Concept for a Planning and Decision Model for Logistics in Tunnelling using Supply Chain Management and Outranking

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Abstract

It is necessary to guarantee an optimal supply of all kinds of resources in construction production processes during the construction phase, including information in order to fulfil the requirements of optimal tunnelling logistics. This requires a systematic and holistic planning and decision model for logistics in tunnelling.

In this paper, a basic planning and decision model is introduced with the aim of a systematic development of an overall logistics system (OLS) in tunnelling. This OLS will be developed on the basis of Supply Chain Management (SCM) and is comprised of different partial logistics systems (PLS). These PLS (e.g. conveyor belt, trucks etc.) have to be defined for all different steps in the Supply Chain (SC) of all necessary resources (e.g. disposal of concrete, removal of construction waste etc.). After the definition of different PLS for each step, their merging to different OLS follows. Afterwards, a systematic decision making process (Outranking) identifies the optimal OLS out of all different OLS.

At the end of the paper, a short summary is provided as well as an outlook of how the presented model can be improved with additional parts.

Keywords: Tunnelling, Logistics, Supply Chain Management, Decision Making

1. Introduction

The idea of supply chain management (SCM) is based on efficiently dealing of limited resources as well as on holistic and network oriented logistics, structured by several demand and supply chains. The approach of logistics utilizing SCM achieved an immense reduction of costs and an increased efficiency in the stationary industry and the production process industry (cf. Graf 2004, Sennheiser 2008). Meanwhile, an enormous lack of efficiency exists in the construction industry. This lack of efficiency is caused mainly by inadequately planned construction production processes and/or logistics processes. A systematic and holistic logistics planning is essential especially in tunnelling, because narrow logistics paths in the tunnel and high uncertainty (e.g. geology, hydrology etc.) in different construction phases

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can result in inefficiencies. For example, inefficiencies may be caused by searching for construction materials, forced working breaks because of blocked working areas (by logistics or construction tasks), insufficiently dimensioned logistics processes, insufficient maintenance of construction machines, accidents and many other situations. These situations can often be avoided with an adequate planning of all logistics-logistics, logistics-construction and construction-construction interfaces. A similar lack of efficiency in logistics has also been identified also by several authors in the last few years (Vrijhoef and Koskela 1999, Krauss 2005, AbouRizk et al. 2011).

The aim of optimized logistics is to optimally secure the supply and waste disposal for the tunnel driving, the shell construction and the lining works in the tunnel. Therefore, an integrated logistics approach has to influence the construction production processes directly. For example: the use of mechanized formworks and pumped concrete instead of truck-transported concrete with manual formwork panels has a profound effect on these construction processes. Another point to consider is lean construction: Lean construction implies a holistic waste management for all logistics and construction processes so to reach optimized recycling and disposal tasks as well as to avoid unnecessary construction waste.

Hence, the research project “Operational Tunnelling Logistics” was initiated at the ETH Zurich with the aim of developing a planning and decision model for holistically optimized and integrated tunnelling logistics. In the field of construction process management several research papers and books have been published which give direction to the following model (Girmscheid 2010, Kersting and Girmscheid 2011a, Kersting and Girmscheid 2011b). The following project is structured in three different levels: On a **first level,** a general model for the logistics processes in tunnelling is modelled; on a **second level** a superior logistics concept for the general contractor is presented, while on the **third level**, specific logistics concepts for the single contractor are identified. A planning and decision model for an overall logistics system (OLS) is introduced in this paper, as a part of the first level. An OLS can be developed with this model. The model generates a flexible, with multiple criteria optimized tunnelling logistics on the principal’s level. Similar to the configuration, evaluation and selection tool for tunnel construction methods (developed by Schaiter and Girmscheid 2007) the whole model should also adhere to the economical minimal principle.

2. Methodologies and Theories

2.1 Research Methodology

The scientific framework of the presented work is embedded in the hermeneutic science program to understand, interpret and construct new socio-technical realities. Within the hermeneutic science program, Glasersfeld (1998) developed the constructivist research paradigm. Girmscheid (2004) introduced the research methodology of construction management science in accordance with these paradigms. The presented work is directly based on this logic based, deductive methodology.

2.2 Resource-Flow in Supply Chain Management

A key point of Supply Chain Management (SCM) is to organize and control the resource-flow using a holistic approach. All resources, which are required for construction processes, have to be managed. These resources are summarized according to Krauss (2005) in Figure 1. The resource-flow (see Figure 2) in tunnelling consists of procurement, distribution and delivery of resources to the production. After the production, the resource-flow continues with removal, processing and disposal of either the resource itself or its related construction waste. In the example of shotcrete (construction material), the **procurement** includes providing gravel, cement, water and chemicals; **distribution** entails distributing and storing on the installation site, next to **delivery** by pumping processes to the working face; *production* is the spraying process itself including the scaling of the rebound; **removal** involves the transportation of the rebound out of the tunnel; **processing** stands for the storage and treatment of the waste material; **disposal** represents the transport to the according disposal site. All processes, excluding production, belong to the logistics processes and build up the SC of a specific resource. Additionally, a forward and backward-looking information flow has to be guaranteed in the SC between every single process. Missed information or incomplete information leads to misunderstandings and cause additional, non-value-adding process time in construction production processes or logistics processes. Therefore, the information flow has to be standardized in the SC-Network.

