi}\le 1 \qquad t=1,...,T;\ k=1,...,K \tag{7.43}$$

$$s_{kigt}\in\{0,1\} \qquad k=1,...,K;\ i=1,...,I;\ g=1,...,G;\ t=1,...,T \tag{7.44}$$

7.5 Waste management company's roll-on roll-off planning problem for bulk material

Roll-on roll-off planning problems are a variant of the classical vehicle routing problem, which is introduced and further discussed in section 7.6. Roll-on roll-off vehicle routing problems (RRVRP) arise, for instance, at construction sites or locations with material accumulating in high volumes. Thereby, a truck carries containers between different locations and recovery facilities or landfill while usually only one container can be serviced at a time. The four, in Figure 34 illustrated, basic types are differentiated (Golden et al. 2002, 252):

1. Round trip,
2. exchange trip,
3. new site, and
4. removal.

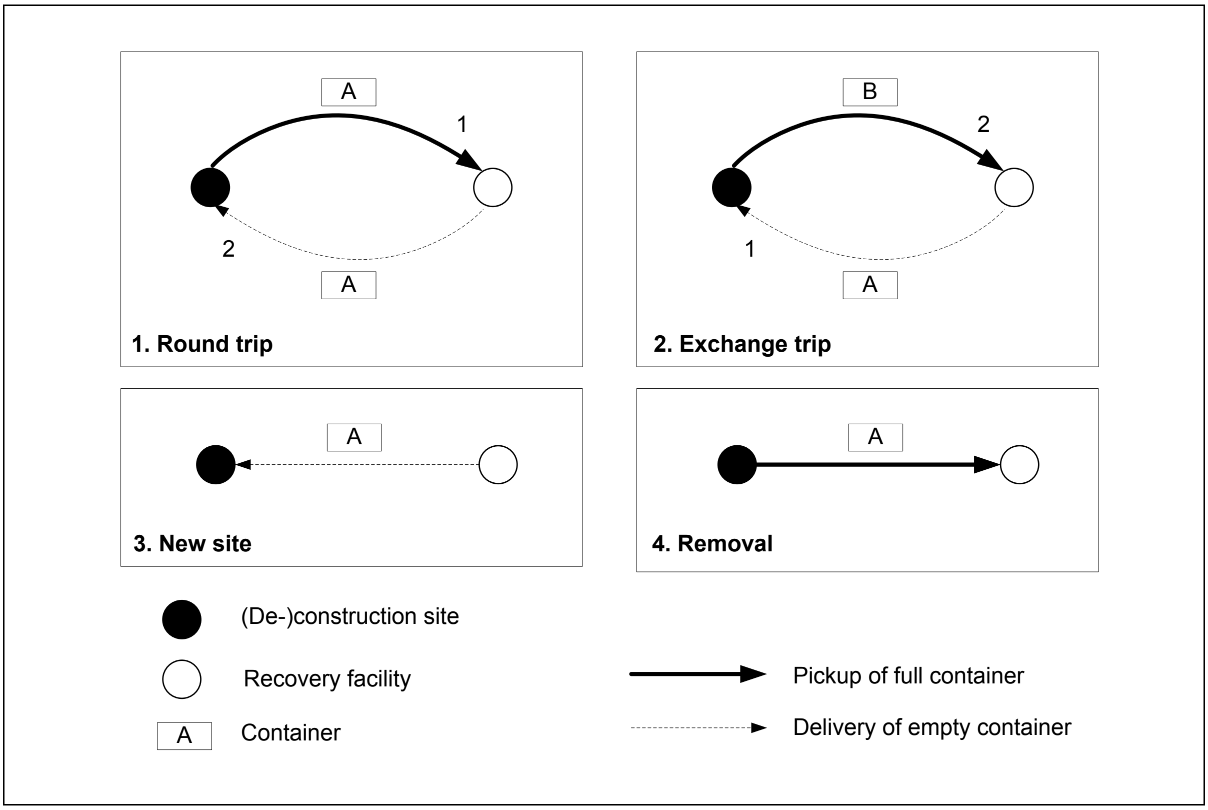

Figure 34: Types of roll-on roll-off planning problems

In *round trips*, the full container is picked up by a truck, brought to the recovery facility, emptied and returned back to the original customer, e. g. (de-)construction site. *Exchange trips* occur, when an empty container is picked up at the recovery facility or landfill, brought to the (de-)construction site and after delivery a full container is picked up at the site and brought back to the recovery facility. Roll-on roll-off problems for *new sites* occur when an empty container is brought to a site and *removal* problems occur, when a full container is picked up at an old site (Golden et al. 2002, 252).

The objective of the RRVRP is the minimization of the number of trucks required to pick up the containers and their total travel time subject to limited numbers of working hours per day for the drivers. Thereby, possible sequences of moves would be for exchange trips, that an empty container is brought from the depot to contractor *A*, a full container is picked up, brought to the recovery facility and then brings the empty container to contractor *B* where a full container is picked up, delivered to the recovery facility and afterwards contractor *C* is serviced, etc. Each trip from the recovery facility to the client and back to the recovery facility is characterized by a duration. As the traveling time per day is limited by working hours, the aim is to pack customers into routes such that the number of trucks used for the transport of the containers is minimized. The resulting problem can then be considered as bin packing problem. If only round trips are performed, an empty truck would travel to contractor *A* to pick up a full container. This container is brought to the recovery facility, emptied and brought back to contractor A. After delivery of an empty container to contractor A the empty truck travels to contractor B to pick up a full container at the (de-)construction site, delivers it to the recovery facility, empties it, brings it back to customer B , and so on. As travel times between the contractors play an important role for the optimization problem, this problem has a strong routing component (Golden et al. 2002, 253).

Usually, a WMC performs mixed services, i. e. round trips as well as exchange trips during one day. Together with possible limitations of time windows for servicing one contractor, the roll-on roll-off problem might emerge as a very complex optimization problem. Further problems arise, when a driver has to service customers with different container sizes and different requirements, for instance, driver-experience level, vehicle type, container type, and material type (Golden et al. 2002, 253; Kim et al. 2006, 3625).

Propositions for the RRVRP were already made in literature and are sufficient to describe real world instances for the collection of bulk material from (de-)construction sites. Models are developed, for instance, in (Bodin et al. 2000; de Meulemeester et al. 1997).

7.6 Waste management company's vehicle routing problem for low volume material

The waste management company's planning problem refers to the collection of valuable or hazardous material usually accumulating in low amounts. This material is exposed to deterioration and thievery on site, hence, makes a quick pickup necessary. Due to the low amounts accumulating, a complete utilization of the vehicle of the WMC is usually not feasible; hence, the WMC will try to service several construction sites consecutively in one route to avoid underutilization of vehicle capacity. Concluding, considering the collection of valuable or hazardous material, other, more difficult, planning problems arise for the WMC.

In the case of given information on the time and amount of material collection, the construction contractor decides upon the amount and time of material collection. Therefore, placing the orders, the construction contractor specifies a time window during which a collection takes place to ensure that site activities are not disturbed by the collection activity.

Concluding, this particular material collection problem is characterized by a WMC which represents the recovery facility or depot. This WMC has a pool of vehicles of a given capacity available to service several construction contractors, i. e. the vehicles leave the WMC and return to the recovery facility at the end of the day. The construction contractors are characterized by a particular amount of material to be picked up and additionally define time windows for service by the WMC. This planning problem belongs to the class of VRPTW introduced in the following.

7.6.1 Vehicle routing problem with time windows

The VRPTW is a generalization of the vehicle routing problem (VRP) which, itself, is based on the well known traveling salesman problem (TSP). The objective of the TSP is to find a minimum distance tour through a set of *n* cities with the restriction that each city has to be visited exactly once. Generalizing the TSP to the multi traveling salesman problem (*m*-TSP) by introducing multiple salesmen *m* the objective changes to the minimization of the total distance travelled by all salesmen. Therefore, the solution contains a route for each salesman—starting and finishing at a depot—such that each city is visited by exactly one salesman (Asbach 2008).

A further generalization of the TSP is the VRP—sometimes also called capacitated vehicle routing problem (CVRP)—where customers now represent the former cities in the TSP and *m*-TSP and are delivered by vehicles instead of salesmen. In addition to the *m*-TSP demands and capacity constraints are added in the VRP. Thereby, the customers are assigned a demand which can vary from customer to customer while the pool of vehicles comprises vehicles of the same capacity. Usually, the objective of the VRP refers to traveling costs instead of traveling times like in the TSP. Hence, the objective of the VRP is to minimize the total costs by satisfying the demands of all customers and not exceeding the available vehicle capacity on one tour (Asbach 2008).

The VRPTW results if a time component in terms of time windows for service at a customer and traveling times between customers is added to the VRP. The objective of the VRPTW is similar to the one of the VRP, however, with the additional constraints, that the customers might only be delivered within their specified time window and that traveling times have to be considered. Thereby it can be differentiated between soft and hard time windows. While soft time windows can be violated at a cost, hard time windows force a vehicle to arrive latest at the latest possible arrival time of the related customer to begin service. In this case a vehicle would also have to wait if it arrives before the first possible servicing time of that customer (Asbach 2008). The VRPTW is well suitable as basic principle for the modeling of logistic planning problems in construction. An example is the ‘concrete delivery problem’ by Asbach et al. (2009). In the concrete delivery problem, tours of concrete mixer vehicles from concrete-producing depots have to be scheduled to concrete-demanding customers and vice versa over a working day.

In a general representation, the VRPTW can be depicted as a directed graph. The graph $G = (N, A)$ consists of a set of nodes $N = \{0,1,...,n,n+1\}$ and a set of arcs A. While the depot is represented by the nodes 0 and $n+1$, the set of customers C is given by the nodes $1,...,n$, i. e. $C = N \setminus \{0, n+1\}$. Thereby, customers are characterized by a positive demand d_i. As vehicles have to leave the depot and return back to the depot, all feasible vehicle routes start from node *0* and end at node *n+1* while modeling the depot as 2 nodes enables a more feasible formulation of the problem. To each node a service time s_i, a demand d_i and a time window ranging from a_i to b_i during which service at customer *i* can be started is assigned. With node *0* and node *n+1* denoting the depot, the time window of the depot is defined as

$$[a_0, b_0] = [a_{n+1}, b_{n+1}] = [E, L] \tag{7.45}$$

with *E* representing the earliest possible departure and L defining the latest possible arrival at the depot. No vehicle can start its tour earlier than a_0 and is not allowed to arrive later than b_{n+1}. Furthermore, the depot is characterized by zero demand and zero service time with $d_0 = d_{n+1} = 0$ and $s_0 = s_{n+1} = 0$.