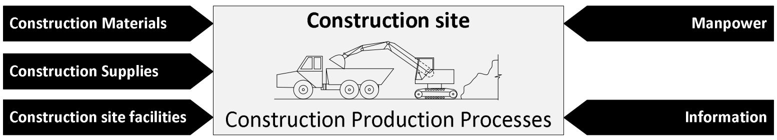


Figure 1: Necessary resources on a construction site

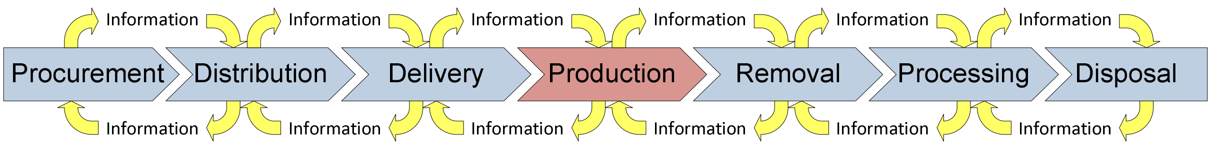


Figure 2: Supply Chain in tunnelling

The management of all SC merged to a supply chain network (SC-Network) is called Supply Chain Management (SCM) and is aligned with a specific strategy. The strategy of the SCM in tunnelling can be deducted in the following way: The main requirement for the logistics in tunnelling (or any other construction project) is to secure the support of the construction production processes. The construction production processes are the actual construction tasks such as excavation, shotcrete spraying, anchor setting as well as shell and lining construction processes. All these construction production processes are leading processes and logistics processes have to support them in any case. An interruption of a construction production process, caused by inaccurate logistics, leads to decreasing productivity of these processes, or in the worst case to an interruption of the construction works.

Therefore, the strategy of SCM in tunnelling should encourage innovative **holistic** logistics systems enabling a **lean** and **flexible** construction operation. **Lean**, because unnecessary transports, processes and waste have to be avoided; **flexible**, because unforeseen events can happen anytime; **holistic**, because between all processes interaction occurs and the overall goal can consequently only be reached with a holistic approach. Missing optimisation of one or several interfaces (and therefore the interactions) can lead to suboptimal process sequences and cause a decreasing efficiency.

2.3 Outranking

Outranking was introduced by Roy (1968) and is a specific field of Operations Research (OR). OR is a scientific discipline which deals with systematic decision making. Multiple Criteria Decision Analysis (MCDA) is a part of OR and Outranking Methods are a specific field of MCDA. Outranking Methods support the decision making process similar to cost-utility-analysis (CUA) or the Analytic Hierarchy Process (AHP). Additionally (compared with CUA or AHP) Outranking Methods can deal with data inaccuracies in the decision making process. Furthermore, a pairwise comparison is calculated including for each pair the specific degree of preference for each pair. Outranking does not generate a single solution of decision problems, rather a ranking of the different alternatives. The ranking can be in one case strict (complete ranking) and in another case show the preferences and the indifferences between alternatives (partial ranking). This means less loss of data during the decision process and therefore a more transparent decision making process.

Basically, two different widespread outranking methods exist: ELECTRE and PROMETHEE. ELECTRE was introduced by Roy (1968). Further, Brans et al. (1986) developed PROMETHEE I (partial ranking) and PROMETHEE II (complete ranking), PROMETHEE allows more stable results than ELECTRE. The stepwise procedure of PROMETHEE is shown in Figure 3. Macharis et al. (2004) integrated AHP in PROMETHEE to calculate the weights in step 3.

Step 1

Determination of deviation based on pair-wise comparison

$$d_j(a,b) = g_j(a) - g_j(b)$$

a,b ≡ Alternatives of the discreet solution set A ($a,b \in A$)

$d_j(a,b)$ ≡ Difference between the evaluation values of *a* and *b* on criterion j of $\vec{T}(A)$

$g_j(a)$ ≡ Achievement of objectives function of the criterion j of alternative *a*

$\vec{T}(A)$ ≡ Target vector with optimization criteria of A

Step 2

Application of the preference function

$$P_j(a,b) = F_j\left[d_j(a,b)\right]$$

$P_j(a,b)$ ≡ Preference function of criterion j of the alternatives *a* and *b* as a function of $d_j(a,b)$

Step 3

Calculation of a global preference index

$$\pi(a,b) = \sum_{j=1}^{k} P_j(a,b) \cdot w_j$$

π(a,b) ≡ Weighted sum of all preference values of alternative *a* over alternative *b*

w_j ≡ Weight of criterion j with *j = 1,…,k*

Step 4

Calculation of outranking flows (The PROMETHEE I partial ranking)

$$\Phi^+(a) = \frac{1}{n-1}\sum_{x \in A}\pi(a,x) \quad \text{und} \quad \Phi^-(a) = \frac{1}{n-1}\sum_{x \in A}\pi(x,a)$$

$\Phi^+(a)$ ≡ Positive outranking flow of alternative *a*

$\Phi^-(a)$ ≡ Negative outranking flow of alternative *a*

n ≡ Amount of alternatives

x ≡ Alternative of the discreet solution set A ($a, x \in A$)

Step 5

Calculation of net outranking flow (The PROMETHEE II complete ranking)

$$\Phi(a) = \Phi^+(a) - \Phi^-(a)$$

Φ(a) ≡ Net outranking flow of alternative *a*

Figure 3: Stepwise procedure for PROMETHEE II [Behzadian et al. (2010)]

3. Developing logistics systems alternatives

3.1 Concept

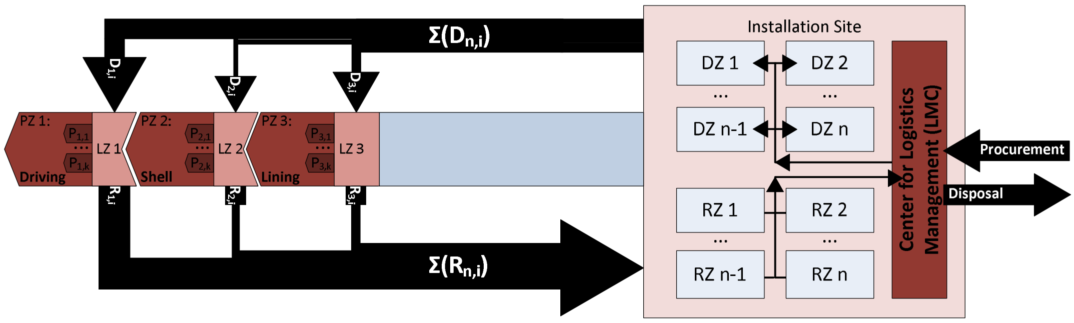
To guarantee a lean and flexible construction operation with a holistic logistics system, every single resource in the construction production processes needs to be planned based on the following procedure, in accordance with the SC introduced in Figure 2:

In a **first step,** the procurement of the resources has to be organized. This includes the raw material production and pre-manufacturing. To allow a fast and high quality construction process: prefabricated components, ready for installation should be preferred. This step must define, if the resource will be delivered by train or by truck and for sensitive resources a back-up system has to be determined as well. This is necessary to secure the SC, even if the regular system fails. The procurement ends with delivery to the Centre for Logistics Management (LMC). In a **second step**, the LMC distributes the resources to the different Delivery Zones (DZ) on the installation site. For this purpose, it is again necessary to define logistics systems alternatives for every resource. This includes mainly storage, but necessary processing processes in DZ, too.

In a **third step**, the LMC defines delivery systems to the Logistics Zones (LZ) nearby the Productions Zones (PZ) and the storing management (amount of stored resources) in the LZ. Deliveries to LZ are initiated by orders of the production zones; order and delivery can be executed either automatically or manually. The logistics zones have to be positioned as close as possible to the PZ, such to avoid any further resource transportation. Directly after the delivery the construction production processes starts. These processes end as soon as the fourth step starts. The **fourth step** of any SC is comprised of removal. Every construction production process generates waste: This waste then, has to be removed and transported to the installation site. The construction waste will be processed on the installation site. Construction waste is for example package material, excess material or excavated material from the heading face. Logistics systems have to be defined for every resource so that the transportation of its construction waste out of the PZ to the LZ in the tunnel and further to the Removal Zone (RZ) on the construction site is guaranteed.

As a **fifth step**, the LMC organizes the collection and processing (e.g. direct recycling on the installation site or separating in component parts) of the various resources. To avoid unnecessary disposal and to choose optimal logistics systems, the focus should remain on local recycling of the construction waste and excavated material. This allows a minimum of transportation after processing and more sustainable construction operations. As a **sixth step,** the unused material and construction waste has to be disposed. For every resource an optimal transportation and waste management system needs to be defined.

By defining possible PLS for every step, various OLS can be assembled by combination of the PLS. Not every combination is realizable, so that as a final step, the realizable systems have to be filtered out in a pre-selection. Only these realizable OLS fulfilling the system requirements of the whole construction project will be analysed in the decision process. The schema, which the realizable OLS have to fit, is shown in Figure 4.



PZ i: Production zone **i**
$\mathbf{P_{i,k}}$: Production process **k** in PZ **i**
LZ i: Logistics zone **i** for PZ i

$\mathbf{D_{n,i}}$: Delivery of ressource **n** for PZ **i**
$\mathbf{R_{n,i}}$: Removal of ressource **n** for PZ **i**

DZ n: Delivery Zone of ressource **n**
RZ n: Removal Zone of ressource **n**

Figure 4: Production and Material Flow in Tunnelling

A construction process chain needs an increasing capacity with every single process to guarantee the overall functionality. Therefore every PLS following a previous PLS must possess a higher capacity to guarantee the functionality of the OLS. Furthermore, a system handling various different resources should be preferred. Another important aspect is that the OLS is dynamic. It changes during the construction phase, depending on the various construction lots. These dependencies between the phases have to be considered in logistics planning as well.