The set of arcs $(i, j) \in A$ contains directed edges with $i, j \in N, i \neq j$ from node *i* to node *j*. Hence, *A* comprises edges between the depot *0* and all customers, between the customers as well as between the customers and the depot *n+1*. The consideration of directed graphs makes especially sense, if restrictions on the use of particular streets between *i* and *j* by route diversion or one ways might exist. If it shall be considered in the VRPTW that a vehicle can stay at the depot, for instance minimizing the number of vehicles, an additional edge $(0, n+1)$ with zero costs and zero traveling time has to be added to *A*. Furthermore, travel times t_{ij} and travel costs c_{ij} are assigned to each arc, while some edges between two nodes can be eliminated. Among others, temporal constraints lead to the elimination of edges if it is not possible to service a succeeding customer *j* at its latest possible servicing time when starting service at customer *i* at the earliest possible time, i. e.

$$a_i + s_i + t_{ij} > b_j \tag{7.46}$$

Capacity constraints restrict *A* if the demands of two succeeding customers exceed the vehicle capacity *C*, i. e.

$$d_i + d_j > C \tag{7.47}$$

For the costs c_{ij} as well as for the travel times t_{ij} it is necessary, that the triangle inequality holds. This means that the direct distance and the travel time between two nodes always has to be shorter than the route via a third node:

$$c_{ij} \le c_{il} + c_{lj} \qquad \forall i; j, l \in N \tag{7.48}$$

and

$$t_{ij} \le t_{il} + t_{lj} \qquad \forall i; j, l \in N \tag{7.49}$$

Furthermore, customers are serviced by vehicles $k,\ k \in K$ of a homogeneous fleet of vehicles with the capacity *Q*. The vehicle capacity *Q* represents a resource that has to be allocated and is subject to decision variables which have to be introduced for the mathematical formulation of the VRPTW. Thereby, the VRP consists of two planning problems:

1. The allocation of vehicles to customers and
2. the definition of the sequence of customers to be visited for each vehicle.

Both planning problems can be tackled by decision flow variables defined as

$$x_{ijk}: \quad \begin{cases} 1 & \text{, if arc } (i,j) \text{ used by vehicle } k \\ 0 & \text{, else} \end{cases} \qquad (i,j) \in A, k \in K$$

and by decision time variables w_{ik} which impose timely restrictions on the collection and denote the time at which vehicle $k, k \in K$ starts its service at customer *i*.

Now the VRPTW can be formulated as MIP (Cardeneo 2005, 97; Cordeau et al. 2002; Larsen 2001):

$$MIN \quad \sum_{k \in K} \sum_{(i,j) \in A} c_{ij} \cdot x_{ijk} + \sum_{j \in \Delta^+(0) \setminus \text{n+1}} x_{0jk} \cdot c_k \tag{7.50}$$

subject to

$$\sum_{k \in K} \sum_{j \in \Delta^+(i)} x_{ijk} = 1 \qquad \forall i \in C \tag{7.51}$$

$$\sum_{j \in \Delta^+(0)} x_{0jk} = 1 \qquad \forall k \in K \tag{7.52}$$

$$\sum_{i \in C} d_i \sum_{j \in \Delta^+(i)} x_{ijk} \le Q \qquad \forall k \in K \tag{7.53}$$

$$\sum_{i \in \Delta^-(j)} x_{ijk} - \sum_{i \in \Delta^+(j)} x_{jik} = 0 \qquad \forall k \in K, \forall j \in C \tag{7.54}$$

$$\sum_{i \in \Delta^-(n+1)} x_{i.n+1,k} = 1 \qquad \forall k \in K \tag{7.55}$$

$$w_{ik} + s_i + t_{ij} - M\left(1 - x_{ijk}\right) \le w_{jk} \qquad \forall k \in K, \forall \left(i,j\right) \in A \tag{7.56}$$

$$a_i \left(\sum_{j \in \Delta^+(i)} x_{ijk} \right) \le w_{ik} \le b_i \left(\sum_{j \in \Delta^+(i)} x_{ijk} \right) \qquad \forall k \in K, \forall i \in C \tag{7.57}$$

$$E \le w_{ik} \le L \qquad \forall k \in K, \forall i \in \left\{0, n+1\right\} \tag{7.58}$$

$$x_{ijk} \in \left\{0,1\right\} \qquad \forall k \in K, \left(i,j\right) \in A \tag{7.59}$$

with

N : set of nodes, $N = \left\{0,...,n,n+1\right\}$
A : set of arcs, $(i,j) \in A$
$\Delta^+(i)$: set of direct successors of i
$\Delta^-(i)$: set of direct predecessors of i
C : set of customers, $C = N \setminus \left\{0, n+1\right\}$
d_i : demand of customer i
s_i : service time at customer i
a_i : beginning of time window to start service at node i
b_i : end of time window to start service at node i
k : vehicle, $k \in K$
Q : capacity of vehicle k
t_{ij} : travel time between all nodes
c_{ij} : travel costs between all nodes
M : large constant

The objective function (7.50) minimizes the costs of the set of vehicle routes considering transport costs from i to j as well as fix costs for vehicle k, which occur for every vehicle leaving the depot in node *0* driving directly to any other node except *n+1*. Thereby, fix costs do not occur for vehicles staying at the depot, i. e. driving from node *0* to node *n+1*. Constraints (7.51) ensure that each customer is assigned to exactly one vehicle route. Constraints (7.52) enforce for each vehicle to leave the depot node *0* exactly once.

Furthermore, constraints (7.53) ensure that the vehicle capacity is not exceeded per tour. Constraints (7.54) are flow-conservation constraints to guarantee that a vehicle k only leaves a node that it has entered before. The constraints (7.55) ensure that each vehicle arrives at the depot node $n+1$ exactly once. The restrictions on traveling times and service times along the arcs $(i, j) \in A$ are enforced by constraints (7.56). Constraints (7.57) ensure that the time window for each customer is not violated and additionally forces w_{ik} to be zero, if vehicle k does not service customer i. The restrictions on the time window of the depot are depicted in constraints (7.58). Finally, equations (7.59) define the decision variable as binary.

Apart from introducing time windows into the VRP, other extensions are possible. These extensions address for instance a splitting of deliveries or the consideration of simultaneously delivering and collecting goods. Furthermore, multiple depots as well as vehicle reuse or the use of heterogeneous vehicles can be considered and stochastic elements can be introduced to the VRP. For an overview on extension of the VRP it is referred to (Asbach 2008; Cardeneo 2005).

If one wants to use the VRPTW to model pickups instead of deliveries, the model can be used without alterations. The conceptual difference is that a vehicle leaves the depot empty and returns back loaded. The constraints on the capacity of the vehicle and on the demand of the customer, now denoted as amount of material, remain the same.

7.6.2 Multi day vehicle routing problem with time windows

In the former model it is assumed, that vehicles leave the depot and return back to the depot at the same day. However, in (de-)construction projects it might be possible, that the material requested to be picked up during one day does not lead to reasonable capacity utilization or, even worse, when for instance n construction sites have to be serviced at n different days. A tour would then comprise only one customer at a day and result in high underutilized vehicle capacities.

A rather simple solution after receipt of all orders would be to rearrange them and bundling them in order to service all of them at a particular day. However, this would require additional organizational effort for calling and rearranging the orders of the construction contractors and the cooperativeness of the construction contractors. To avoid this organizational effort after the receipt of orders, the WMC could define particular days on which a collection might take place in advance. These days are known to the construction contractors who then place orders with the amount and time window at which the pickup of this particular material can take place. In both cases, the VRPTW could be applied again.

However, externally set collection intervals by the WMC might not always be feasible considering that hazardous material might not be allowed to be stored on site for long periods or that valuable materials should be collected as soon as possible to prevent thievery. Also clients might be upset if the WMC tries to change set orders afterwards.

Concluding, for valuable or hazardous material accumulating in such low amounts that a significant high number of customers would have to be serviced during one day to utilize the vehicle capacity, client's orders tend to differ in day. To avoid rearranging effort and strict requirements for the collection intervals the WMC could ask the contractor to define various different time windows during which a collection would be possible. On the one hand, the customer could still decide at which time intervals the collection might take place and on the other hand the WMC gets the opportunity to arrange the tours themselves according to the delivery options for each contractor.

However, the idea of introducing multiple time windows per customer is not new. Models have been introduced in (Cordeau et al. 2002) and an additional extension considering various delivery locations in accordance with various time windows is given in (Cardeneo 2005). However, in these models, the time windows are distributed over one day only. With this respect, multiple time windows have primarily been discussed in the period VRP (PVRP) or multiperiod VRP where they comprise one full day. Within a given planning horizon T each customer must be visited a certain number of times (Cordeau et al. 2002). Therefore, a set of different visiting schedules is determined for each customer of which one has to be chosen (Christofides and Beasley 1984; Mingozzi 2005; Tan and Beasley 1984). For the underlying planning problem, however, it is possible to allocate the time windows as defined in the VRPTW and the related amount of material to different days of the planning horizon.

In the following, an integrated approach for the VRPTW is developed, where in contrast to the assignment of multiple time windows to a contractor at one day, these time windows can be assigned to various days at which a pickup could take place. The resulting problem is called multi day vehicle routing problem with time windows (MDVRPTW). Therefore, the single day VRPTW is merged with the PVRP.

In the MDVRPTW it is assumed, that each contractor only assigns at most one time window to one day. In contrast to the PVRP, the contractor only requests service *once* during the planning horizon $t=1,\dots,T$. Thereby, the contractor will not necessarily need to assign a time window $[a_{it},b_{it}]$ to each day of the planning horizon if service on a particular day is not possible. Contrary, a time window has to be assigned to the depot by the WMC to each day of the planning horizon.