3.2 Example

A hypothetical highway-tunnel project is considered utilizing an open shield machine and a segmental lining in heavily rugged sandstone. Length of the tunnel is 4000 m, diameter is 11 m and the project lasts approximately 4 years. To keep the example simple, only the resources such as excavation material, concrete segments, mortar and personal are treated. **First**, the different possible PLS have to be identified for each step in the SC and for all resources (Table 1). Mainly, the alternatives are transportation by road or train as well as onsite or offsite production/recycling. To avoid any misunderstandings, it is recommended to develop plans and prepare further descriptions of the different PLS. **Second**, the combination of the different PLS to the OLS follows (Table 2). Here, it is inevitable to develop plans and further descriptions of the different OLS for the evaluation.

Table 1: Survey of different PLS along the SC of different resources

	Excavation material	Concrete Segments	Mortar	Personnel
Procurement		Onsite production	Company A (local)	Own personnel
	-	Offsite production with train transport	Company B (non local)	Contractor's personnel
		Offsite production with truck transport		
Distribution		JiT distribution	Storage for 1 week	Accomodation on construction site
	-	Storage for 1 week	Storage for 1 month	No accomodations
		Storage for 1 month		
Delivery		Train	Pumping	Walking
	-	Truck	Train	Buses
			Truck	Train
Production				
Removal	Conveyor belt	Train	Train	Walking
	Train	Truck	Truck	Buses
	Truck			Train
	Dumper			
Processing	Onsite recycling and storing	Onsite recycling and storing	Onsite recycling and storing	
	Offsite recycling	Offsite recycling	Offsite recycling	-
	Onsite storing	Onsite storing	Onsite storing	
Disposal	Truck transport to a local dumping site	Truck transport to a local dumping site	Truck transport to a local dumping site	Dismiss
	Train transport to a non local dumping site	Train transport to a non local dumping site	Train transport to a non local dumping site	Send to another construction site
	Using as filling material in the tunnel			

Table 2: Survey of three different OLS

		Alternatives a	Alternatives b	Alternatives c
Excavtion material	Procurement	-		
	Distribution			
	Delivery			
	Production			
	Removal	Conveyor Belt	Train	Truck
	Processing	Local recycling	Local recycling	Local storing
	Disposal	Truck to local dumping site	Train to non local dumping site	Truck to local dumping site
Concrete Segments	Procurement	Onsite production	Offsite production (train)	Onsite production
	Distribution	Storage for 1 month	Storage for 1 month	Storage for 1 month
	Delivery	Truck	Train	Train
	Production			
	Removal	Truck	Train	Train
	Processing	Onsite recycling	Offsite recycling	Onsite recycling
	Disposal	Truck to local dumping site	Train to non local dumping site	Train to local dumping site

		Alternatives a	Alternatives b	Alternatives c
Mortar	Procurement	Company A (local)	Company B (non local)	Company B (non local)
	Distribution	Storage for 1 week	Storage for 1 month	Storage for 1 week
	Delivery	Truck	Pumping	Pumping
	Production			
	Removal	Truck	Train	Train
	Processing	Onsite recycling	Offsite recycling	Onsite recycling
	Disposal	Truck to local dumping site	Train to non local dumping site	Train to local dumping site
Personnel	Procurement	Own personnel	Contractor's personnel	Own personnel
	Distribution	Accomodation on construction site	No accomodations	Accomodation on construction site
	Delivery	Buses	Train	Train
	Production			
	Removal	Buses	Train	Train
	Processing	-		
	Disposal	Send to another construction site	Dismiss	Send to another construction site

4. Selection of the optimal overall logistics system

4.1 Concept

4.1.1 Decision process

Especially in long term tunnelling projects with complex boundary conditions concerning technical feasibility, environment, economic situation and politics it is difficult to set up a realistic decision model. Therefore, it is necessary to provide a flexible and transparent decision model, to guarantee the consideration of the decision maker's experience as well as to ensure a systematic decision making process. These requirements are fulfilled by the outranking method PROMETHEE. It is possible to consider experience and unclear boundary conditions when making the final decision with PROMETHEE I, the partial outranking. An objective and systematically made decision can be still generated with PROMETHEE II, the complete outranking. Furthermore, it is proposed to use the techniques of AHP to systematize the criteria's weighing process.

4.1.2 Optimization Criteria

To reach a comparable and transparent decision finding process, it is inevitable to use standardized optimization criteria. Additionally, these criteria should be used to measure the performance of each process on the construction site. Measuring of performance permits to managing the SC according to Behrouzi and Wong (2011).

This leads to the conclusion that on one hand, the decision process for optimal logistics systems in tunnelling has to be a multi-criteria decision process and, on another hand these criteria have to be assessable during the planning phase and measureable during the construction phase. To control the SC-Network implies, controlling the degree of achievement with the different criteria as indicators. These indicators have to be calculated from the optimization criteria, so to guarantee a consistent SCM. The optimization criteria are also used to analyse the OLS and to calculate the partial and complete outranking with PROMETHEE. A catalogue of criteria was developed based on these requirements with the results in Table 3. The criteria are separated in main-criteria (costs, flexibility and environment) and sub-criteria. The proposed unit to be considered is defined in Table 3 as well as the maximization or minimization conditions.