For the MDVRPTW, a new decision variable x_{ijkt} has to be introduced.

$$x_{ijkt}: \begin{cases} 1 & \text{, if arc } (i,j) \text{ used by vehicle } k \text{ at day } t \qquad (i,j) \in A, k \in K \\ 0 & \text{, else} \end{cases}$$

With the underlying assumptions, the MDRPTW (7.60)–(7.69) is modeled as an extension of the VRPTW (7.50)–(7.59):

$$MIN \quad \sum_{t \in T} \sum_{k \in K} \sum_{(i,j) \in A} c_{ij} \cdot x_{ijkt} + \sum_{t \in T} \sum_{j \in \Delta^+(0) \setminus \text{n+1}} x_{0jkt} \cdot c_k \tag{7.60}$$

subject to

$$\sum_{t \in T} \sum_{k \in K} \sum_{j \in \Delta^+(i)} x_{ijkt} = 1 \qquad \forall i \in C \tag{7.61}$$

$$\sum_{t \in T} \sum_{j \in \Delta^+(0)} x_{0jkt} = 1 \qquad \forall k \in K \tag{7.62}$$

$$\sum_{i \in C} d_i \sum_{j \in \Delta^+(i)} x_{ijkt} \le Q \qquad \forall k \in K, t \in T \tag{7.63}$$

$$\sum_{i \in \Delta^-(j)} x_{ijkt} - \sum_{i \in \Delta^+(j)} x_{jikt} = 0 \qquad \forall k \in K, \forall j \in C, t \in T \tag{7.64}$$

$$\sum_{t \in T} \sum_{i \in \Delta^-(n+1)} x_{i.n+1,kt} = 1 \qquad \forall k \in K \tag{7.65}$$

$$w_{ikt} + s_i + t_{ij} - M\left(1 - x_{ijkt}\right) \le w_{jkt} \qquad \forall k \in K, \forall (i,j) \in A, t \in T \tag{7.66}$$

$$a_{it}\left(\sum_{j \in \Delta^+(i)} x_{ijkt}\right) \le w_{ikt} \le b_{it}\left(\sum_{j \in \Delta^+(i)} x_{ijkt}\right) \qquad \forall k \in K, \forall i \in C, t \in T \tag{7.67}$$

$$E_t \le w_{ikt} \le L_t \qquad \forall k \in K, \forall i \in \{0, n+1\}, t \in T \tag{7.68}$$

$$x_{ijkt} \in \{0,1\} \qquad \forall k \in K, (i,j) \in A, t \in T \tag{7.69}$$

In case, the (de-)construction contractor does not want to be serviced at a particular day, the related time window is modeled as $[a_{it}, b_{it}] = [0,0]$ to enforce a violation of constraints (7.67) for that particular day.

As it is a special case of the underlying problem that every customer only requests service once during the planning horizon in the MDVRPTW, modifications are necessary, if a contractor needs several collections during T. This modification refers to the modeling of the contractor as input variable for the model. Thereby, for every collection necessary at contractors site a new contractor *i* is generated which is assigned a particular time window and amount of material to be collected.

An example for the modeling of time windows for a contractor *i* who requests three pickups during 10 days is given in Table 14. Thereby, the first pickup has to take place either on day 2 between t=7 and t=9 on day 3 between t=1 and t=4, the second pickup has to take place on day 6 between t=10 and t=11 and the third pickup can take place either on day 9 between t=8 and t=9 or on day 10 between t=6 and t=8.

If the additional condition holds, that a particular type of usually hazardous material is prohibited to be stored on site longer than a given period of time, the model has to be extended by collection interval combinations defining how often a construction contractor has to be serviced during the planning horizon, like in the PVRP. For this case, the assumption of only one visit during the planning horizon of the MDVRPTW has to be released and the model has to be modified according to formal description given for the PVRP with multiple time windows, e. g. (Cardeneo 2005).

Table 14: Example: Modeling of 3 pickups at one customer in the MDVRPTW

t		1	2	3	4	5	6	7	8	9	10
1. pickup	$[a_{1t},b_{1t}]$	[0,0]	**[7,9]**	**[1,4]**	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]
2. pickup	$[a_{2t},b_{2t}]$	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	**[10,11]**	[0,0]	[0,0]	[0,0]	[0,0]
3. pickup	$[a_{2t},b_{2t}]$	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	**[8,9]**	**[6,8]**

The model could be further extended to incorporate for instance, multiple depots (e. g. Cordeau et al. 1997; Federgruen and Simchi-Levi 1995; Mingozzi 2005), split pickups or two level recovery networks with integrated warehouses or handover points. However, for the description of reverse logistic tasks in construction, the introduced model covers the main aspects of the planning problem. Due to the complexity and also unique character of the planning situation every time an order arrives, the effort for a more detailed planning would be not justified by the outcome. Furthermore, the complexity of the model significantly influences the availability of efficient solution procedures. The VRP is known to be an NP-hard problem. Hence, it is implied that also its generalizations are NP-hard as containing the VRP as underlying problem (e. g. Larsen 2001, 10). Concluding, it is not just a matter of how to model the problem, but how to solve the problem with real world instances.

7.7 Waste management company's inventory routing problem for low volume material

Having discussed the case that the WMC is given collection intervals by the contractor, the second case addresses the WMC who is assigned the full responsibility to for the collection of material, i. e. it has to monitor the material accumulation on site and decide on its own, when to pick up the material and in which order it has to service the client. Therefore, the storage space on site has to be considered as well, unlike for the VRPTW formulation where this was in charge of the construction contractor.

Regarding the forward supply chain in the traditionally manufacturing industries a practice called VMI replenishment has been adopted by many companies for similar issues, as discussed in section 5.2.2.2. In VMI the vendor takes over the inventory control at its customer's warehouses and decides upon the time and amount of replenishment of inventory at each customer; i. e. the vendor decides on the replenishment policy for each retailer. Applications of VMI can be found in logistics in the petrochemical and industrial gas industry (Federgruen and Simchi-Levi 1995, 336). In reverse logistics in construction, the WMC as collector monitors the material accumulation on site, servicing multiple construction sites or construction contractors, and decides on the pickup policy for the particular pool construction sites it has to service. The WMC then has to solve a material-routing problem and can, in contrast to the collection problem from the contractor's perspective, organize a more efficient resource utilization. Hence, the benefits of the application of VMI are twofold. On the one hand, the collector can decide on the routing of its vehicles while reducing the transportation costs through a better capacity utilization of its vehicles. On the other hand, the construction contractor has to spend fewer resources on monitoring material accumulation on site and placing orders for pickup in order to guarantee that storage space on site is not exceeded, similar to the control of inventory levels in traditional manufacturing (e. g. Archetti et al. 2007, 382). Instead, the WMC monitors material on site and if the deconstruction project progress is disturbed and material accumulation does not match forecasted amount, the WMC has to cope with it.

An important differentiation is to be made between manufacturing and construction: While the VMI problem is applied to long term partnerships in the manufacturing industries with set maximum inventory levels and a periodic schedule, in construction applied to C&D waste collection it refers to short term planning problems due to the project character of the construction industry and the generation of one time schedules. A problem formulation used to solve the integrated inventory and distribution problem of VMI is the IRP, the Inventory Routing Problem. For further reading it is referred to relevant literature given, for instance, in (Archetti et al. 2007, 382; Bertazzi et al. 2002; Campbell et al. 2002; Federgruen and Simchi-Levi 1995).

The IRP is concerned with the repeated distribution of a product from a single facility to a set of customers over a given planning horizon. Each customer consumes the product at a given rate and has a known capacity to maintain a local inventory of the product. The IRP combines a routing problem from a central depot with customer inventory control. Customers are characterized by a daily usage rate of a product and a local storage capacity, and must be supplied before they run out of stock. In the IRP, like in the PVRP, a routing problem with a subset of customers is solved on each day of a planning horizon. However, unlike the PVRP, the solution is not static and must be recalculated periodically for each consecutive planning horizon.

For the collection of material applying the concept of VMI the IRP could be applied if storage space on site is set low enough to ensure quick collection. Nevertheless, for reasons of security and to prevent thievery, the application of the MDVRPTW with time windows seems to be more reasonable to avoid long waiting times at the site. However, if a model for vendor managed inventory routing in material collection is to be developed, reference can be made, for instance, to (Archetti et al. 2007).

7.8 An approach for integrated project and vehicle routing planning

Applying the introduced models for the organization of reverse logistic operations in (de-)construction projects, one would assume that the planning problem has been tackled successfully. However, problems occur, if the solution, which is based on the results of the project scheduling, is infeasible. In contrast, these two planning decisions are usually considered isolated from each other.

From the starting and finishing times of the project schedule the waste accumulation function and time windows for the collection can be derived. However, the application of the extensions of the VRPTW can be limited if the number of available vehicles at the WMC's place is not sufficient. On the one hand, the WMC could try to raise additional resources in terms of vehicle capacities. If this is not possible, on the other hand, a negative feedback would be given to the contractor who than has to find alternative solutions for the collection of valuable and hazardous material. Either the contractor is able to find other companies ready to collect its material or he has to reschedule the project in accordance to the available vehicles. Therefore, the WMC has to give information on the number and related capacities of the vehicles to the contractor.

To reschedule the project in accordance to the vehicle availabilities the in Figure 35 depicted process is proposed. Thereby, to process the activity *reschedule project*—highlighted with the grey circle—a further disaggregation has to take place:

1. Separation of project activities: at time *t* at which a collection would have taken place according to initial schedule if material has to be collected while the activity is still in progress. It is neglected, however, that some activities might not be allowed to be interrupted due to technical reasons, for instance, painting.
2. Introduction of additional collection activities: with smallest possible duration > 0 at original collection time into the network, not violating current precedence relations.
3. Assignment of resource consumption to collection activities: in terms of vehicle capacities of the renewable resource *vehicle*; i. e. treatment of vehicle capacities as renewable resource in the RCPSP, assuming that the RCPSP is used for project scheduling.
4. Reschedule.

Rescheduling the project, the contractor can again make use of one of the various extensions of the RCPSP as introduced in section 4.2. Thereby, rescheduling the project it is either sped up if additional resource consumption is possible, delayed behind its original finish if sufficient resources are not available for schedule adjustment without compromising the original solution or the current project finish is maintained. Extensions of the RCPSP which could be used would be the TCPSP (minimization of additional resource consumption) or the MMRCPSP (minimization of project finish or cash flows), in dependency on the objective function.

The same integrated proposed approach can also be applied for material procurement in construction projects. A material procurement would become necessary if the material or component supplier cannot deliver within the given time horizon and project activities would have to be shifted according to material availability on site. Thereby, it is strived for short storage periods of material on site due to on-site congestion, deterioration or thievery; i. e. a consumption of material and components shortly after delivery to the site.

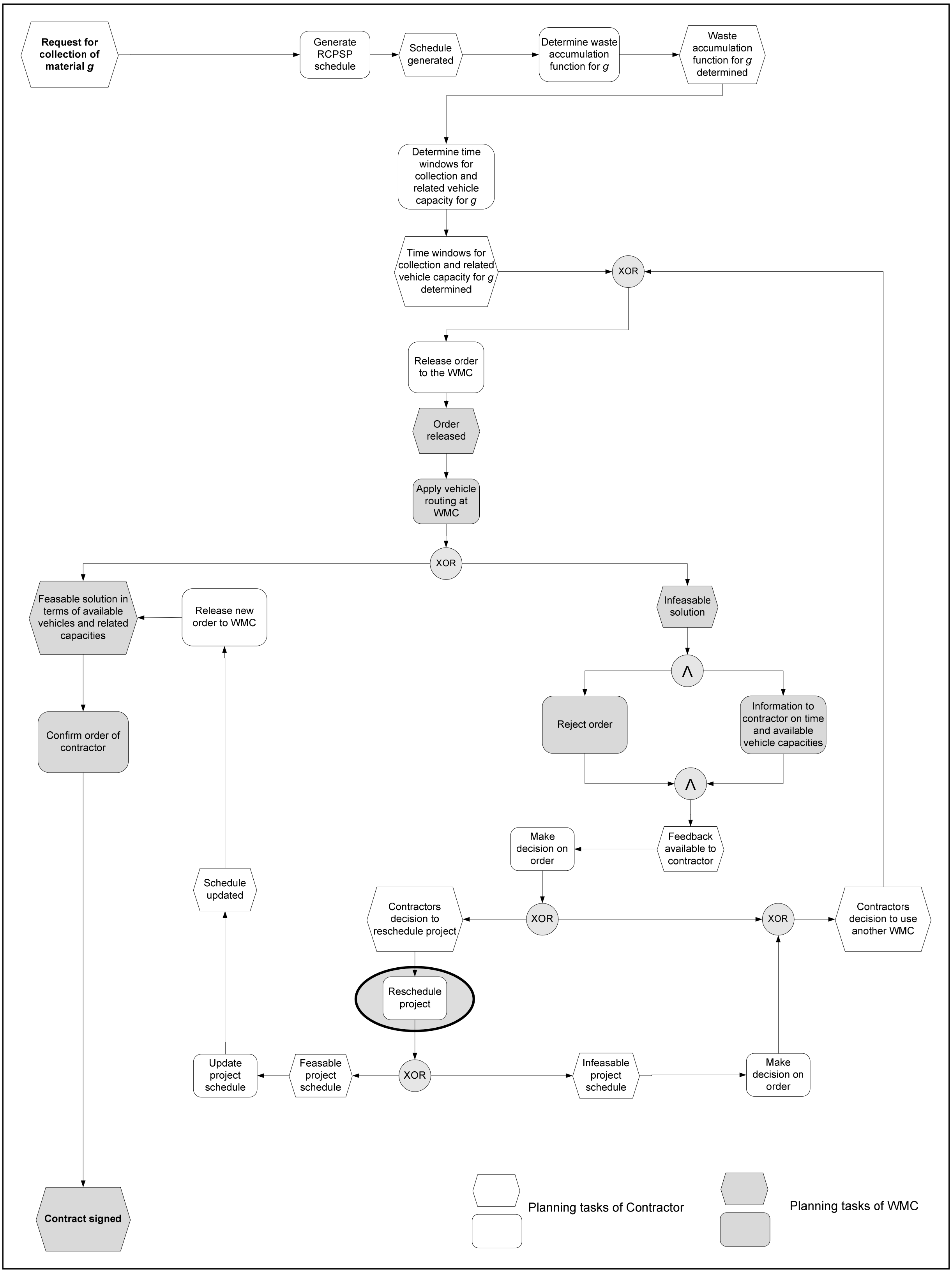

Figure 35: Integrated project scheduling and vehicle routing approach

7.9 Discussion of results

Reverse logistic aims at the establishment of closed-loop supply chains and was addressed with respect to logistic activities of arising material from (de-)construction projects which needs to be collected from the (de-)construction site and transported to recovery facilities.

Logistic activities arise for the delivery but also for the collection of bulk material as well as for valuable and hazardous material. For these materials different optimization models have been developed for the contractor as well as for the WMC. The objective is the minimization of collection costs for the contractor as well as for the WMC. Thereby, the general appropriateness of the application of optimization models for 'forward' logistic operations in construction has been highlighted in a case study undertaken at the University of Siegen using multi-criteria variation and linear referencing from geographic information systems (GIS), where a decrease in distances traveled up to 41 % was reported (Schumann 2008). Similar results are expected to occur for reverse logistic operations.

Keeping in mind, that reveres logistic operations take place based on the project schedule the feasibility of the project schedule in terms of available resources for project execution and for processing reverse logistic activities can be ensured by using an integrated project and vehicle routing planning approach. With the integrated approach, project performance in terms of schedule reliable, as addressed in section 3.2.2, can be ensured.

If uncertainties in project progress should be considered additionally, approaches from reactive scheduling could be applied for sub-projects according to project progress. Hence, the integrated project planning and vehicle routing approach could be extended for the separate treatment of sub-projects. In doing so, it would also be possible to separate routing decisions for bulk material from those for low volume material.

8 Energy-oriented end-of-life management

After having introduced several models for the planning of reverse logistics operations in construction in section 7, this section focuses on energy efficiency in construction. At first, the role of energy efficiency in construction is discussed. In the following, an integrated deconstruction-recovery model for deconstruction project planning is developed to include ecological as well as economic benefits. Based on a life cycle energy analysis, recovery options can be selected for deconstructed components and materials dependent on the chosen deconstruction techniques (e. g. demolition, selective deconstruction, manual deconstruction, and deconstruction using various resources). Thereby, a measure called energy-savings value (ESV) that is based on life cycle energy analysis (LCEA) is derived. This measure aims at the evaluation of the environmental impact of product recovery and allows a comparison of the use of recovered components and building materials with the production of components and building materials from primary resources. The ESV is used in a MMRCPSP model, an extension of the RCPSP discussed in section 4.2, to determine a project schedule and related deconstruction techniques such that the best possible environmental and economic benefit in terms of energy efficiency is achieved. Therefore, the MMRCPSP considering just time- and resource-resource trade-offs is extended to additionally incorporate energetic issues as energy-time-resource trade-offs. These energy-time-resource trade-offs reflect the realization of energy savings or costs over the life cycle of a building.

8.1 The role of energy efficiency in construction

The impact of construction on the environment originates from the resource extraction and the production of construction materials, the nature of the design of the houses, the construction methods, the location and layout, as well as from energy consumption. Energy consumption is steadily increasing caused by (Langston and Langston 2008; Ofori 1992):

- The production and use of energy intensive materials, for instance, high strength concrete, aluminum, and stainless steel,
- larger buildings,
- more frequent refurbishment cycles,
- higher machine utilization in construction processes in terms of the operation of plant equipment on site,
- higher machine utilization in terms of running of machinery in completed buildings, heating or cooling, as well as
- higher transportation effort for the movement of equipment, materials, and components to and between sites.

This means, that the construction industry is not only characterized by:

1. A high and diverse amount of materials employed and a huge amount and heterogeneous mix of C&D waste as tackled in section 7 under the aspect of reverse logistics, but also by
2. a high energy intensity.

Due to the high energy consumption of the construction industry the call for energy efficiency arises. In order to regain the materials and energetic value inherent in construction materials and components, the establishment of closed material cycles, i. e. the circuitry of construction materials, should be a major effort in the construction industry. However, activities to encounter the problems related to the construction industry are limited to reactive behavior, i. e. rather trying to respond to occurring damages than avoiding them. Following the principles of *construction ecology* (Kibert et al. 2002), a shift from reactive to proactive behavior needs to take place, in order to decrease the negative environmental impacts of the construction industry.

Especially focusing on the potential of realizing energy savings during deconstruction, an approach for the recovery of building materials has to be developed that covers the whole life cycle of a building. This life cycle includes the extraction of raw materials, the manufacturing of components and materials, the construction, occupation, and deconstruction to enable closed-loop material flows under consideration of energetic aspects.

8.2 Energetic evaluation of product reuse and recovery

The application of deconstruction techniques in a deconstruction project depends on the availability of usually scarce resources, such as workers, cranes, or other construction equipment. Existing project planning approaches neglect issues like recovery planning for deconstruction projects (see sections 3.2 and 4.2). In order to plan a deconstruction project and select suitable techniques to enable the best possible energy savings in material treatment and recovery, an integrated deconstruction-recovery planning approach has to be developed. However, the integration of recovery options for EOLPs requires a quantifiable measure of recovery benefit of the various recovery options, such as the ESV. For the ESV, information about energy consumption of recovered components and materials as well as energy consumption for primary building materials and components is required.

The method assessing the lifetime building energy is known as LCEA, which is a deduced form of LCA (Fay et al. 2000). The energy of a building can be measured as, for example, emergy (e. g. Brown and Buranakarn 2003; Odum 1988; Odum 2002; Pulselli et al. 2007) or embodied energy (e. g. Fay et al. 2000; Treloar et al. 2001; Venkatarama Reddy and Jagadish 2003).

Emergy is a measure for comparing energy flows of different kinds (e. g. labor, solar energy, raw materials) used in direct and indirect processes to generate a particular flow or product, measured in solar emergy joules (*sej*). The different energy flows are converted to a common basis by using transformation and are measured in (*sej/J)* (e. g. Odum 1988; Odum 2002). In contrast, embodied energy, measured in joule per unit (e. g. J/kg, J/m^2), only considers direct energy flows abstracting from workforce, pollution, the energy needed for the production of raw materials in nature, etc. For illustrative purposes in this thesis the measure of embodied energy, *EE*, of a building, its components, and materials is used to analyze the circuitry of building materials while being aware of the apparent simplicity of this measure.

According to Fay et al. (2000) the life cycle energy, LCE, of a building comprises the initial embodied energy, recurrent embodied energy, and operational energy over its lifetime T. The initial embodied or primary energy, $EE_{initial}$, is understood as the energy for manufacturing the building materials and includes energy for the extraction of raw material, transport, and manufacturing, and the final assembly on-site in construction processes (Fay et al. 2000; Thormark 2000). The recurring embodied energy, $EE_{recurring}$, of a building addresses the effort spent in the maintenance, repair, and replacement of materials and components by assigning replacement rates and adding the initial embodied energy of the component or material every multiple of the replacement period[32]. Finally, the operational energy, $E_{operational}$, of a house is the energy used for the operation of the house, e. g. heating or lighting (Fay et al. 2000; Treloar et al. 2000). Additionally, and for the purpose of the development of the integrated deconstruction-recovery planning model, deconstruction and recovery embodied energy, $EE_{dec+rec}$, is added to the life cycle energy of a building. The deconstruction and recovery energy of a building is the energy effort for deconstruction activities and the related recovery of the components and building materials. Hence, the life cycle energy of a building comprises the energy to extract and transport raw materials, the energy consumption in the production of building materials (e. g. steel and cement), the manufacturing of components, their distribution to the site, the energy spent in the construction process, during occupation and maintenance, as well as that for deconstruction, recovery, and final disposal.