Table 3: Evaluated Optimization Criteria with preference functions

					Alternatives						Preference function		Parameters		
					a		b		c				s	q	σ
Costs	f_1	Purchase of resources	C_{res}^{fix}	min	65	[Mio. $]	70	[Mio. $]	62	[Mio. $]	d_1	Gaussian criterion			4.04
	f_2	Acquistion of land	C_{land}^{fix}	min	5	[Mio. $]	5	[Mio. $]	5	[Mio. $]	d_2	Gaussian criterion			1.00
	f_3	Rental of resources	C_{res}^{var}	min	11	[Mio. $]	8	[Mio. $]	12	[Mio. $]	d_3	Gaussian criterion			2.08
	f_4	Rental of land	C_{land}^{var}	min	2	[Mio. $]	1	[Mio. $]	2	[Mio. $]	d_4	Gaussian criterion			0.58
	f_5	Costs of personnel	C_{pers}^{var}	min	44	[Mio. $]	55	[Mio. $]	46	[Mio. $]	d_5	Gaussian criterion			5.86
Flexibility	f_6	Maximal capacity: driving	F_{driv}^{per}	max	30	[m/d]	45	[m/d]	30	[m/d]	d_6	Crit. with lin. preference & indiff.	20	5	
	f_7	Maximal capacity: shell construction	F_{shell}^{per}	max	30	[m/d]	45	[m/d]	30	[m/d]	d_7	Crit. with lin. preference & indiff.	20	5	
	f_8	Maximal capacity: lining	F_{lin}^{per}	max	30	[m/d]	-	[m/d]	30	[m/d]	d_8	Crit. with lin. preference & indiff.	20	5	
	f_9	Revision induced interruption	$F_{inter,r}^{per}$	min	20	[%]	25	[%]	21	[%]	d_9	Gaussian criterion			2.65
	f_{10}	Failure induced interruption	$F_{inter,f}^{per}$	min	0.3	[%]	0.9	[%]	0.1	[%]	d_{10}	Gaussian criterion			0.42
	f_{11}	System redundancy	F_{red}^{res}	max	80	[%]	10	[%]	90	[%]	d_{11}	Gaussian criterion			43.59
	f_{12}	Overcapacity of weakest link	F_{over}^{res}	max	30	[%]	60	[%]	30	[%]	d_{12}	Gaussian criterion			17.32
Environment	f_{13}	Average noise emissions	E_{noise}^{soc}	min	66	[dB]	72	[dB]	68	[dB]	d_{13}	Gaussian criterion			3.06
	f_{14}	Average vibration emissions	E_{vib}^{soc}	min	-	[a]	-	[a]	-	[a]	d_{14}	Gaussian criterion			1.00
	f_{15}	Average dust emissions	E_{dust}^{soc}	min	1	[mg/m³]	1	[mg/m³]	1	[mg/m³]	d_{15}	Gaussian criterion			0.25
	f_{16}	Suplementary traffic	E_{traf}^{soc}	min	50	[Veh/d]	10	[Veh/d]	150	[Veh/d]	d_{16}	Gaussian criterion			72.11
	f_{17}	New infrastructure induced economic growth	E_{econ}^{soc}	max	1.5	[%]	2.0	[%]	1.5	[%]	d_{17}	Gaussian criterion			0.29
	f_{18}	CO_2 output	E_{CO2}^{eco}	min	unknown	[t]	unknown	[t]	unknown	[t]	d_{18}	Gaussian criterion			1.00
	f_{19}	Recycled excavated material	E_{recyc}^{eco}	max	90	[%]	80	[%]	85	[%]	d_{19}	Gaussian criterion			5.00
	f_{20}	Normal construction waste	$E_{waste,n}^{eco}$	min	120'000	[t]	220'000	[t]	170'000	[t]	d_{20}	Gaussian criterion			50000
	f_{21}	Polluted construction waste	$E_{waste,p}^{eco}$	min	20'000	[t]	4'000	[t]	20'000	[t]	d_{21}	Gaussian criterion			9238
	f_{22}	Water consumption	E_{water}^{eco}	min	10'000	[m³/a]	8'000	[m³/a]	11'000	[m³/a]	d_{22}	Gaussian criterion			1528
	f_{23}	Acquistion of land	E_{land}^{eco}	min	-	[m²]	-	[m²]	-	[m²]	d_{23}	Gaussian criterion			1

The **costs** (C_j^{fix}, C_j^{var}) in Table 3 have to be minimized and are separated in fix and variable costs of resources, land and personnel. The **flexibility** (F_j^{per}, F_j^{res}) is separated in the sub-criteria performance and flexibility. The maximal capacities of the logistics system and the assessed percentage of revision and failure induced interruptions determine the criterion's performance. Responsiveness can be measured based on the percentage of system redundancy and the overcapacity of the weakest link in the SC-Network. The main criteria **environment** (E_j^{soc}, E_j^{eco}) is composed by various social and ecological aspects, such as noise, dust and vibrations emissions, supplementary traffic and induced economic growth as well as CO_2 output, construction waste, water consumption or acquisition of land. Together, all these criteria constitute the target vector T (1).