For the evaluation of the advantageousness of a recovery option in comparison with the use of primary components and materials, the LCE of a building has to be divided into the LCE of its components and materials. Therefore, the following assumptions have to be made. As the recovered material is usually of a different type and quality than the originally deconstructed

[32] For an overview on replacement periods for building components and related materials, see Mithraratne and Vale (2004).

component or material, the analysis has to focus on the comparison of the life cycle energy with the substitute from primary resources of the same type. Hence, for this analysis it is considered that the deconstruction and recovery embodied energy is assigned to the new user of the recovered or reused component or material. Having addressed $E_{operational}$ in the life cycle of a building, it is to note that this energy cannot be assigned to a component or material separately. In addition, for reasons of simplification it is assumed that for each recovery option only one component or material of specific type, quality and functionality can be produced. For instance, the recycling of glass: glass could be melted as well as shredded and used for different purposes. Both ways of recovery are related to recycling. The following discussion only considers one possible way of recycling and only a predetermined quality of the outcome, whereas the outcome only differs in quality but not in functionality with the primary component or material. This means that quality differences might change the durability, i. e. replacement cycles, but the functionality, e. g. insulation, is the same. Furthermore, the transportation energy is considered in as far as primary components and materials as well as recovered components and materials are distributed to the same warehouse before final distribution to the customer's site. Energy from the warehouse to the customer is not considered for reasons of comparison and because the transport distances to the construction site are unknown at the date of deconstruction planning and recovery. When calculating the recurrent embodied energy, only the replacement of parts is considered. It is assumed that replacement takes place with the same type of component or material and, hence, in constant replacement intervals. The annual occurring energy effort for maintenance activities is not considered. Furthermore, the transportation energy has to be added for every replacement. The transportation energy for replacement equals the transportation energy for erection, i. e. from the extraction of raw materials to the manufacturing plant to the warehouse, as well as for transport of deconstructed materials from the construction site to recovery facilities and finally to the warehouse.

Therefore, the life cycle energy, E^a, of a primary building component or material a, $a \in A$, A denoting the set of primary building components and materials, is calculated according to the following equation:

$$E^a = EE^a_{initial} + EE^a_{recurring} \qquad a \in A \qquad (8.1)$$

$$EE^a_{initial} = E^a_{extraction\ of\ raw\ materials} + E^a_{manufacturing} + E^a_{transport} + E^a_{erection} \qquad a \in A \qquad (8.2)$$

The life cycle energy, E^b, of the substitute b, $b \in B$, B representing the set of recovered building components and materials, is defined as:

$$E^b = EE^b_{initial} + EE^b_{recurring} \qquad b \in B \qquad (8.3)$$

$$EE^b_{initial} = EE^b_{dec+rec} + E^b_{recovery} + E^b_{transport} + E^b_{erection} \qquad b \in B \qquad (8.4)$$

Calculating the recurring embodied energy of a primary building component or material a or recovered building component or material b, the lifetime T of a building and the replacement periods of (recovered) building components or materials t^a, t^b, need to be known. Assuming that these periods remain constant, the recurring embodied energy can then be calculated as:

$$EE^a_{recurring} = EE^a_{initial} \cdot \left\lfloor \frac{T}{t^a} \right\rfloor \qquad a \in A \qquad \left\lfloor \frac{T}{t^a} \right\rfloor \text{ next smallest number } \in \mathbb{N} < \frac{T}{t^a} \qquad (8.5)$$

$$EE^b_{recurring} = EE^b_{initial} \cdot \left\lfloor \frac{T}{t^b} \right\rfloor \qquad b \in B \qquad \left\lfloor \frac{T}{t^b} \right\rfloor \text{ next smallest number } \in \mathbb{N} < \frac{T}{t^b} \qquad (8.6)$$

To calculate separately the embodied energy of building materials and components, for instance brick, copper, plastics, and heating installation, the hybrid embodied energy analysis method can be applied,[33] together with product quantities calculated with process analysis, and material energy intensities calculated determined with input-output analysis. The material energy intensities can then be multiplied by the product quantities, and summed up. A comprehensive example is given by Fay et al. (2000).

8.3 An approach for integrated deconstruction-recovery planning

Although deconstruction and recovery generally permit the decrease of demolition waste which would otherwise be land-filled or incinerated, it can cause pollution and resource use which would not have occurred if the recovery of components and materials had not been processed. Hence, the various recovery options have to be weighted against the use of virgin raw or primary materials, and perhaps final disposal has to be preferred to recovery for the sake of environmental preservation when comparing the energy savings of the options. As the

[33] For more information on the determination of embodied energy, see Fay et al. (2000).

recovery of components and materials and, thus, the recovery of the inherent embodied energy depends on the deconstruction technique, deconstruction techniques have to be assessed for their ability to supply components and materials in a quality sufficient for the recovery purpose after the determination of environmental beneficial treatment of deconstruction waste.

8.3.1 Project planning with energy-time-resource trade-offs

Project planning using the MMRCPSP model, as introduced in section 4.2.2, it is solely possible to plan (de-)construction projects under resource constraints and with time and cost objectives. The next step is to shift the focus to recovery options. As already stated in section 6.2.2, the recovery of components and materials significantly depends on the deconstruction technique applied, e. g. demolition, selective deconstruction, deconstruction, referred to as modes m in the model. Currently, each activity j in mode m is assigned a deterministic duration, d_{jm}, as well as resource consumption, q_{jmr} and q_{jmn}. Taking the recovery of deconstructed components and materials into account, energy-time-resource trade-offs become evident and an additional variable, representing the ESV, is assigned to each activity mode m. This variable is denoted as ESV_{jm} and determines how much energy can be saved applying activity j in mode m by recovering the components and materials affected by that activity and the associated deconstruction technique and recovery option, $w=1,...,W$ (Figure 26)[34] instead of producing the material or component from virgin raw or primary materials. Hence, ESV_{jm} has to be calculated for each activity and assigned deconstruction technique separately dependent on the affected components and materials b as well as their purpose after recovery.

The ESV_{jm}^{bw} per component or material b in dependency on the recovery option w is calculated using:

$$ESV_{jm}^{bw} = E_{jm}^{aw} - E_{jm}^{bw} \qquad j=1,...,J;\ m=1,...,M;\ a \in A;\ b \in B;\ w=1,...,W \tag{8.7}$$

The quality[35] differences between the recovered material and its substitute from primary materials are considered in the term of recurring embodied energy ($EE_{recurring}^{aw}, EE_{recurring}^{bw}$), as discussed above.

[34] In Figure 26, eight options have been introduced, i. e. *W=8*.

[35] Quality here refers to the life-time expectancy of the material or component which is directly related to its replacement periods.

The field of application of the recovered material depends on the recovery options w. Concluding, the ESV_{jm}^{bw} may vary in dependency on the recovery option. This means that for a determined deconstruction technique, suitable recovery options W have to be analyzed in terms of their contribution to ESV_{jm}^{b}. Finally, the recovery option w has to be chosen with the highest ESV_{jm}^{bw} and be assigned as ESV_{jm}^{b} to component or material b. If a component or material has a negative ESV_{jm}^{bw}, recovery is disadvantageous in comparison with the use of primary materials. In this case, the ESV_{jm}^{bw} is set to zero. The deconstructed components and materials are land-filled or incinerated, assuming that the energy effort for land fill or incineration does not exceed the additional energy effort for recovery. Finally, the ESV_{jm} is the sum over all ESV_{jm}^{b} of components and materials. The assignment of the energy-saving values to the jobs and their modes is presented in Figure 36.

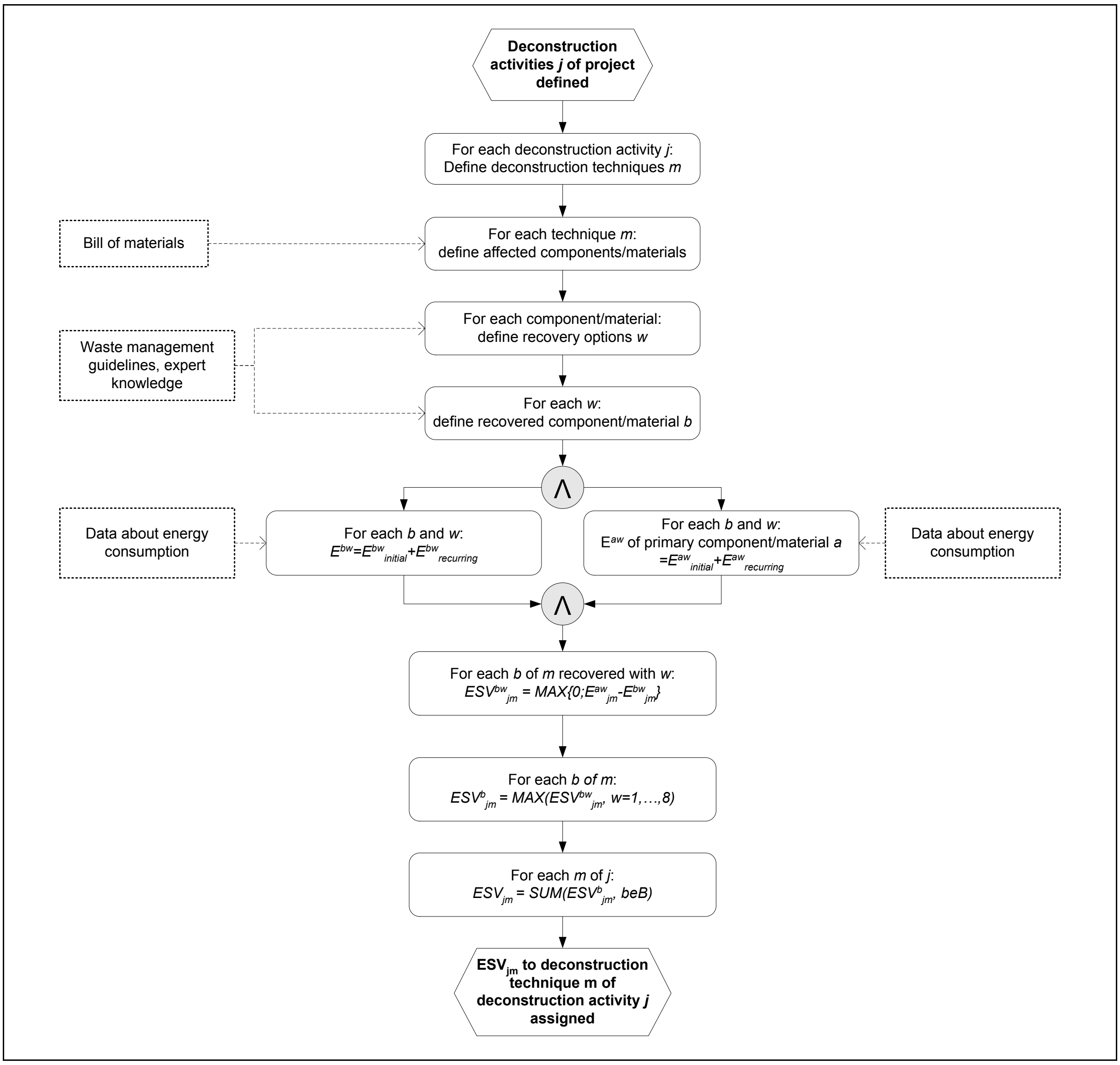

Figure 36: Assignment of the *ESV* to job *j* in mode *m*

An ESV^{b}_{jm} or ESV_{jm} does not necessarily have to be assigned to every component or material, nor to every activity. Certain activities underlay common practice or are subject to strict legislation. Common practice activities address, for instance, the deconstruction of electronic appliances and their disposal at the producer's facilities. Legislation regulates, for instance, the treatment of hazardous substances and employment protection for exposure to asbestos. For these activities no freedom of choice of a deconstruction technique is given and the treatment of materials has to be realized according to legal requirements.