Target vector: (1)

$$\vec{T}(A)=\left[C_{res}^{fix};C_{land}^{fix};C_{res}^{var};C_{land}^{var};C_{pers}^{var};F_{driv}^{per};F_{shell}^{per};F_{lin}^{per};F_{inter,r}^{per};F_{inter,f}^{per};F_{red}^{res};F_{over}^{res};E_{noise}^{soc};E_{vib}^{soc};E_{dust}^{soc};E_{traf}^{soc};E_{econ}^{soc};E_{CO2}^{soc};E_{recyc}^{soc};E_{waste,n}^{eco};E_{waste,p}^{eco};E_{water}^{eco};E_{land}^{eco}\right]^T$$

$$with \quad \left[C_{res}^{fix};C_{land}^{fix};C_{res}^{var};C_{land}^{var};C_{pers}^{var};F_{inter,r}^{per};F_{inter,f}^{per};E_{noise}^{soc};E_{vib}^{soc};E_{dust}^{soc};E_{traf}^{soc};E_{CO2}^{soc};E_{waste,n}^{eco};E_{waste,p}^{eco};E_{water}^{eco};E_{land}^{eco}\right]^T \rightarrow min$$

$$with \quad \left[F_{driv}^{per};F_{shell}^{per};F_{lin}^{per};F_{red}^{res};F_{over}^{res};E_{econ}^{soc};E_{recyc}^{soc}\right]^T \rightarrow max$$

4.2 Example

The three OLS of chapter 3.2 were evaluated in accordance with the defined criteria of Table 3. During the estimation, preference functions were defined for the different criteria as well. The Gaussian function (2) was chosen as preference function for all criteria, except for the maximal capacity. In this specific function with linear preference and indifference area (3) provides the best fit. In total six different preference functions exist and they are defined in Brans et al. (1986).

Gaussian function: (2)

$$P_j(a,b) = P_j(d) = 1 - e^{-\frac{d^2}{2\sigma^2}}$$

Function with linear preference and indifference area: (3)

$$P_j(a,b) = P_j(d) = \begin{cases} 0 & if \quad d \leq 0 \\ \dfrac{d-q}{s-q} & if \quad q \leq d \leq s \\ 1 & if \quad s \leq d \end{cases}$$

d ≡ Differences
s ≡ Threshold value
σ ≡ Standard deviation of the estimated values
q ≡ Indifference-threshold value

According to Figure 3, in a **first step** the differences in the criteria values are calculated in the first six columns of Table 4. If a criterion has to be minimized according to the target vector (1), then the difference is multiplied with -1. In the **second step** all preferences are calculated with the preference functions (2) and (3). A value of 0 means, that both alternatives are equal (indifference) when considering this specific criterion, while a value of 1 expresses strict preference. In the **third step,** the weights of the different criteria are defined next to the calculation of the global preference indexes as the sum of the weighted preferences (Table 4 and Figure 5). The positive and negative outranking flow is calculated in the **fourth step**. Furthermore, the partial outranking is defined (PROMETHEE I in Figure 5). An evaluation using PROMETHEE generated the following results: alternative *a* and alternative *c* are preferred compared to alternative *b*, since π(*a*,*b*) and π(*c*,*b*) are significant higher than π(*b*,*a*) and π(*b*,*c*). Furthermore, alternatives *a* and *c* are indifferent (no significant difference between π(*a*,c) and π(*c*,*a*)). In the **fifth step** the Netto-Outranking-Flow is calculated and the complete outranking is generated (PROMETHEE II in Figure 5) with alternative *a* as the optimal OLS, since Φ(*a*) > Φ(*c*) > Φ(*b*).

Table 4: PROMETHEE-calculation of the example

		Differences						Preferences						Weight	Weight Preferences					
		$d_i(a,b)$	$d_i(a,c)$	$d_i(b,a)$	$d_i(b,c)$	$d_i(c,a)$	$d_i(c,b)$	$P_i(a,b)$	$P_i(a,c)$	$P_i(b,a)$	$P_i(b,c)$	$P_i(c,a)$	$P_i(c,b)$	w_i	$w_i*P_i(a,b)$	$w_i*P_i(a,c)$	$w_i*P_i(b,a)$	$w_i*P_i(b,c)$	$w_i*P_i(c,a)$	$w_i*P_i(c,b)$
Costs	f_1	5	-3	-5	-8	3	8	0.75	0.00	0.00	0.00	0.39	0.97	11.1%	0.08	0.00	0.00	0.00	0.04	0.11
	f_2	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	2.8%	0.00	0.00	0.00	0.00	0.00	0.00
	f_3	-3	1	3	4	-1	-4	0.00	0.12	0.68	0.86	0.00	0.00	5.6%	0.00	0.01	0.04	0.05	0.00	0.00
	f_4	-1	0	1	1	0	-1	0.00	0.00	0.59	0.59	0.00	0.00	2.8%	0.00	0.00	0.02	0.02	0.00	0.00
	f_5	11	0	-11	-11	0	11	0.66	0.00	0.00	0.00	0.00	0.66	11.1%	0.07	0.00	0.00	0.00	0.00	0.07
Flexibility	f_6	-15	0	15	15	0	-15	0.00	0.00	0.67	0.67	0.00	0.00	4.8%	0.00	0.00	0.03	0.03	0.00	0.00
	f_7	-15	0	15	15	0	-15	0.00	0.00	0.67	0.67	0.00	0.00	4.8%	0.00	0.00	0.03	0.03	0.00	0.00
	f_8	30	0	-30	-30	0	30	1.00	0.00	0.00	0.00	0.00	1.00	4.8%	0.05	0.00	0.00	0.00	0.00	0.05
	f_9	5	1	-5	-4	-1	4	0.39	0.02	0.00	0.00	0.00	0.27	4.8%	0.02	0.00	0.00	0.00	0.00	0.01
	f_{10}	0.6	-0.2	-0.6	-0.8	0.2	0.8	0.86	0.00	0.00	0.00	0.20	0.97	4.8%	0.04	0.00	0.00	0.00	0.01	0.05
	f_{11}	70	-10	-70	-80	10	80	0.93	0.00	0.00	0.00	0.05	0.97	4.8%	0.04	0.00	0.00	0.00	0.00	0.05
	f_{12}	-30	0	30	30	0	-30	0.00	0.00	0.39	0.39	0.00	0.00	4.8%	0.00	0.00	0.02	0.02	0.00	0.00
Environment	f_{13}	6	2	-6	-4	-2	4	0.99	0.39	0.00	0.00	0.00	0.86	3.0%	0.03	0.01	0.00	0.00	0.00	0.03
	f_{14}	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	3.0%	0.00	0.00	0.00	0.00	0.00	0.00
	f_{15}	-0.5	-0.25	0.5	0.25	0.25	-0.25	0.00	0.00	0.12	0.03	0.03	0.00	3.0%	0.00	0.00	0.00	0.00	0.00	0.00
	f_{16}	-40	100	40	140	-100	-140	0.00	1.00	0.86	1.00	0.00	0.00	3.0%	0.00	0.03	0.03	0.03	0.00	0.00
	f_{17}	-0.5	0	0.5	0.5	0	-0.5	0.00	0.00	0.12	0.12	0.00	0.00	3.0%	0.00	0.00	0.00	0.00	0.00	0.00
	f_{18}	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	3.0%	0.00	0.00	0.00	0.00	0.00	0.00
	f_{19}	10	5	-10	-5	-5	5	0.86	0.39	0.00	0.00	0.00	0.39	3.0%	0.03	0.01	0.00	0.00	0.00	0.01
	f_{20}	100000	50000	-100000	-50000	-50000	50000	0.86	0.39	0.00	0.00	0.00	0.39	3.0%	0.03	0.01	0.00	0.00	0.00	0.01
	f_{21}	-16000	0	16000	16000	0	-16000	0.00	0.00	0.99	0.99	0.00	0.00	3.0%	0.00	0.00	0.03	0.03	0.00	0.00
	f_{22}	-2000	1000	2000	3000	-1000	-3000	0.00	0.20	0.59	0.86	0.00	0.00	3.0%	0.00	0.01	0.02	0.03	0.00	0.00
	f_{23}	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	3.0%	0.00	0.00	0.00	0.00	0.00	0.00

Global Preference Index					
π(a,b)	π(a,c)	π(b,a)	π(b,c)	π(c,a)	π(c,b)
0.39	0.08	0.22	0.24	0.06	0.38
Outranking Flow					
Positive			Negative		
$\Phi^+(a)$	$\Phi^+(b)$	$\Phi^+(c)$	$\Phi^-(a)$	$\Phi^-(b)$	$\Phi^-(c)$
0.24	0.23	0.22	0.14	0.39	0.16
Netto Outranking Flow					
$\Phi(a)$		$\Phi(b)$		$\Phi(c)$	
0.10		-0.16		0.06	