8.3.2 Integrated deconstruction-recovery model

The integrated deconstruction-recovery model for project planning is an extension of the MMRCPSP (equations (4.18)–(4.23)) discussed in section 4.2.2. The MMRCPSP is extended by introducing energy-time-resource trade-offs as discussed above. The objective of the extended MMRCPSP (EMMRCPSP) is to find a project schedule such that the highest energy saving is achieved in the recovery of components and materials in comparison with the use of prime materials.

Thereby, the ability for recovery depends on the deconstruction technique denoted as mode *m*. Hence, an ESV_{jm} is assigned to every mode *m* of a deconstruction activity *j*. Furthermore, the execution of a deconstruction technique depends on the renewable and non-renewable resources available. These restrictions are already contained in the MMRCPSP. Without modifying the constraints of the MMRCPSP the objective function of the EMMRCPSP is written as:

$$MAX \quad \theta = \sum_{j=1}^{J} \sum_{m=1}^{M_j} ESV_{jm} \tag{8.8}$$

The new objective function (8.8) maximizes the total energy savings of a project if the components and materials are recovered after deconstruction according to the selected deconstruction technique under precedence and capacity constraints. Adherence to project milestones and the project deadline is ensured by calculating proper time windows for each deconstruction activity. Adherence to the project budget is modeled as non-renewable resource whose capacity is not allowed to be exceeded due to the capacity constraints on non-renewable resources.

The objective of maximizing total energy savings is an environmental-driven objective which cannot be assigned to a specific project partner or stakeholder of the deconstruction project. Generally, project participants follow economic objectives apart from budget adherence, e. g. cost minimization or profit maximization. A simple way to consider the monetary objective of a construction operator responsible for the deconstruction project is to calculate its overall costs for deconstruction and disposal as well as gains from selling valuable materials to the operators of recovery plants. These costs are associated to each technique *m* of a deconstruction activity *j* and are defined as:

$$C_{jm} = c_{deconstruction}^{jm} + c_{disposal}^{jm} - r_{sale}^{jm} \tag{8.9}$$

with

c_{jm}	:	total costs for deconstruction activity j performed in mode m
$c_{deconstruction}^{jm}$	:	costs for deconstruction activity j performed in mode m
$c_{disposal}^{jm}$	:	costs for all disposed of deconstructed components and materials of deconstruction activity j performed in mode m
r_{sale}^{jm}	:	revenue for all sold valuable deconstructed components and materials of deconstruction activity j performed in mode m

Concluding, the cost-oriented objective function of the construction operator can be written as:

$$MIN \quad \theta = \sum_{j=1}^{J} \sum_{m=1}^{M_j} C_{jm} \tag{8.10}$$

If one wants to consider additional objectives simultaneously, such as earliest project finish or leveled resource consumption, approaches from MCDM have to be applied, which is, however, not within the scope of this thesis.

The EMMRCPSP model comprises an objective function (8.8) which relates to the aims of sustainable construction, e. g. the preservation of natural resources, the reduction of pollutants and the decrease of energy consumption. Its application in practice would not only just help to increase the amount of recovered components and materials, but also to select the best possible recovery options and deconstruction techniques. Objective function (8.10) can additionally be considered if a particular interest in terms of costs of a general contractor or another participant is to be achieved.

8.4 Discussion of results

Especially during deconstruction projects, the sustainability of the construction industry could be increased by focusing not only on material issues, but expanding the view to energetic aspects of deconstruction processes and related C&D waste. Thus, an integrated deconstruction-recovery planning approach for deconstruction projects was introduced. Thereby, the relevancy of integrated deconstruction-recovery planning for two fields of research has been addressed:

1. Recovery strategies in construction and their relevance for deconstruction project planning, and
2. project planning using methods from operations research and criteria of sustainability such as the recovery of components and materials, which have not yet been incorporated in project planning approaches.

The integration of recovery aspects into deconstruction planning procedures based on the multi-mode resource-constrained project scheduling problem enables the consideration of ecological concepts, such as closed-loop structures or zero-waste strategies, as well as budget and time constraints. For this approach the ESV was introduced as an indicator for sustainability in terms of material recovery.

The MMRCPSP has already been proven to be successful for deconstruction projects achieving time and cost objectives. The practical significance of the integrated EMMRCPSP is seen for the design of sustainable construction supply chains and cooperation between its participants in order to realize overall benefits of the supply chain, especially under the focus of sustainability and reverse supply chains.

Despite the expected ecological as well as economic benefits of integrated deconstruction-construction planning the model underlies some limitations:

- The assumptions are made that a market and demand for recovered components and materials exists.
- Recovery options might not be reasonable if statutory provisions and regulations account for quality standards of products or materials for reasons of safety and reliability which cannot always be guaranteed for recovered products though they would realize higher energy savings.
- Besides the use of energy, other impact factors well-known from LCA approaches are not considered in the ESV.

- If a recovery option for a deconstructed component or material is chosen, more than just one recovered component or material could be produced. This is especially evident for recycled material, i. e. its purposes depend on the recycling technique. For instance, if deconstructed material is melted, shredded, etc. Thus, an extension of the model should respect that the substitute *b* is extended to a vector $B = b_1,...,b_n$.

To overcome these limitations future research will have to address the incorporation of additional ecological impacts besides energy use in the measure for the advantageousness of recovery. As the extension of the MMRCPSP leads to a higher complexity of the model and aggravates the efficient and unambiguous solvability of the model, future efficient solution procedures for the approach will have to be developed and be validated in case studies.

9 Summary and outlook

The construction industry, in contrast to the manufacturing industries, is characterized by an unstable and complex project planning environment. Moreover, construction still is an unsustainable industry, especially focusing on economic and ecological aspects of sustainability. From the economic perspective it was revealed that construction projects are often delayed and over budget, i. e. they suffer poor performance. Poor performance can be traced back to project planning procedures. Main causes for project failures are thereby insufficient scheduling with respect to resource allocation to project activities and the non-availability of material on-site at the time required. Methods applicable to tackle these deficiencies can be found in sophisticated project planning procedures taking resource limitations and the classification of project resources into account and in supply chain management (SCM) known from the manufacturing industries to increase material availability on site. Thereby, these methods had to be adapted to the particularities of the construction industry. With respect to the ecological dimension of sustainability, the construction industry can be regarded as major polluter to the environment due to its high construction and demolition waste accumulation and its high energy intensity. Numerous regulations and guidelines on the handling of construction and demolition (C&D) waste exist, and research has already been undertaken. Regulations mainly refer to the treatment of C&D waste. Research already undertaken addresses the development of methods for the recovery of C&D waste, especially from underground engineering, and architectural and design specifications, for instance, the use of environmentally sound materials, design for deconstruction, the use of renewable energies, and the design of passive houses. Lacks of knowledge exist especially when it comes to the organization of deconstruction projects as well as to the organization of related logistic activities, necessary to establish closed-loop material flows. For the ecologically end-of-life management of construction outputs, models for project planning introduced can be adapted to the particularities of deconstruction projects taking different recovery options in dependency on the deconstruction technique into account. For the organization of the logistic processes from the deconstruction site back to recovery facilities, formal descriptions taken from operations management help to structure and describe the related planning problems in detail.

To tackle insufficient scheduling practice, a resource classification scheme is introduced and a hierarchical project planning approach integrating both, common project planning methods such as the critical path method (CPM), the metra potential method (MPM) or the programme evaluation and review technique (PERT), and resource-constrained project planning approaches is developed. Thereby, the elaborated resource classification scheme is based on the ABC/XYZ inventory analysis from manufacturing and permits the characterization of resources as critical, risk-prone, or non-critical. Detailed planning—generally related to high planning effort—should be devoted to critical resources only to reduce planning effort. With respect to the resource classification, strategies are derived to reduce the criticality of particular resources and, hence, reduce uncertainties in resource availability. This scheme is not only a framework for resource allocation in construction project planning, but can easily be adapted to other project types and resources. Furthermore, it is reasonable to apply sophisticated project planning approaches, like the resource-constrained project scheduling problem (RCPSP), to critical resources to benefit from the improvement of schedule reliability due to the integrated time and capacity planning. However, due to its complexity, a sole application of resource-constrained methods results in inefficient and time consuming scheduling procedures. In response, a hierarchical project planning approach is introduced. Thereby, the appropriate integration of resource-constrained project planning into current project planning procedures in construction, i. e. a combination of the RCPSP and its extensions together with project planning methods such as CPM, MPM or PERT, could significantly increase the performance of construction projects. The proposed combination of both, 'traditional' as well as sophisticated project planning approaches raises the acceptance of more sophisticated planning methods by practitioners and supports the easy application of these usually hard to solve problem structures due to their high number of variables.

For the improvement of the efficiency of materials management in construction projects selected concepts for the design and operation of supply chains from manufacturing are adopted. Thereby, most SCM concepts which are suitable for mass production are applicable in construction by additionally considering shorter planning horizons and uncertain demand patterns. In particular, a step is taken towards the planning of the construction supply chain (CSC) by highlighting opportunities to apply, adopt and modify certain well-known SC techniques.

The high amounts of C&D waste accumulating lead to the request of closed-loop supply chains. Within closed-loop supply chains, waste management and reverse logistic are of importance. With respect to the C&D waste, distinguished into bulk as well as valuable and hazardous material, accumulating especially during deconstruction projects, a major challenge in C&D waste management is the efficient transport of these materials from the site to the recovery facility. Thereby, the processing of logistic activities depends on the project schedule. Various quantitative models for the collection of bulk as well as valuable and hazardous materials are developed. These models assist the construction contractor as well as the WMC to better allocate collection orders to collection times and vehicles subject to resource constraints in terms of storage space on site and vehicle capacity. Additionally, to ensure project performance in terms of schedule reliability an integrated project and vehicle routing planning approach is developed.

To encounter the energy intensity of the construction industry, it is focused on the recovery of C&D waste under energetic aspects. Thereby, the integration of recovery aspects into deconstruction planning based on the multi-mode resource-constrained project scheduling problem (MMRCPSP) enables the consideration of ecological concepts, such as closed-loop structures or zero-waste strategies, as well as budget and time constraints. For this approach the energy-savings value (ESV) is introduced as an indicator for sustainability in terms of material recovery. Thus, with the reverse logistic models as well as with the energy oriented deconstruction and recovery planning approach two instruments are given to decrease the negative ecological impacts of the construction industry.

Concluding, to tackle the problems of poor scheduling practices, insufficient materials management as well as the huge amount of C&D waste accumulation and the energy inefficiency of construction, new solution approaches for construction project planning are developed. These approaches adopt concepts taken from the manufacturing industries and set out new perspectives on the reorganization of common planning processes in construction.

The research undertaken in this work represents a combination of different approaches for selected planning problems in the construction industry. The empirical validation among practitioners could prove the direct benefits of the application of the developed new planning methods for construction practitioners by operationalizing their potential in terms of economic and ecological sustainability. Thereby, the empirical validation can be supported by implementing the developed approaches into a prototype of a decision making systems, especially with respect to the hierarchical planning approaches for project scheduling as well as for the integrated project scheduling and vehicle routing planning. Nevertheless, the proposed approaches rely on deterministic data. Aspects of project monitoring and control are not yet included. Thereby, problems faced during project progress might lead to schedule changes during project progress, and a rescheduling of the project would be necessary. On the one hand, this problem is tackled by introducing the hierarchical planning approaches for project scheduling and the integrated project and vehicle routing planning. On the other hand, quality of schedules might be improved by using concepts of reactive scheduling (Ahuja and Thiruvengadam 2004, 28). In this case, the empirical validation of the models could give valuable insights into interfaces for possible modifications.

Relating back to the life cycle of a building, the focus of this work lies on the phases of construction and end-of-life in terms of deconstruction and waste management. The phase of occupation is excluded. Here, approaches of facility management could be explored. In particular, these might address replacement strategies of building components (for instance Zhang and Yang 2006) as well as investment strategies for capacity expansions or the renovation of buildings.

Finally, the proposed approaches require IT support acting as disseminator and enabler for innovation in construction and for the exploration of possibilities to support project scheduling, material procurement and waste management. These technologies comprise, for instance, the application of radio frequency identification (RFID), Knowledge Management Systems, and Enterprise Resource Planning (ERP) Systems. In particular, this refers to the relationships between the material supplier and the contractor or sub-contractors for material procurement in terms of order processing, as well as between the project manager and the contractor or sub-contractors for project monitoring. Thereby, the optimization of the interfaces between the various partners of the construction supply chain and the extension of a common information system platform between all CSC partners will have to become focus of future research.

10 Zusammenfassung (German)

Die Bauindustrie ist einer der ältesten Industriezweige. Die wohl bekanntesten Beispiele für Bauprojekte sind die ägyptischen Pyramiden (3. Jahrtausend v. Chr.) sowie die Aquädukte zur Wasserversorgung von Städten und Produktionsstätten, wie z. B. Goldminen, welche ca. 300 v. Chr. im Römischen Reich erbaut wurden. Durch die Komplexität, die Anzahl und die Anordnung von Gebäuden, die Vielzahl bei Bauprojekten auszuführender (Planungs-)Aktivitäten sowie die heterogene Zusammensetzung der Bauwerke aus den unterschiedlichsten Baustoffen und Baumaterialien haben sowohl der Taylorismus als auch die Spezialisierung der Produktion schon früh Einzug in die Bauindustrie gehalten. Abgesehen von Bestrebungen zur Standardisierung der Bauindustrie im Sinne von Modulbauten oder Fertigteilhäusern, hat sich die Projektorganisation in der Bauindustrie für Jahrhunderte bewährt. Trotz ihres langen Bestandes zeichnet sich die Bauindustrie jedoch noch nicht durch eine hohe Nachhaltigkeit bezüglich der wirtschaftlichen, der umweltbezogenen sowie der sozialen Faktoren aus. Dabei gelten aufgrund der hohen Stoff- und Energieintensität die Bauindustrie und die durch diese induzierten Aktivitäten als zentraler Bestandteil künftiger Bemühungen zur nachhaltigen Entwicklung.

Die ökonomische Nachhaltigkeit wird insbesondere durch die Projektrisiken beeinflusst, denen die Bauindustrie durch ihre zeit- und kostenintensiven Produktionsprozesse ausgesetzt ist. Dabei werden nicht nur viele Projekte verspätet fertiggestellt, sondern haben auch Budgetüberschreitungen zu verzeichnen. Die Ursachen dieser Probleme liegen hauptsächlich in der Projektablaufplanung sowie den damit verbundenen Prozessen, wie beispielsweise der Materialbeschaffung, begründet. Zusätzlich zu den ökonomischen Unzulänglichkeiten ist die Bauindustrie für einen hohen Anteil an negativen Umwelteinflüssen verantwortlich. So ist sie Verursacher von ca. 30–40 % des globalen Energieverbrauchs und hat einen Anteil von 20–30 % an den Treibhausgasemissionen (UNEP 2007). Dieser Effekt wird darüber hinaus durch die großen Mengen an Bau- und Abbruchabfällen verstärkt.

Aufgrund vielfältiger Faktoren, wie beispielsweise der Notwendigkeit der Anpassung an örtliche Gegebenheiten, der persönlichen Präferenzen des Investors sowie vorhandener Infrastruktur vor Ort, ist die Bauindustrie durch ihre Individualität charakterisiert. Da die Projekte kundenauftragsgetrieben sind, handelt es sich in der Regel um den Bau von Unikaten, verbunden mit einer vornehmlich örtlich konzentrierten Produktion und hohen Investitionen, verursacht durch die Komplexität der Produkte.

Diese Eigenschaften bedingen, dass die Wertschöpfungsketten in der Bauindustrie um ein Vielfaches komplexer als die der traditionellen Fertigungsindustrien sind. Hinzu kommt eine unsichere Planungsumgebung sowie die Vielzahl von Interessenseignern an Bauprojekten, welche entsprechend ihrer Rolle und Zielstellung koordiniert werden müssen. Dies führt dazu, dass für architektonisch anspruchsvolle Bauten, aber auch für Straßen oder Tunnel nicht immer standardisierte Bauprozesse Anwendung finden können, um einen Wettbewerbsvorteil auf- und auszubauen. Daher ist es notwendig, anspruchsvollere Methoden für die Projektplanung und –kontrolle zu entwickeln, welche in diesen sogenannten design-to-order Planungsumgebungen eingesetzt werden können. Trotz dieser Notwendigkeit finden die Entwicklung und der Einsatz von Planungsmethoden zur Bewältigung der komplexen Planungssituationen in der Bauindustrie kaum Eingang in die Wissenschaft, da die Verallgemeinerung der Planungsansätze wegen des Individualcharakters schwierig ist. Stattdessen liegt der Fokus gegenwärtiger Forschungsarbeiten, die sich mit der Gestaltung von Wertschöpfungsketten befassen, überwiegend auf Fertigungsindustrien mit standardisierten Fertigungsprozessen. Für diese Industrien wurden bereits zahlreiche qualitative als auch quantitative Planungsverfahren entwickelt.

Ein wesentlicher Aspekt bei der Planung von Wertschöpfungsketten in der Bauindustrie ist eine angemessene Projektablaufplanung. Seit mehreren Jahrzehnten haben sich Methoden, wie beispielsweise die Critical Path Method (CPM), die Programme Evaluation and Review Technique (PERT) sowie die Metra Potential Method (MPM) oder Gantt-Diagramme, bei der Planung von Bauprojekten durchgesetzt. Trotz ihrer Verbreitung berücksichtigen diese Techniken jedoch die Komplexität der Planung von Bauprojekten nicht adäquat und sind daher vorwiegend für die Bestimmung von Zeitfenstern für die Ausführung von Projektaktivitäten geeignet. Die Probleme, welche bei der Planung von Bauprojekten beachtet werden müssen, reichen jedoch von der gleichzeitigen Ausführung mehrerer Projekte bis hin zu extern auferlegten Beschränkungen durch unterschiedliche Interessenseigner sowie gesetzlichen Regelungen, zum Beispiel zur Berücksichtigung von Umweltaspekten.

Als Ergänzung zu den in der Praxis eingesetzten Planungsmethoden, welche vornehmlich auf die wirtschaftliche Dimension der Nachhaltigkeit abzielen, existieren Richtlinien und Gesetze, die umweltrelevante Themen aufgreifen. Es erscheint jedoch mit der alleinigen Anwendung dieser Instrumente nicht möglich, den erwähnten Problemen in ausreichendem Maße zu begegnen. Alternativen, die als Ersatz bzw. als Ergänzung zu diesen Instrumenten angewendet werden könnten, stellen quantitative Ansätze dar. Dabei hat die Entwicklung quantitativer Ansätze für die Bauindustrie erst begonnen. Die Anwendungsreife dieser Ansätze ist jedoch noch nicht weit genug fortgeschritten, um einen umsetzbaren Beitrag zur Problemlösung darzustellen. Um die komplexe Planungsumgebung von Bauprojekten angemessen zu berücksichtigen, müssen daher höher entwickelte Ansätze entworfen werden.

Die Zielstellung dieser Arbeit ist es, zum einen neue Lösungsansätze für Planungsprobleme bei Bauprojekten zu entwickeln, indem in der Fertigungsindustrie verwendete Konzepte zur

Produktionsplanung an die Besonderheiten der Bauindustrie angepasst werden. Zum anderen sind neue Perspektiven für die Reorganisation gegenwärtiger Projektplanungsansätze aufzuzeigen. Während viele Forschungsarbeiten Planungsansätze für die Bauwirtschaft vorstellen, ohne den Blick auf andere Wirtschaftsektoren zu werfen, werden in der vorliegenden Arbeit bewusst Lösungsansätze, die erfolgreich für andere Industrien entwickelt und angewendet worden sind, einbezogen und modifiziert.