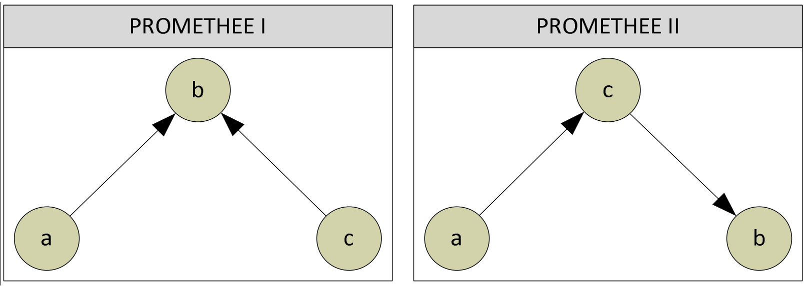


Figure 5: Results of PROMETHEE I & II

5. Results

The whole model is summarized in Figure 6. In a **first phase** (identification of different PLS), different handling systems have to be planned for each of the five different types of resource (Figure 1). This includes the procurement, distribution and delivery of the resources as well as the removal, processing and disposal of the construction waste (Figure 2). The sub-processes and single activities have to be considered for the identifications of the PLS as well. In a **second phase** (identification of OLS) the various PLS will be assembled to different OLS (system combination). After the combination a pre-selection follows, because some PLS-combinations do not work as an OLS. Also, some other OLS may not be realizable because of political or other boundary conditions. These not realizable systems have to be sorted out to optimize the effort in the decision process. The realizable OLS are analysed with PROMETHEE and the target vector (1). These criteria in the target vector should also be used to control the optimal OLS as the effective solution during the construction works. Additionally, the decision maker's experience is considered in the final decision due to the partial outranking of PROMETHEE I. Consequently, an objective decision can be provided for the optimal OLS with the Netto Outranking Flow.

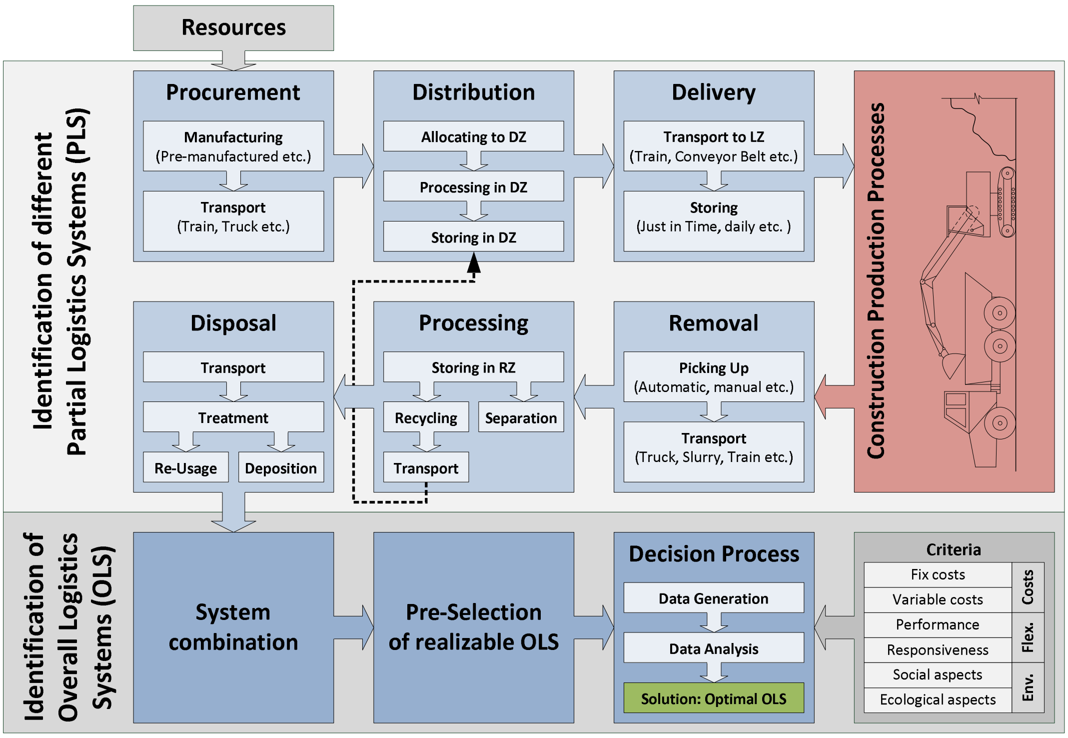


Figure 6: Planning model of an optimal OLS in tunnelling

6. Conclusion

SCM in the stationary industry is well investigated and is continuing improving. But the implementation of the ideas of SCM in the construction industry is a novel topic and not yet well investigated. Basic models exist, which describe, how SCM in construction production processes can be implemented. The present publication developed the existing models further to include implementation of SCM and OR in logistics planning in tunnelling. Therefore, the presented planning model can be used as a basis for a systematic and flexible development of OLS in tunnelling.

The advantage of this model is a holistic consideration of the material flow, with the construction production processes as the leading processes. The logistics processes can be optimally scheduled, to support the construction production processes with all necessary resources. Furthermore, all resources are considered including manpower and information.

Nevertheless, some parts of the proposed planning model can still be improved on. This concerns specifically the consideration of the different construction phases, the system combination, the data generation in the decision process and the information flow. The consideration of construction phases has to be implemented in the system combination, so to ensure an integrated approach of the total system. The data generation in the decision process of the existing model is based on an estimation of the values of the various criteria. The final aim of the model is to be integrated into a logistics simulation, which generates the values for the different OLS. To guarantee a stable information flow, a central information logistics should be developed, similar to the central logistic management introduced by Girmscheid and Etter (2012a) and Girmscheid and Etter (2012b). This centre manages all information generated by the whole project and ensures the support of all parties and processes with the necessary information. Additionally, the aspect and influence of long-term partnerships in tunnelling logistics should be investigated in greater detail.

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