Um die bisherigen Mängel der Zeit- und Kostenüberschreitungen in der Projektplanung zu berücksichtigen, wird zunächst ein Schema zur Klassifikation von Projektressourcen entwickelt. Dieses Klassifikationsschema basiert auf der ABC/XYZ Analyse zur Güterklassifikation aus der Materialwirtschaft und dient zur Einteilung der Projektressourcen in kritische, risikobehaftete sowie nicht-kritische Ressourcen. Dabei sollte sich die detaillierte Projektplanung zur Reduktion des Planungsaufwandes auf kritische Ressourcen beschränken. Auf Grundlage dieses Klassifikationsschemas für Projektressourcen werden Strategien zur Verminderung der Risikoanfälligkeit bestimmter Ressourcen herausgearbeitet, um Unsicherheiten bei der Ressourcenverfügbarkeit zu reduzieren. Damit dient dieses Schema nicht nur als Instrument zur Ressourcenallokation in Bauprojekten, sondern universell für alle Ressourcen, welche in Fertigungsprozessen zum Einsatz kommen. Für kritische Ressourcen ist es weiterhin sinnvoll, fortschrittlichere Projektplanungsansätze mit integrierter Zeit- und Kapazitätsplanung, wie das kapazitierte Projektplanungsproblem (resource-constrained project scheduling problem, RCPSP), einzusetzen, um die Zuverlässigkeit des Projektplanes zu erhöhen. Durch die Komplexität von quantitativen Methoden führt jedoch die alleinige Anwendung des RCPSP zu ineffizienten und sehr zeitaufwendigen Rechenläufen. Um die Ineffizienz bei der Lösung derartiger Probleme zu kompensieren, wird ein hierarchischer Projektplanungsansatz entwickelt. Dabei kann die angemessene Integration von Methoden zur kapazitätsbeschränkten Projektplanung in herkömmliche Planungsverfahren den Projekterfolg erheblich steigern. Die in dieser Arbeit vorgestellte Kombination aus traditionellen und fortgeschrittenen Planungsansätzen erhöht sowohl die Akzeptanz solcher Ansätze unter Bauprojektplanern als auch deren Verfügbarkeit in der Praxis. Sie unterstützt somit die Anwendung dieser aufgrund der Vielzahl an Variablen sonst schwer zu lösenden Problemstrukturen.

Für die Verbesserung der Materialbeschaffung in Bauprojekten werden ausgewählte Konzepte des Wertschöpfungskettenmanagements, das sogenannte Supply Chain Management (SCM), aus den Fertigungsindustrien modifiziert. Dabei sind die meisten in der Massenfertigung angewendeten Konzepte des SCM auch auf die Bauindustrie übertragbar, wenn kürzere Planungshorizonte aufgrund des Projektcharakters und Unsicherheiten im Nachfrageverhalten beachtet werden. Mit der Anwendung dieser Konzepte in der Bauindustrie wird es möglich, die Materialverfügbarkeit bei gleichzeitiger Lagerkostensenkung zu erhöhen.

Für das Management von Bau- und Abbruchabfällen werden in dieser Arbeit sowohl Modelle für die Planung der Rückführlogistik als auch ein Ansatz zur energieorientierten Rückbau- und Verwertungsplanung entwickelt. Bei den eingeführten Modellen zur Rückführlogistik wurde zwischen Planungsansätzen für Massengüter und Planungsansätzen für hochwertige Materialien (z. B. Kupfer) sowie Sonderabfall unterschieden. Die vorgeschlagenen Modelle unterstützen dabei den Bauunternehmer und den Entsorger der Bauabfälle bei der Ermittlung von Zeiträumen für die Abholung sowie bei der Zuteilung von Entsorgungsaufträgen. Die entwickelten Ansätze berücksichtigen hierbei besondere Spezifika wie einen begrenzt vorhandenen Lagerplatz auf der Baustelle sowie eine begrenzte Kapazität von Transportfahrzeugen. Um den Projekterfolg auch bei unzureichenden Kapazitäten sicher zu stellen, wird zusätzlich ein integrierter Projekt- und Tourenplanungsansatz entwickelt.

Zur Berücksichtigung der Energieintensität von Bauaktivitäten wird exemplarisch ein Projektplanungsansatz für den Umgang mit Bau- und Abbruchabfällen entwickelt. Dieser Projektplanungsansatz integriert energetische Aspekte als Erweiterung des RCPSP mit mehreren Modi bzw. Ausführungsvarianten (Multi-mode resource constrained project scheduling problem, MMRCPSP). Somit ist es möglich, neben ökonomischen Zielen, wie beispielsweise der Kosten- oder Projektdauerminimierung, auch ökologische Kriterien bei der Projektplanung einzubeziehen. Dafür wird der Energy Savings Value (ESV) eingeführt. Der ESV ist eine Maßzahl, welche die Energieeinsparungen bei der Verwertung für Bau- und Abbruchabfälle im Gegensatz zum Einsatz von Primär-Ressourcen angibt. Das Ziel einer energieorientierten Vorgehensweise beim Rückbau von Bauwerken ist es, diejenigen Techniken auszuwählen, die eine in Abhängigkeit der zu wählenden Verwertungsoption ausreichend hohe Güte der rückgebauten Materialien und Komponenten gewährleisten. Mit den Modellen zur Rückführlogistik sowie dem energieorientierten Rückbau- und Verwertungsplanungsansatz werden zwei Instrumente geschaffen, die dazu beitragen, die negativen Umweltauswirkungen von Bauaktivitäten zu reduzieren.

Diese Arbeit repräsentiert eine Zusammenstellung neuer Lösungsansätze für ausgewählte Planungsprobleme in der Bauwirtschaft. Die Validierung dieser Lösungsansätze könnte den unmittelbaren Nutzen der neuen Planungsansätze für die Praxis herausstellen, indem die Potentiale bezüglich der ökonomischen sowie ökologischen Nachhaltigkeit operationalisiert werden. Die entwickelten Ansätze beziehen sich jedoch bislang überwiegend auf deterministische Daten. Zudem werden Aspekte der Projektsteuerung und -kontrolle nicht betrachtet. Dabei können während des Projektfortschritts Probleme auftreten, die zu Änderungen am Projektplan führen und damit eine Neuplanung des Projektes erforderlich machen. Dieser Umstand wird zum einen durch den in dieser Arbeit vorgestellten hierarchischen Projektplanungsansatz sowie den integrierten Ansatz zur Projekt- und Tourenplanung berücksichtigt. Zum anderen kann die Zuverlässigkeit eines Projektplanes auch durch den Einsatz von reaktiven Projektplanungsansätzen verbessert werden (Ahuja and Thiruvengadam 2004, 28).

Bei der Reorganisation bestehender Planungsabläufe in der Bauindustrie ist jedoch, neben der Entwicklung neuer, in dieser Arbeit vorgestellter Planungsansätze, auch die Ausgestaltung der Schnittstellen zwischen den Partnern der Wertschöpfungskette von hoher Bedeutung. Nur durch die effiziente Organisation der Beziehungen aller am Bauprojekt Beteiligten können die aufgezeigten Potentiale der in dieser Arbeit entwickelten Ansätze realisiert werden. Ziel weiterer Forschungsarbeiten ist daher, die aufgestellten Ansätze in der Praxis zu erproben und deren Praxistauglichkeit nachzuweisen, und damit die Reorganisation von Schnittstellen zwischen den Projektbeteiligten zur Steigerung der Effizienz von Bauprojekten als Forschungsgegenstand aufzugreifen.

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Appendix

Construction and demolition waste classification according to the European Waste Catalogue (EWC)

Table 15: C&D debris

EWC Code	Description
Construction and demolition debris	
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

Table 16: Road construction waste

EWC Code	Description
Road construction waste	
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	aluminum
17 04 03	lead
17 04 04	zinc
17 04 05	iron and steel
17 04 06	tin
17 04 07	mixed metals
17 04 09	metal waste contaminated with dangerous substances
17 04 10	cables containing oil, coal tar and other dangerous substances
17 04 11	cables other than those mentioned in 17 04 10

Table 17: Excavated earth

EWC Code	Description
Excavated earth	
17 05	**soil (including excavated soil from contaminated sites), stones and dredging spoil**
17 05 03	soil and stones containing dangerous substances
17 05 04	soil and stones other than those mentioned in 17 05 03
17 05 05	dredging spoil containing dangerous substances
17 05 06	dredging spoil other than those mentioned in 17 05 05
17 05 07	track ballast containing dangerous substances
17 05 08	track ballast other than those mentioned in 17 05 07
17 06	**insulation materials and asbestos-containing construction materials**
17 06 01	insulation materials containing asbestos
17 06 03	other insulation materials consisting of or containing dangerous substances
17 06 04	insulation materials other than those mentioned in 17 06 01 and 17 06 03
17 06 05	construction materials containing asbestos (7)

Table 18: Gypsum-based construction material

EWC Code	Description
Gypsum-based construction material	
17 08	**gypsum-based construction material**
17 08 01	gypsum-based construction materials contaminated with dangerous substances
17 08 02	gypsum-based construction materials other than those mentioned in 17 08 01
17 09	**other construction and demolition wastes**
17 09 01	construction and demolition wastes containing mercury
17 09 02	construction and demolition wastes containing PCB (for example PCB-containing sealants, PCB-containing resin-based floorings, PCB-containing sealed glazing units, PCB-containing capacitors)
17 09 03	other construction and demolition wastes (including mixed wastes) containing dangerous substances
17 09 04	mixed construction and demolition wastes other than those mentioned in 17 09 01, 17 09 02 and 17 09 03

Table 19: Construction waste

EWC Code	Description
Construction waste	
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 04	**metals (including their alloys)**
17 04 01	copper, bronze, brass
17 04 02	aluminum
17 04 03	lead
17 04 04	zinc
17 04 05	iron and steel
17 04 06	tin
17 04 07	mixed metals
17 04 09	metal waste contaminated with dangerous substances
17 04 10	cables containing oil, coal tar and other dangerous substances
17 04 11	cables other than those mentioned in 17 04 10
17 06	**insulation materials and asbestos-containing construction materials**
17 06 01	insulation materials containing asbestos
17 06 03	other insulation materials consisting of or containing dangerous substances
17 06 04	insulation materials other than those mentioned in 17 06 01 and 17 06 03
17 06 05	construction materials containing asbestos (7)
17 09	**other construction and demolition wastes**
17 09 01	construction and demolition wastes containing mercury
17 09 02	construction and demolition wastes containing PCB (for example PCB-containing sealants, PCB-containing resin-based floorings, PCB-containing sealed glazing units, PCB-containing capacitors)
17 09 03	other construction and demolition wastes (including mixed wastes) containing dangerous substances
17 09 04	mixed construction and demolition wastes other than those mentioned in 17 09 01, 17 09 02 and 17 09 03